

# Optical and Energy Performance Analysis of Multi-Layer Glazing Systems Incorporating Solid–Solid Phase Change Materials

by

Hossein ARASTEH

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# **Analyse des performances optiques et énergétiques de systèmes de vitrage multicouches intégrant des matériaux à changement de phase solide–solide**

Hossein ARASTEH

## **RÉSUMÉ**

Les systèmes de vitrage constituent l'un des composants les plus sensibles du point de vue énergétique de l'enveloppe du bâtiment en raison de leur faible inertie thermique et de leur forte transmittance solaire, en particulier dans les bâtiments fortement vitrés. L'intégration de matériaux à changement de phase dans les systèmes de fenestration est apparue comme une stratégie passive prometteuse pour améliorer la régulation thermique; toutefois, l'obtention de gains énergétiques sans compromettre les performances optiques et en assurant un comportement adapté aux conditions climatiques demeure un défi majeur. Cette thèse examine les performances optiques et énergétiques de systèmes de vitrage multicouches intégrant des matériaux à changement de phase solide–solide comme dispositifs de stockage latent d'énergie thermique. Une modélisation numérique avancée, fondée sur la dynamique des fluides numérique et la méthode des volumes finis, est mise en œuvre afin de simuler les transferts thermiques transitoires, les échanges radiatifs, le comportement de transition de phase ainsi que la convection naturelle au sein des cavités de vitrage sous des conditions climatiques réalistes. Les performances des systèmes de vitrage proposés sont évaluées pour différents climats, orientations et scénarios météorologiques extrêmes. Les résultats montrent que les matériaux à changement de phase solide–solide peuvent accroître l'inertie thermique et réduire les besoins en chauffage et en climatisation dans les climats à prédominance de chauffage et les climats mixtes, lorsque des températures de transition de phase et des propriétés matérielles appropriées sont sélectionnées. L'efficacité du système proposé se révèle fortement dépendante du climat. Dans les climats à prédominance de chauffage, tels que celui de Montréal, la convection naturelle joue un rôle négligeable en conditions estivales, tout en exerçant une influence significative sur la dynamique de transition de phase et les performances énergétiques globales en période hivernale. Les analyses optiques confirment en outre que des couches de matériaux à changement de phase soigneusement conçues permettent de maintenir une transparence visuelle complète durant les heures d'occupation, ce qui en favorise l'application dans les bâtiments commerciaux et de bureaux. Globalement, cette thèse propose une évaluation complète et fondée sur la physique des systèmes de vitrage intégrant des matériaux à changement de phase et fournit des éléments quantitatifs ainsi que des orientations de conception pour le développement de technologies de fenestration intelligentes, écoénergétiques et adaptées aux conditions climatiques.

**Mots-clés:** matériaux à changement de phase solide–solide, systèmes de vitrage intelligents, énergie des bâtiments, performance optique, dynamique des fluides numérique



# **Optical and Energy Performance Analysis of Multi-Layer Glazing Systems Incorporating Solid–Solid Phase Change Materials**

Hossein ARASTEH

## **ABSTRACT**

Glazing systems represent one of the most energy-sensitive components of the building envelope due to their low thermal inertia and high solar transmittance, particularly in highly glazed buildings. Integrating phase change materials into fenestration systems has emerged as a promising passive strategy to enhance thermal regulation; however, achieving energy benefits without compromising optical performance and ensuring climate-appropriate behavior remain key challenges. This thesis investigates the optical and energy performance of multi-layer glazing systems incorporating solid–solid phase change materials as latent thermal energy storage media. Advanced numerical modeling based on computational fluid dynamics and finite volume methods is employed to simulate transient heat transfer, radiative exchange, phase transition behavior, and natural convection within glazing cavities under realistic climatic boundary conditions. The performance of the proposed glazing systems is evaluated across multiple climates, orientations, and extreme weather conditions. The results demonstrate that solid–solid phase change materials can enhance thermal inertia and reduce heating and cooling demands in heating-dominated and mixed climates when appropriate phase transition temperatures and material properties are selected. The effectiveness of the proposed system is shown to be strongly climate-dependent. In heating-dominated climates, such as Montreal, natural convection plays a negligible role under summer conditions, while exerting a significant influence on phase transition dynamics and overall energy performance during winter. Optical analyses further confirm that carefully designed phase change material layers allow full visual transparency during occupied hours, supporting their applicability in commercial and office buildings. Overall, this thesis provides a comprehensive, physics-based assessment of phase change material-enhanced glazing systems and offers quantitative insights and design guidance to support the development of energy-efficient and climate-responsive smart fenestration technologies.

**Keywords:** solid–solid phase change materials, smart glazing systems, building energy, optical performance, computational fluid dynamics



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|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|

## **LIST OF ABBREVIATIONS AND ACRONYMS**

|           |                                                                        |
|-----------|------------------------------------------------------------------------|
| CFD       | Computational fluid dynamics                                           |
| DGW       | Double-glazed window                                                   |
| DGW-REF   | Reference double-glazed window                                         |
| DGW-SSPCM | Double-glazed window integrated with solid–solid phase change material |
| DO        | Discrete Ordinates (radiation model)                                   |
| HVAC      | Heating, ventilation, and air conditioning                             |
| NC        | Natural convection                                                     |
| PCM       | Phase change material                                                  |
| REF       | Reference configuration                                                |
| SLPCM     | Solid–liquid phase change material                                     |
| SSPCM     | Solid–solid phase change material                                      |



## LIST OF SYMBOLS AND UNITS OF MEASUREMENT

|        |                                                                           |
|--------|---------------------------------------------------------------------------|
| A      | Area, $\text{m}^2$                                                        |
| $c_p$  | Specific heat capacity, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$   |
| d      | Air gap depth, m                                                          |
| d'     | Optical thickness, m                                                      |
| E      | Energy, J                                                                 |
| g      | Gravitational acceleration, $\text{m}\cdot\text{s}^{-2}$                  |
| h      | Heat transfer coefficient, $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ |
| $h_s$  | Sensible enthalpy, $\text{J}\cdot\text{kg}^{-1}$                          |
| H      | Enthalpy, $\text{J}\cdot\text{kg}^{-1}$                                   |
| I      | Radiation intensity, $\text{W}\cdot\text{m}^{-2}$                         |
| k      | Thermal conductivity, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$      |
| $\ell$ | Air gap height, m                                                         |
| L      | Latent heat of fusion, $\text{kJ}\cdot\text{kg}^{-1}$                     |
| n      | Refractive index, dimensionless                                           |

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|                   |                                                                                    |
|-------------------|------------------------------------------------------------------------------------|
| $p$               | Pressure, Pa                                                                       |
| $P_{\text{atm}}$  | Atmospheric pressure, Pa                                                           |
| $q''$             | Total heat flux through air gap, $\text{W}\cdot\text{m}^{-2}$                      |
| $R$               | Specific gas constant for dry air, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$ |
| $Ra$              | Rayleigh number, dimensionless                                                     |
| $Ra_{\text{avg}}$ | Time-averaged Rayleigh number, dimensionless                                       |
| $Re$              | Reynolds number, dimensionless                                                     |
| $Re_{\text{avg}}$ | Time-averaged Reynolds number, dimensionless                                       |
| $\vec{r}$         | Position vector, m                                                                 |
| $s$               | Sample thickness (optical path length), m                                          |
| $\vec{s}$         | Direction vector, dimensionless                                                    |
| $\vec{s}'$        | Scattering direction vector, dimensionless                                         |
| $t$               | Time, s                                                                            |
| $T$               | Temperature, $^{\circ}\text{C}$                                                    |
| $T_c$             | Phase transition temperature, $^{\circ}\text{C}$                                   |



|                  |                                                                      |
|------------------|----------------------------------------------------------------------|
| $\Delta H$       | Latent heat, $\text{J}\cdot\text{kg}^{-1}$                           |
| $\Delta T$       | Air gap temperature difference, $^{\circ}\text{C}$                   |
| $\Delta T_c$     | Phase transition temperature range, $^{\circ}\text{C}$               |
| $v$              | Velocity magnitude, $\text{m}\cdot\text{s}^{-1}$                     |
| $\vec{V}$        | Velocity vector, $\text{m}\cdot\text{s}^{-1}$                        |
| $V_{\text{avg}}$ | Volume-averaged velocity, $\text{m}\cdot\text{s}^{-1}$               |
| $x$              | x-direction coordinate, m                                            |
| $y$              | y-direction coordinate, m                                            |
| $z$              | z-direction coordinate, m                                            |
| $\alpha$         | Thermal diffusivity, $\text{m}^2\cdot\text{s}^{-1}$                  |
| $\beta$          | Transparency fraction, dimensionless                                 |
| $\beta'$         | Thermal expansion coefficient, $\text{K}^{-1}$                       |
| $\lambda$        | Thermal conductivity, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ |
| $\mu$            | Dynamic viscosity, $\text{Pa}\cdot\text{s}$                          |
| $\nu$            | Kinematic viscosity, $\text{m}^2\cdot\text{s}^{-1}$                  |

XXX

|                     |                                         |
|---------------------|-----------------------------------------|
| $\rho$              | Density, $\text{kg}\cdot\text{m}^{-3}$  |
| $\sigma_{\text{a}}$ | Absorption coefficient, $\text{m}^{-1}$ |
| $\sigma_{\text{s}}$ | Scattering coefficient, $\text{m}^{-1}$ |
| $\sigma_{\text{e}}$ | Extinction coefficient, $\text{m}^{-1}$ |
| $\tau$              | Transmittance, dimensionless            |
| $\emptyset$         | Phase function, dimensionless           |
| $\Omega'$           | Solid angle, rad                        |

## INTRODUCTION

The building sector is widely recognized as one of the most energy-intensive sectors worldwide and a major contributor to greenhouse gas emissions. According to international energy assessments, residential and commercial buildings together account for approximately one third of global final energy consumption and nearly 15% of direct carbon dioxide emissions, with the combined share increasing to approximately 40–48% when indirect emissions associated with electricity generation and material production are included (*International Energy Agency, Tracking Buildings*, 2022). These figures underline the significant role of buildings in global energy and climate challenges. Moreover, current projections indicate that achieving carbon neutrality in buildings by 2050 remains a substantial challenge, particularly in the context of continued population growth, rapid urbanization, and the expansion of building floor area across both developed and developing regions (Long et al., 2025). Additional pressures arise from increasing demand for space cooling in warm and humid climates, rising expectations for indoor comfort, and greater penetration of energy-intensive appliances and equipment. As a result, space heating and cooling already represent the dominant share of building energy use, and this dominance is expected to intensify further if effective mitigation strategies are not implemented (Cao et al., 2016). These trends highlight the urgent need for scientifically sound and scalable solutions aimed at reducing energy demand and associated emissions in the built environment.

At the scale of individual buildings, the envelope plays a central role in controlling energy exchange between indoor and outdoor environments. Acting as a physical and environmental boundary, the building envelope governs heat transfer, moisture transport, air leakage, and solar gains, all of which directly influence indoor comfort and energy performance (Mirrahimi et al., 2016). Among the various envelope components, fenestration systems—including windows, curtain walls, and skylight devices—are particularly influential due to their direct exposure to external climatic conditions. These transparent elements are widely identified as the primary pathways for heat loss and heat gain in buildings and are responsible for a substantial portion of overall thermal exchange between indoor and outdoor environments (Ming et al., 2024). Consequently, improving the thermal performance of fenestration systems

has become a priority in efforts to reduce energy demand associated with heating, ventilation, and air conditioning systems.

Research aimed at enhancing the performance of glazing systems has traditionally focused on three broad strategies: controlling solar radiation, increasing thermal resistance, and enhancing thermal inertia. Solar control strategies seek to regulate the amount and spectral characteristics of incoming solar radiation through the use of advanced glazing technologies. These include chromogenic materials such as thermochromic and thermotropic systems that dynamically respond to temperature changes (Araújo et al., 2023; Sun et al., 2021), photovoltaic glazing that converts a portion of incident solar radiation into electricity (Radwan et al., 2020), switchable glazing systems that adjust optical properties on demand (Ke et al., 2022), and surface treatments such as low-emissivity and laminated coatings designed to reduce radiative heat transfer (Maduru and Shaik, 2022; Sorooshnia et al., 2025). In parallel, improvements in thermal resistance have been achieved by modifying glazing configurations, including the use of inert gases within multi-layer glazing cavities to reduce conductive and convective heat transfer (Taleb and Antony, 2020), as well as by incorporating low thermal conductivity materials such as aerogels and hydrogels (Mohamed et al., 2023; Soares et al., 2023). While these approaches can effectively reduce heat transfer through glazing systems, they primarily address steady-state performance and do not significantly increase the thermal mass of transparent envelope components.

The inherently low thermal inertia of glazing systems therefore remains a critical limitation, particularly in buildings with large transparent areas. Glazing components provide essential architectural and functional benefits, including daylighting, visual connection to the outdoor environment, and passive solar gains; however, these benefits are accompanied by challenges related to high solar transmittance (0.80–0.87 for clear single glazing), limited thermal resistance ( $0.17 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$  for single glazing, up to  $1 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$  for triple low-e), and minimal heat storage capacity ( $9 \text{ kJ} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$  per 4 mm pane), with the latter reflecting the low thermal inertia of glazing compared to opaque walls. (Gloriant et al., 2021). Previous studies have shown that glazed components can account for a considerable portion of total building energy consumption, especially in buildings characterized by high window-to-wall ratios and

extensively glazed façades (Hee et al., 2015). Numerical investigations further demonstrate that glazing area, orientation, and configuration exert a strong influence on overall energy performance, with optimal solutions varying significantly depending on climate, building use, and operational conditions (Bumajdad et al., 2020). These findings emphasize that improving glazing performance requires approaches that go beyond conventional insulation and solar control measures.

In parallel with these performance challenges, broader trends in the construction industry have further amplified the importance of high-performance glazing systems. The increasing adoption of lightweight building technologies, driven by benefits such as reduced material consumption, faster construction timelines, and architectural flexibility, has led to the widespread use of curtain walls and highly glazed façades, particularly in urban environments (Leśniak and Górka, 2018). While these design choices enhance daylight availability and aesthetic quality, they can substantially increase thermal losses and gains if not carefully optimized. Previous research highlights the inherent trade-offs between daylighting, thermal comfort, and energy efficiency, emphasizing that an appropriate balance must be achieved based on envelope properties, building function, and local climatic conditions (Yu et al., 2020). Climate classification frameworks, such as the Köppen–Geiger system, provide a valuable basis for evaluating and comparing glazing performance across regions with similar long-term climatic characteristics, enabling climate-responsive design strategies to be developed and assessed (Beck et al., 2018).

Within this context, increasing the thermal inertia of glazing systems through thermal energy storage has emerged as a promising complementary strategy. Thermal energy storage technologies are widely recognized for their potential to improve energy efficiency not only in buildings but also in other energy systems, including solar power plants, photovoltaic installations, and heat pump applications (Khamlich et al., 2021; Koşan and Aktaş, 2021; Navakrishnan et al., 2021). Among available storage methods, latent heat storage offers a substantially higher energy storage density than sensible heat storage, making it particularly attractive for integration into building envelopes where space and thickness are often constrained (Farid et al., 2004; Hanchi et al., 2017). Phase change materials are the most

commonly used latent heat storage media and have been extensively studied for their ability to absorb and release thermal energy during phase transitions, thereby moderating indoor temperature fluctuations, shifting peak thermal loads, and reducing heating and cooling energy demand (Huang et al., 2021; Li et al., 2022; Dong Li et al., 2022; Rathore et al., 2022).

Phase change materials have been incorporated into both opaque and transparent components of the building envelope, including windows (Wei et al., 2022), curtain walls (Liu and Cui, 2015), glazed roofs (Zhang et al., 2022), walls (Sun et al., 2022), ceilings (Khattari et al., 2022), and floors (Sun et al., 2020). In glazing applications, the phase change mechanisms most relevant to thermal regulation occur through solid–liquid and solid–solid transitions (Akeiber et al., 2016). Solid–liquid phase change materials have been widely investigated; however, their application in glazing systems often requires encapsulation to prevent leakage and may reduce thermal resistance when the material occupies the glazing cavity. In contrast, solid–solid phase change materials offer several distinct advantages for glazing applications, including the absence of leakage, reduced phase segregation, minimal volume change, low subcooling, encapsulation-free implementation, enhanced durability under repeated thermal cycling, and more stable optical properties (Fallahi et al., 2017).

Solid–solid phase change materials remain in a solid state throughout the phase transition process and can be applied as thin layers on glazing surfaces while preserving the low thermal conductivity of the intervening air or inert gas layer. At the molecular scale, these materials undergo transitions between semi-crystalline and amorphous states, in which only the soft molecular segments participate in the phase change while being supported by a rigid polymeric backbone with a higher melting temperature (Gao et al., 2021; Wang et al., 2023). Although this constrained molecular mobility results in lower phase transition enthalpy compared to solid–liquid phase change materials, it provides improved structural stability and optical consistency, which are critical requirements for transparent envelope applications. Despite these advantages, research on solid–solid phase change materials in smart glazing systems remains limited, and experimental investigations are particularly scarce (Wang et al., 2023). Existing review studies consistently emphasize the need for further research to clarify material selection criteria, thermophysical behavior, and climate-specific performance in order to fully

exploit the potential of solid–solid phase change materials in advanced glazing systems (Raj et al., 2020).

### **Thesis structure**

This thesis is organized into six chapters. Chapter 1 establishes the scientific background and identifies key research gaps, Chapters 2 through 5 present the original research contributions of this work, and Chapter 6 synthesizes the main findings and outlines directions for future research.

- **Chapter 1:** A critical literature review of solid-liquid phase change material (SLPCM)- and solid-solid phase change material (SSPCM)-incorporated glazing units, including passive and active approaches and combined technologies, with emphasis on thermal and energy performance trends, optical limitations, and research gaps relevant to SLPCM and SSPCM implementation. Following the literature review, the chapter presents the research gap and problem statement and concludes with the research objectives.
- **Chapter 2:** Development and validation of a CFD-based numerical framework for SSPCM-integrated double glazing, followed by a parametric investigation under real climatic boundary conditions to quantify energy performance sensitivity to SSPCM transition temperature and transition range.
- **Chapter 3:** Climate-dependent energy and transparency assessment of SSPCM-enhanced double glazing under extreme and variable weather conditions (sunny and cloudy days) across Montreal, Vancouver, and Miami, with detailed quantification of energy savings and penalties and conditions for maintaining transparency during office hours.
- **Chapter 4:** Extended multi-climate evaluation of SSPCM-glazing performance with focus on the interaction between SSPCM transition behaviour and weather-driven forcing, further clarifying when the concept is beneficial and identifying climates where limitations dominate.

- **Chapter 5:** Detailed investigation of natural convection effects in SSPCM-enhanced glazing cavities, demonstrating the conditions under which natural convection has negligible influence and the conditions under which it substantially alters phase change dynamics and energy performance, thereby informing modelling simplifications and design decisions.
- **Chapter 6:** This chapter synthesizes the main findings from Chapters 2 to 5 and discusses them in a unified framework to highlight overarching trends, key mechanisms, and practical implications for SSPCM-integrated glazing systems. The results are critically analyzed with respect to climate dependency, energy performance trade-offs, optical behavior, and modeling assumptions. The limitations of the present study are explicitly discussed, and directions for future research are proposed, including long-term performance assessment, material development, and the integration of SSPCM-based glazing systems into advanced building envelope designs.



**CHAPTER 1**  
**LITERATURE REVIEW**  
**ENERGY AND THERMAL PERFORMANCE ANALYSIS OF**  
**PCM-INCORPORATED GLAZING UNITS COMBINED WITH PASSIVE AND**  
**ACTIVE TECHNIQUES: A REVIEW STUDY**

Hossein Arasteh <sup>a</sup>, Wahid Maref <sup>a</sup>, Hamed H. Saber <sup>b</sup>

<sup>a</sup> Department of Construction Engineering, École de technologie supérieure,  
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C1K3

<sup>b</sup> Deanship of Research and Industrial Development, and Mechanical Engineering  
Department at Jubail Industrial College, Royal Commission of Jubail and Yanbu, Jubail  
Industrial City, 31961, Saudi Arabia

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**Abstract**

The building envelope provides thermal comfort, an excellent visual view, and sunlight for the occupants. It consists of two parts: (i) an opaque (non-transparent) part (e.g., walls and roofs) and (ii) a transparent part (e.g., windows, curtain walls, and skylight devices). Recently, the use of fully-glazed facades, especially in large cities, has increased due to their aesthetical and structural advantages. This has led this study to review the performance of the currently passive smart glazing technologies. Phase Change Materials (PCMs) as latent energy storage material is the focus of this review, as well as other individual and combined techniques, including shading systems, solar cells (photovoltaic), and chromogenic (thermotropic and thermochromic) materials. PCM-integrated glazing systems have been extensively studied and rapidly developed over the past several decades from the standpoint of unique system designs, such as passive, active, and passive/active mixed designs, intelligent management, and sophisticated controls. In the academic literature, numerous studies on PCM-integrated building envelopes have been conducted, but a comprehensive review of PCM-integrated GUs

combined with other passive and active techniques using dialectical analysis and comparing the climatic conditions of each study using Köppen-Geiger climate classification climate classification has been performed only rarely. Consequently, the primary objective of this study is to reduce this discrepancy for all types of glazing, excluding glazed roofs. This review article also contains literature tables as well as highlights, limitations, and further research suggestions at the end of each subsection.

**Keywords:** smart glazing, PCM, solar photovoltaic, thermotropic, thermochromic, Köppen-Geiger climate classification

## 1.1 Solid-liquid phase change materials: Review Paper

### 1.1.1 Introduction

Residential and building construction together account for about one-third of global final energy consumption and almost 15% of direct CO<sub>2</sub> emissions (40–48% direct and indirect CO<sub>2</sub> emissions), according to the International Energy Agency (IEA), as shown in Figure 1.1 (*International Energy Agency, Tracking Buildings, 2022*). Buildings and building construction continue to require more energy as a result of increased energy availability in emerging nations, rising air conditioning demand in tropical regions, increased ownership and usage of energy-intensive equipment, and quick development in building floor space. Energy trends in the building sector prove the high participation of buildings' heating and cooling share in energy use and CO<sub>2</sub> emissions. If this trend continues, more than 50% of the total energy consumed in the buildings will be used for space cooling and heating up to 2050 (*International Energy Agency, Tracking Buildings, 2022*). Therefore, applying scientific methods to decrease energy consumption and, consequently, CO<sub>2</sub> emissions in this sector could save the environment and reduce the consequences of global warming to a great extent.

The building envelope provides a comfortable zone for the indoor space, including thermal and moisture comfort, acting as a shield against the largely variable and mostly undesired outdoor conditions. In recent years, numerous researchers have adopted various passive and active techniques to enhance the energy performance of the building envelope. Passive options

include natural ventilation, solar radiation, and nighttime radiation from the earth and sky, whereas active solutions include mechanical ventilation and active cooling/heating of water or fluids. Active ventilation and active water-based cooling systems, which improve the system controllability, heat dissipation, and cooling, consequently boosting the system performance, are advantages of active systems over passive techniques. The disadvantages include the energy consumption of pumps and fans, the possibility of liquid leakage, and the high cost of maintenance, etc. (Zhou et al., 2020).

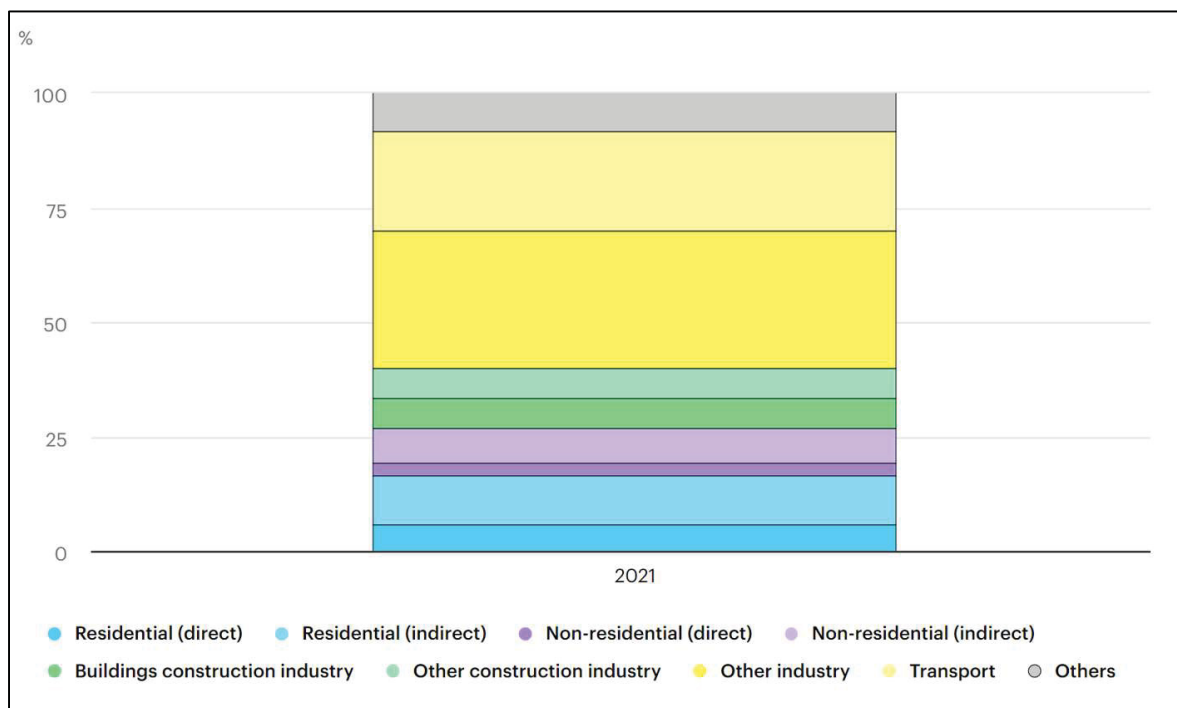


Figure 1.1 Global energy and process emissions from buildings, including embodied emissions from new construction taken from  
(*International Energy Agency, Tracking Buildings, 2022*)

Utilizing Phase Change Materials (PCMs) as a passive approach incorporated into the building envelope has lately garnered the interest of researchers due to the high latent energy storage resulting in a greater thermal mass for structures. PCMs have been incorporated into the building envelope's transparent part, which includes windows (Wei et al., 2022), curtain walls (Liu and Cui, 2015), and glazed roofs (Zhang et al., 2022), and the opaque part that includes walls (Sun et al., 2022), ceilings (Khattari et al., 2022), and floors (Sun et al., 2020). The usage

of PCMs can play a crucial role in managing the indoor temperature, transferring the peak load to off-peak hours, and reducing the energy required for space cooling and heating; nevertheless, further scientific research is required based on recent review studies on PCMs.

Glazing components, such as windows, glazing facades, and glazed roofs, allow daylighting, views of the outdoors, and passive solar gain. Overall, 30% of the building's energy consumption is accounted for by the glazed portions of the building envelope, and when there is a large window-to-wall ratio (WWR), this can grow to 60% by using windows and 90% by using curtain walls (Hee et al., 2015). Concerning the thermal effect of WWR on building energy efficiency, Saber and Hajiah (2020) developed a numerical model to examine the energy performance of PCM-incorporated building envelopes (walls and roofs) in different WWRs ranging from 10 to 70 percent. They discovered that WWRs of 10% and 40% produce the lowest and largest total annual loads, respectively. Despite the fact that several studies have been conducted on energy-saving methods for the glazing unit (GU) parts of a building, this part still suffers from a high solar transmittance factor, high thermal conductivity (low thermal resistance), and low thermal mass (Gloriant et al., 2021).

The type of structure and the climate of the building's location are two of the most powerful aspects determining the energy-saving technologies of glazing units. Based on the Köppen-Geiger climate classification, there are five major climate types (see Table 1.1) (Beck et al., 2018). In addition, Figure 1.2 depicts the world Map of Köppen-Geiger climate classification updated with mean monthly CRU TS 2.1 temperature and VASCLimO v1.1 precipitation data for the period 1951 to 2000 on a regular 0.5-degree latitude/longitude grid. In what follows, all the reviewed studies are designated to a Köppen-Geiger climate class type (Beck et al., 2018). Figure 1.2 corresponds a code to each location with a specific climatic condition. Hence, locations with similar Köppen-Geiger codes to each other can be treated almost the same.

The construction industry has shifted toward the usage of lightweight structures due to its major benefits, such as less material consumption and shorter construction times. Using curtain walls as building glazing facades rather than conventional windows or masonry as a lightweight building technology (Leśniak and Górka, 2018) has resulted in the creation of nearly fully-glazed buildings and skyscrapers, particularly in large cities. It also provides an

architecturally desirable view for the residents and a picturesque view of the front from the interior. In contrast, the low thermal resistance of glazing units and their increased use in recent years have piqued the interest of researchers seeking to maximize the energy performance of glazing units by taking into account the smallest change in optical qualities. Yu et al. (2020) addressed to the paradoxical influence of daylight on indoor thermal and visual comfort and energy use, stating that a “thermal-daylighting balance” must be struck between them. The authors determined that the thermal daylighting balance is dependent on the individual properties of the building envelope and the local climate.

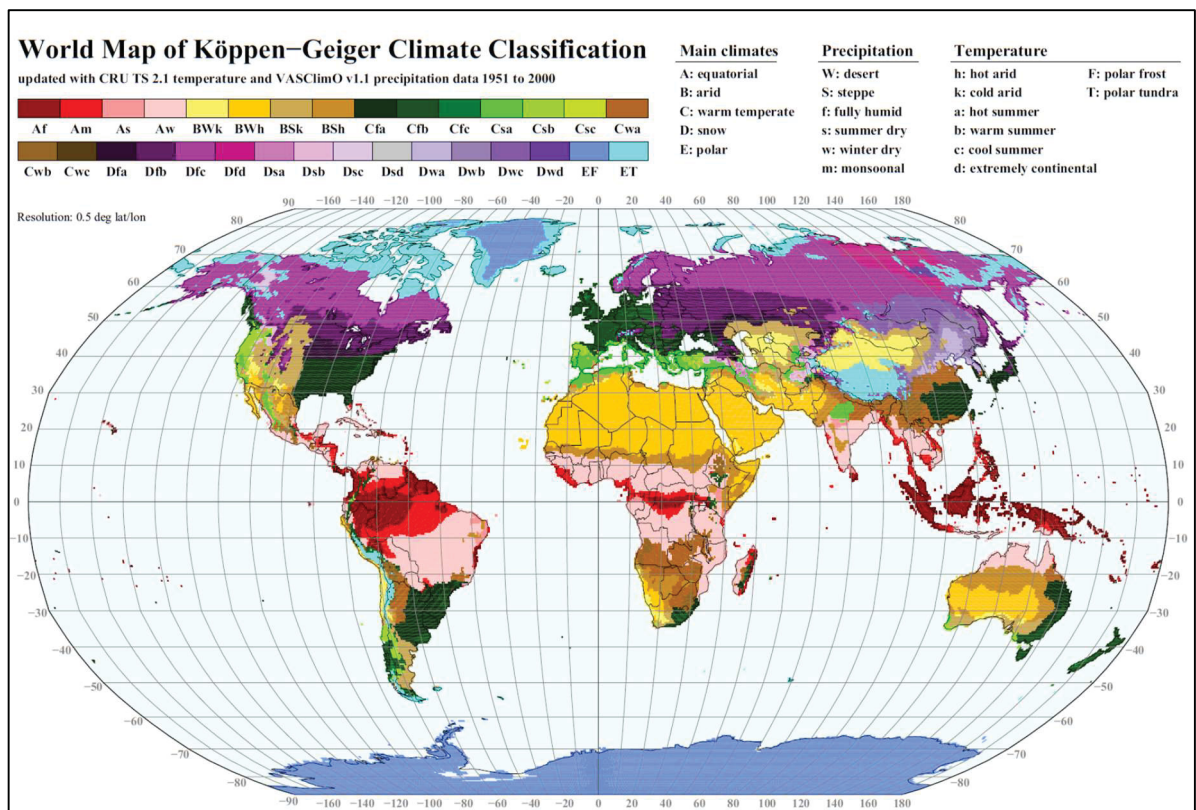


Figure 1.2 World Map of Köppen-Geiger climate classification updated with mean monthly CRU TS 2.1 temperature and VASCLimO v1.1 precipitation data for the period 1951 to 2000 on a regular 0.5 degree latitude/longitude grid taken from Kottek et al. (2006, p. 261)

Table 1.1 Köppen-Geiger climate classification descriptions and corresponding criteria  
adapted from Beck et al. (2018, p. 5)

| 1st      | 2nd | 3rd | Description          | Criterion *                                       |
|----------|-----|-----|----------------------|---------------------------------------------------|
| <b>A</b> |     |     | <b>Tropical</b>      | Not (B) & $T_{cold} \geq 18$                      |
|          | f   |     | - Rainforest         | $P_{dry} \geq 60$                                 |
|          | m   |     | - Monsoon            | Not (Af) & $P_{dry} \geq 100 - MAP/25$            |
|          | w   |     | - Savannah           | Not (Af) & $P_{dry} < 100 - MAP/25$               |
| <b>B</b> |     |     | <b>Arid</b>          | $MAP < 10 \times P_{threshold}$                   |
|          | w   |     | - Desert             | $MAP < 5 \times P_{threshold}$                    |
|          | s   |     | - Steppe             | $MAP \geq 5 \times P_{threshold}$                 |
|          |     | h   | - Hot                | $MAT \geq 18$                                     |
|          |     | k   | - Cold               | $MAT < 18$                                        |
| <b>C</b> |     |     | <b>Temperate</b>     | Not (B) & $T_{hot} \geq 10$ & $0 < T_{cold} < 18$ |
|          | s   |     | - Dry summer         | $P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$         |
|          | w   |     | - Dry winter         | $P_{wdry} < P_{swet}/10$                          |
|          | f   |     | - Without dry season | Not (Cs) or (Cw)                                  |
|          |     | a   | - Hot summer         | $T_{hot} \geq 22$                                 |
|          |     | b   | - Warm summer        | Not (a) & $T_{mon10} \geq 4$                      |
|          |     | c   | - Cold summer        | Not (a or b) & $1 < T_{mon10} < 4$                |
| <b>D</b> |     |     | <b>Cold</b>          | Not (B) & $T_{hot} > 10$ & $T_{cold} \leq 0$      |
|          | s   |     | - Dry summer         | $P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$         |
|          | w   |     | - Dry winter         | $P_{wdry} < P_{swet}/10$                          |
|          | f   |     | - Without dry season | Not (Ds) or (Dw)                                  |
|          |     | a   | - Hot summer         | $T_{hot} \geq 22$                                 |
|          |     | b   | - Warm summer        | Not (a) & $T_{mon10} \geq 4$                      |
|          |     | c   | - Cold summer        | Not (a, b, or d)                                  |
|          |     | d   | - Very cold winter   | Not (a or b) & $T_{cold} < -38$                   |
| <b>E</b> |     |     | <b>Polar</b>         | Not (B) & $T_{hot} \leq 10$                       |
|          | T   |     | - Tundra             | $T_{hot} > 0$                                     |
|          | F   |     | - Frost              | $T_{hot} \leq 0$                                  |

\* Variable definitions: MAT = mean annual air temperature (°C);  $T_{cold}$  = the air temperature of the coldest month (°C);  $T_{hot}$  = the air temperature of the warmest month (°C);  $T_{mon10}$  = the number of months with air temperature  $>10$  °C (unitless); MAP = mean annual precipitation (mm y<sup>-1</sup>);  $P_{dry}$  = precipitation in the driest month (mm month<sup>-1</sup>);  $P_{sdry}$  = precipitation in the driest month in summer (mm month<sup>-1</sup>);  $P_{wdry}$  = precipitation in the driest month in winter (mm month<sup>-1</sup>);  $P_{swet}$  = precipitation in the wettest month in summer (mm month<sup>-1</sup>);  $P_{wwet}$  = precipitation in the wettest month in winter (mm month<sup>-1</sup>);  $P_{threshold} = 2 \times MAT$  if  $>70\%$  of precipitation falls in winter,  $P_{threshold} = 2 \times MAT + 28$  if  $>70\%$  of precipitation falls in summer, otherwise,  $P_{threshold} = 2 \times MAT + 14$ . Summer (winter) is the six-month period that is warmer (colder) between April–September and October–March.

PCM-integrated glazing systems have been extensively investigated and rapidly developed over the past several decades from the perspectives of unique system designs, including passive, active, and passive/active combined designs, intelligent management, and sophisticated controls. In the academic literature, numerous studies have been conducted on PCM-integrated building envelopes, but a comprehensive review of PCM-integrated GUs combined with other passive and active techniques using dialectical analysis and comparing the climatic conditions of each study using Köppen-Geiger climate classification climate classification is missing. Therefore, the primary purpose of this study is to bridge this gap for all types of glazing, except glazed roofs.

This review is organized into two main sections: glazing unit technologies with and without PCM use. The first section is a comprehensive review of PCM-incorporated GUs only and combined with passive and active technologies comprising the vast majority of related studies. This section is divided into three subsections: PCM-incorporated multi-layered GUs, PCM-incorporated shading systems of GUs, and PCM/PV-incorporated multi-layered GUs. In the absence of PCMs, the second section reviews the GU technologies alone and in conjunction with passive and active technologies. This section does not include the large bulk of relevant articles, as there are countless in the literature and only some are chosen. It is subdivided into three subsections, including photovoltaic (PV) windows, shading systems (without PCM), and thermotropic and thermochromic materials in GUs. At the end of each section there are challenges and opportunities, as well as Köppen-Geiger climate classification influences on smart glazing systems.

The papers acquired using the keyword “PCM glazing window” were downloaded, classified, and incorporated into section one of this article. By navigating through so many Google Scholar pages until articles were unrelated to the chosen keyword, nearly all relevant papers were downloaded. Some selected articles were downloaded with the subsection titles of section two for the individual application of the technology without PCM for the technologies employed as a combined approach with PCM. Figure 1.3 depicts the number of reviewed papers in each subsection of Sections 1 and 2.



### 1.1.2 Phase Change Materials

Thermal energy storage (TES) is a viable method for improving the energy efficiency of buildings and other applications, including concentrated solar power plants (Khamlich et al., 2021), PV panels (Navakrishnan et al., 2021), and heat pump systems (Koşan and Aktaş, 2021). TES systems are classified into two main categories as (i) thermal and (ii) thermochemical energy storage. Due to unclear cost and longevity, the second use has not shown to be beneficial (Heier et al., 2015). The first has already been used in many applications and is classified as sensible and latent heat storage (Hanchi et al., 2017). Table 1.2 compares the thermal storage properties of sensible and latent heat. This table demonstrates that the energy storage capacity of a latent heat system is 5 to 13 times that of a sensible heat system (Farid et al., 2004), demonstrating the significant potential of such materials to improve the thermal mass of buildings.

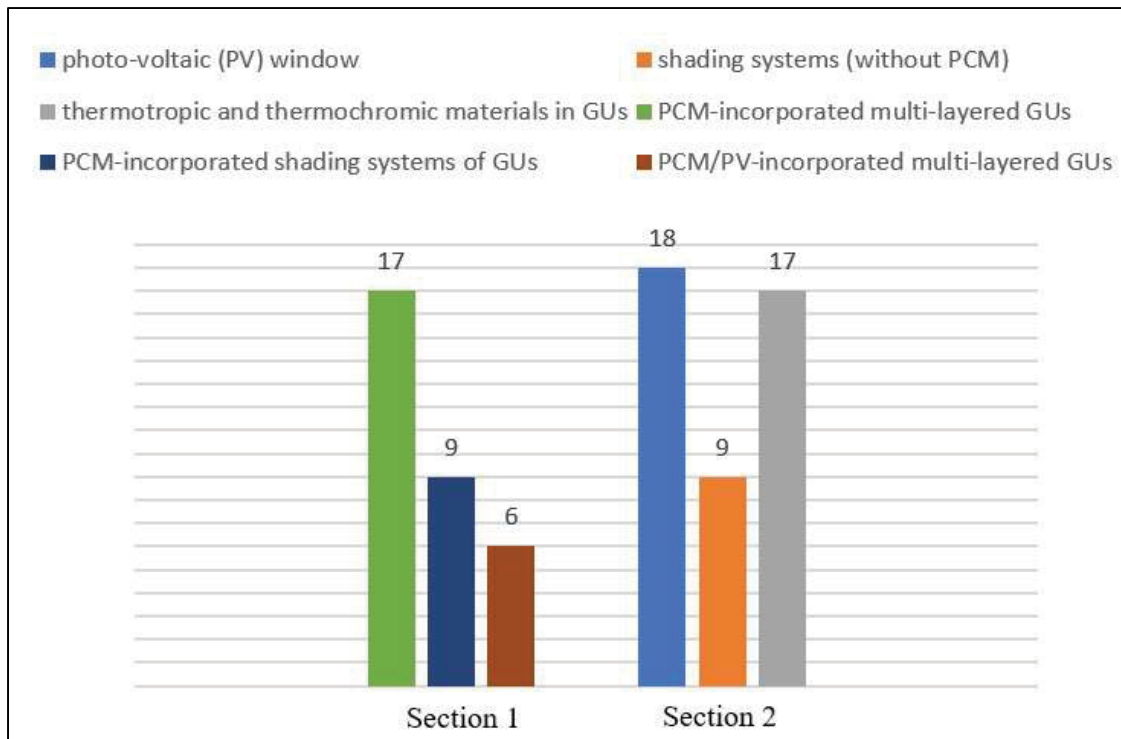


Figure 1.3 The number of reviewed papers in each subsection of Sections 1 and 2



Table 1.2 Comparing the sensible and latent heat of TES materials for 15 K temperature increase and 300 kWh energy storage adapted from Farid et al. (2004, p. 1602)

| Material Property                                         | TES Sensible Heat |        | TES Latent Heat |               |
|-----------------------------------------------------------|-------------------|--------|-----------------|---------------|
| Material                                                  | Rock              | Water  | Organic PCM     | Inorganic PCM |
| Density (kg/m <sup>3</sup> )                              | 2240              | 1000   | 800             | 1600          |
| Specific heat (kJ/(kg·K))                                 | 1                 | 4.2    | 2               | 2             |
| Latent heat (kJ/kg)                                       | -                 | -      | 190             | 230           |
| Latent heat (kJ/m <sup>3</sup> )                          | -                 | -      | 152             | 368           |
| Mass of storage for 10 <sup>6</sup> J (kg)                | 67,000            | 16,000 | 5300            | 4350          |
| Volume of storage for 10 <sup>6</sup> J (m <sup>3</sup> ) | 30                | 16     | 6.6             | 2.7           |
| Mass of relative storage (-)                              | 15                | 4      | 1.25            | 1             |
| Volume of relative storage (-)                            | 11                | 6      | 2.5             | 1             |
| Volume of relative storage (-)                            | 11                | 6      | 2.5             | 1             |

The driving force for the process of charging and discharging the storage determines whether a system is passive or active; active systems use a pump or fan for the process, whereas in passive systems, the phase change is caused by a temperature difference between the environment and the storage (Heier et al., 2015). PCMs supply considerable latent heat throughout their phase transition at a constant temperature, which is a desirable property, particularly during the phase change from solid to liquid and vice versa, as shown in Figure 1.4 (Faraj et al., 2020). The phase change could occur in the solid, liquid, and gas states through vaporization and condensation and in solid and liquid through freezing and melting. In building envelopes, solid–liquid and solid–solid phase changes are the most common (Akeiber et al., 2016). Figure 1.4 illustrates the fluctuating temperature of PCM's storing heat. As depicted in the figure, when the temperature of the PCM exceeds its melting temperature (MT), the chemical bonds of its molecules begin to dissolve in an endothermic process, allowing the PCM to absorb heat and shift from a solid to a liquid phase. In contrast, as the temperature drops and hits the PCM's freezing point, the molecules' chemical bonds begin to renew in an exothermic process, culminating in the PCM's transition from a liquid to a solid state, a process known as discharge (Wang et al., 2018).

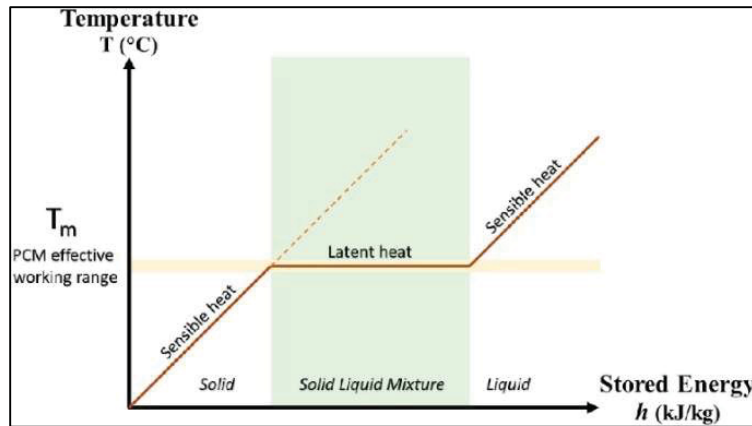


Figure 1.4 PCM energy storage by temperature variations taken from taken from Faraj et al. (2020, p. 4)

Solid–liquid PCMs are divided into three major categories: organic, inorganic, and eutectic, as well as the subgroups depicted in Figure 1.5 (Faraj et al., 2020). Each class has distinct thermal qualities that can be employed depending on the storage system’s operational conditions. Figure 1.6 (Faraj et al., 2020) depicts the melting range and enthalpy of the specified PCM classes. The MT range of paraffin as an organic form of PCM is within a suitable range for heating and cooling applications in buildings, as depicted in this figure. Paraffin has been utilized in the majority of GU-related applications due to its wide range of phase transition temperatures within a thermal comfort range, low cost, and good optical and light transmission properties (Li et al., 2020).

### 1.1.3 *Energy-Saving Technologies of GUs*

Different energy-saving technologies, applied to the transparent parts of building envelope, have been studied by the researchers, including multiple-glazing windows, blind and shading devices, exhaust air windows, water glazing systems, thermotropic and thermochromic materials, low-e coatings, aerogels, PV systems, Prisma solar glasses, different insulating methods, different laminated glasses, phase change materials, and so forth (Akram et al., 2021). The following is a summary and discussion of the aforementioned technologies, with an emphasis on the application of PCMs in GUs. Since the primary purpose of this study is to examine the possible energy-saving technologies coupled with PCMs applied to curtain walls, all glazing units, excluding glazed roofs, were examined. In addition, the examined research is

divided into two categories: (i) technologies of GUs with PCM and (ii) technologies of GUs without PCM.

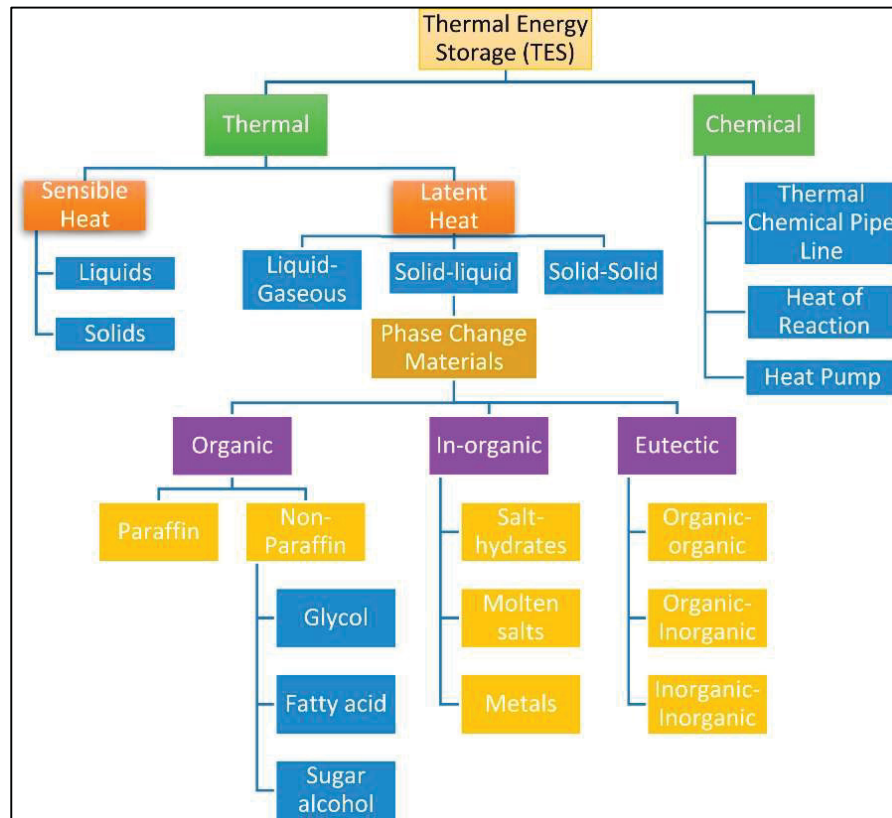


Figure 1.5 Classification of PCMs taken from Faraj et al.(2020, p. 4)

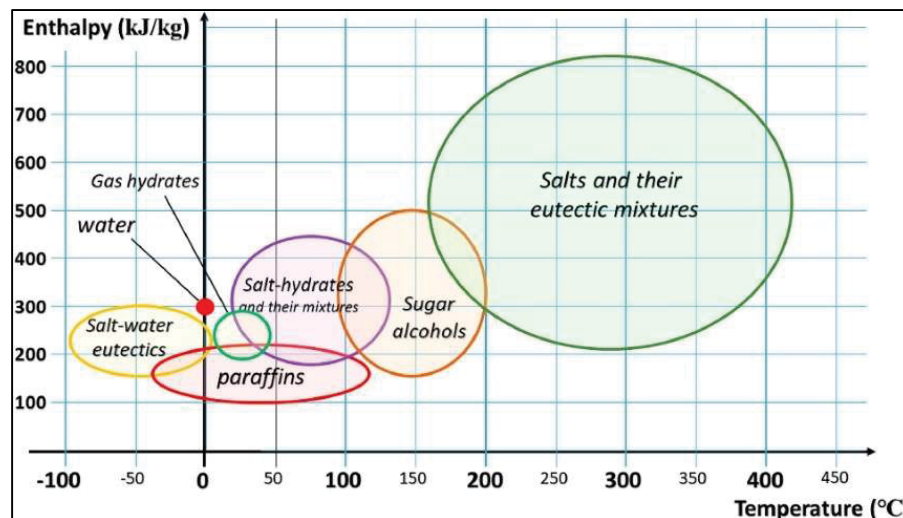


Figure 1.6 Temperature and enthalpy ranges for various PCMs taken from Faraj et al. (2020, p. 5)

### 1.1.3.1 Technologies of GUs with PCM Utilization

#### 1) PCM-Incorporated Multi-Layered GUs

In numerous studies, PCMs have been employed in double-glazed units (DGUs) to improve the thermal performance of the system while maintaining the optical and light transmittance that resident's desire. Goia et al. (2013) conducted a numerical and experimental investigation to compare the thermal performance of PCM-incorporated double glazing windows (DGWs) to that of standard DG windows in warmer areas (Cfa).

Figure 1.7 depicts the test cells employed by the authors, one DGU with PCM and the other without PCM. For their research, the authors utilized RT35 paraffin with a nominal MT of 35 °C. The results demonstrated that the PCM-DG system has the potential to improve the indoor thermal environment, and its efficacy increases as solar irradiation rises. On a cloudy day, however, the thermal comfort produced by the two systems is the same. The presence of PCM in the fenestration system minimizes glare risk and improves eye comfort, according to the study.

Later, Goia et al. (2014) experimentally evaluated the energy performance of a PCM-DG system in a similar study, using the same test cells as in (Goia et al., 2013). They utilized the identical weather and PCM data as in (Goia et al., 2013). Comparing the PCM-DG window to the conventional DG window, they determined that the PCM-DG window results in a 50% decrease in summertime energy gain. However, they argued that in the winter, the energy performance is more complex and requires additional study, as the daytime heat loss lowers while the direct solar gain decreases dramatically. In addition, they suggested control measures such as night ventilation to improve the system's performance. King et al. (2022) conducted an experiment to determine the thermal performance of a PCM-DG window in Coimbatore, India (Aw) during the cooling season. As PCM material, the paraffin RT35 with MT of 29–36 °C was chosen. The PCM-DG window reduces energy usage by 3.76%, temperature fluctuations from 21 °C to 11 °C, interior air temperature by 9 °C, and inner glass temperature by 8.5 °C, according to the findings of the study's authors. Liu et al. (2018) executed an additional experiment to examine the thermal and optical performance of PCM-DG windows

with varying solar energy intensities including 270 ( $\text{W/m}^2$ ), 600 ( $\text{W/m}^2$ ), and 950 ( $\text{W/m}^2$ ). The authors utilized three MTs of 18 °C, 26 °C, and 32 °C with paraffin wax PCM.

Figure 1.8 depicts the solid and liquid states of the PCM used by the authors and the transmittance of the studied PCMs with different MTs. This figure shows that the transmittance in liquid phase is almost 1 regardless of the MT of PCM, while the PCM's MT significantly affects the transmittance in solid phase. Considering PCM's volume growth during the phase change, these researchers filled 97% of the total volume between the panes with PCM. The results indicated that the glazing unit containing PCM in liquid form has a 50% transmittance. Moreover, in order to maintain the optical performance of the GU, these researchers recommend avoiding PCM layers thicker than 16 mm.

Tafakkori and Fattahi (2021) in Tehran, Iran (Bwh), proposed and evaluated various configurations for PCM-DG windows of simple cubic (as the reference case), partition-arranged simple cubic, simple cubic with a cylindrical wall, trapezoidal prism, partition-arranged trapezoidal prism, and trapezoidal prism with the cylindrical wall to reduce energy losses from building envelope. These scientists utilized paraffin MG29 with a melting point of 27 °C. According to their findings, the proposed configurations reduce energy consumption by around 20%. Musial (2020) numerically and experimentally analyzed the energy performance of a DG unit containing RT28 PCM with MT of 27.5 °C as a thermal accumulator unit inside the inner-pane space in Rzeszów, Poland (Cfb) instead of filling the cavity space between the panes of a DGU (see Figure 1.9). In the winter, the author demonstrated that the suggested system produces a 10% more desired daily heat balance than a DG unit with no PCM; however, in the summer, there was no significant change in the daily heat balance. During the cooling interval, the PCM storage unit was also discovered to be overheating.

In another study, Musial and Licholai (2021) implemented a PCM heat accumulator between the panes of a DG window with an external mobile shading system to examine its thermal performance through a numerical and experimental study during the summer season (June to August) in Rzeszów in Poland (Cfb), Naples in Italy (Csa), and Tallinn in Estonia (Dfb). The author chose a eutectic combination of propyl palmitate and butyl stearate as the PCM. The results showed a 29.4% decrease in room overheating in summer for the system with PCM

storage compared to the system without it. A reduction in the amount of heat flowing through the building was also reported as 5.5%, 29.4%, and 24.8% Tallinn, Rzeszów, and Naples, respectively. Durakovi et al. (2019) also examined the use of PCM and water in a DG south-facing window as thermal storage materials in Sarajevo, Bosnia (Cfa) between June and December (25 °C in the summer and 4.5 °C in the winter) to evaluate their experimental performance. The paraffin RT27 was chosen as the PCM material. Compared to air-filled DG windows, the water glazing system exhibited a significantly more desirable damping temperature (more uniform and stable temperature values with fewer fluctuations) but a significantly less desirable average temperature. The PCM glazing system, on the other hand, has a promising average temperature and damping temperature.

As depicted in Figure 1.10, Khetib et al. (2021) explored the placement of PCM between the window frames of a DGW. They evaluated the impact of window angle variation from 0 (vertical mode) to 60° and space cavity depth on the PCM and window heat transfer. Between the window frames, n-eicosane was employed as the PCM with an MT of 37 degrees Celsius. Due to the decrease in natural convection heat transfer within the window, deviating a window from its vertical position by 60 degrees decreases heat transfer by 10%. It was also discovered that expanding the air gap to 40 mm decreases the Nusselt number by 44%. Moreover, it was demonstrated that the heat transmission decreases during the phase change of PCM from solid to liquid, but that PCM loses its heat transfer effectiveness when it totally melts.

Gao et al. (2021) researched the phase transition of the PCM in the solid state on the interior layer of the inner pane of a DGW, as demonstrated in Figure 1.11. Using EnergyPlus software, the optical and thermal performance of the solid–solid translucent PCM window was numerically studied. In warm, mixed, and cold regions, 3 mm PCM integration reduces building energy consumption by up to 9.4%, 6.7%, and 3.2%, respectively. Yang et al. (2020) applied an optimization model to look into the optical characteristics of PCM-based nanofluid, namely the nanoparticle concentration and diameter in GUs. The PCM was paraffin wax and the nanofluid was TiO<sub>2</sub>. The scientists concluded that increasing the nanoparticle diameter from 10 nm to 30 nm increases the scattering coefficient of PCM nanofluid by a factor of 28.7.



Figure 1.7 Test cells composing DGU with clear glasses and DGU-PCM taken from Goia et al. (2013, p. 444)

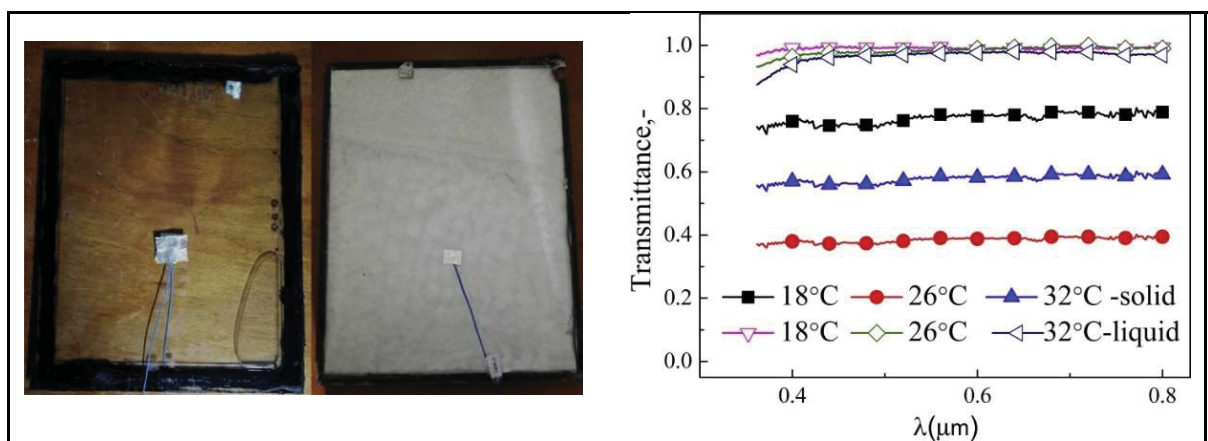


Figure 1.8 Paraffin wax PCM in liquid and solid phases along with their transmittance variations in different MTs taken from Liu et al. (2018, p. 795)



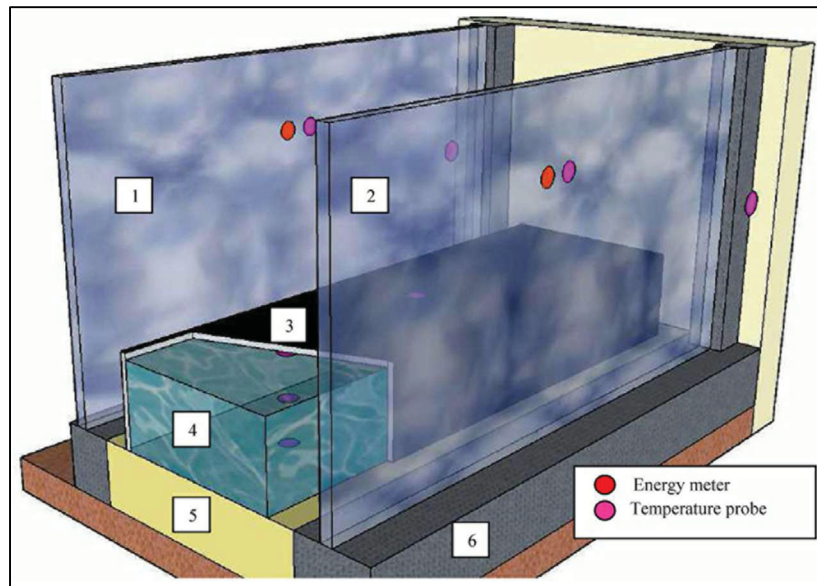


Figure 1.9 A schematic diagram of DGU containing PCM accumulator between the panes. 1. exterior glazing, 2. interior glazing, 3. thermal storage unit, 4. PCM, 5. XPS thermal insulation, 6 – window frames taken from Musiał (2020, p. 204)

As depicted in Figure 1.10, Khetib et al. (2021) explored the placement of PCM between the window frames of a DGW. They evaluated the impact of window angle variation from 0 (vertical mode) to 60° and space cavity depth on the PCM and window heat transfer. Between the window frames, n-eicosane was employed as the PCM with an MT of 37 degrees Celsius. Due to the decrease in natural convection heat transfer within the window, deviating a window from its vertical position by 60 degrees decreases heat transfer by 10%. It was also discovered that expanding the air gap to 40 mm decreases the Nusselt number by 44%. Moreover, it was demonstrated that the heat transmission decreases during the phase change of PCM from solid to liquid, but that PCM loses its heat transfer effectiveness when it totally melts. Gao et al. (2021) researched the phase transition of the PCM in the solid state on the interior layer of the inner pane of a DGW, as demonstrated in Figure 1.11. Using EnergyPlus software, the optical and thermal performance of the solid–solid translucent PCM window was numerically studied. In warm, mixed, and cold regions, 3 mm PCM integration reduces building energy consumption by up to 9.4%, 6.7%, and 3.2%, respectively.



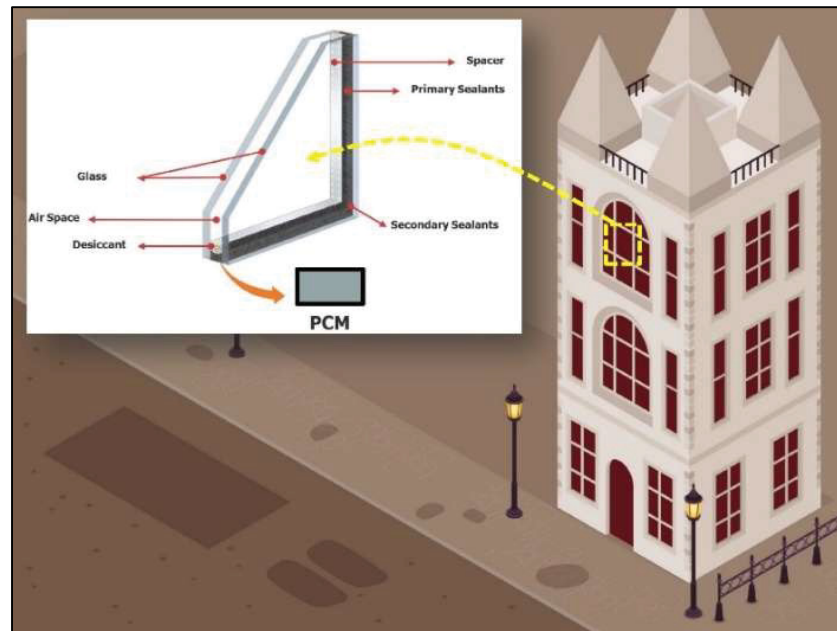


Figure 1.10 Schematic of fenestration system taken from Khetib et al. (2021, p. 2)

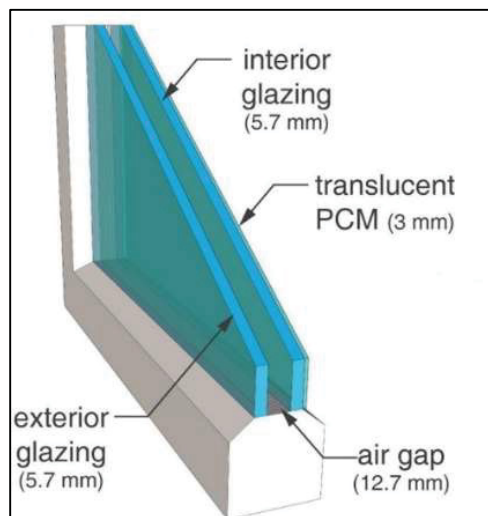


Figure 1.11 Schematic of DG system taken from Gao et al. (2021, p. 5)

Yang et al. (2020) applied an optimization model to look into the optical characteristics of PCM-based nanofluid, namely the nanoparticle concentration and diameter in GUs. The PCM was paraffin wax and the nanofluid was  $\text{TiO}_2$ . The scientists concluded that increasing the

nanoparticle diameter from 10 nm to 30 nm increases the scattering coefficient of PCM nanofluid by a factor of 28.7. PCMs have also been used in triple-glazing (TG) and quadruple-glazing (QG) windows.

In Nanjing, China (Cfa), Li et al. (2018) empirically and mathematically assessed the cooling and heating energy performance of a PCM-TG window. The numerical simulations were carried out utilizing ANSYS Fluent. The PCM material paraffin MG29 with an MT of 27–29 °C was inserted in the outside gap cavity space of the TG window, while the inner cavity was filled with air compared to a TGU and PCM-DGU with an entirely air-filled cavity. Using the PCM-TG window prevents overheating during the cooling time, as demonstrated by the findings. In a typical sunny summer day, comparing the PCM-TG window to the PCM-DG window and hollow TG window, 21.30% and 32.80% reductions in energy consumption were noted. Wieprzkowicz and Heim (2020) evaluated the cooling and lighting energies, glare effect, and thermal and optical discomforts of a PCM-TG window in Lodz, Poland (Dfb), by means of a numerical and experimental investigation. Five PCMs of paraffin RT18HC, RT22HC, RT25HC, RT28HC, and RT31 were chosen to fill the outer cavity space of the glazing system, while Argon gas was used to fill the interior cavity space. The acquired results indicate that there is no optimal unit type of PCM for the system, and that employing PCMs with varied MTs is advantageous from an energy and optical standpoint, as liquid PCM provides an excellent view of the sky and visual comfort, although this is not true for solid PCM. The authors advised covering the lower half of the window with a PCM to ensure the occupant's optical view and filling the upper half of the window with a PCM to prevent overheating caused by energy demand. Considering applying PCM-QG windows, Liu et al. (2019) tested the thermal performance of a south-facing four-glazed unit comprising PCM with MT of 25–28 °C between the two middle panes of the fenestration system numerically and experimentally during the winter time in Daqing, China (Dwa), which has a severe cold winter. The authors highlighted the significance of PCM thickness for the thermal efficiency of the glazed facade system. As a trade-off between improved thermal performance and reduced solar transmittance, it was also proposed that PCMs not exceed 20 mm in thickness. The purpose of Table 1.3 is to facilitate a clear comparison between the aforementioned research on the use of PCMs in GUs.

As stated above, one of the primary difficulties that must be addressed when constructing latent storage added fenestrations systems is the PCM-GU system overheating. As a possible option despite using TGU- and QGU-PCM systems, the Prisma solar glass has been studied. Kara and Kurnuc (2012) conducted an experimental investigation in Erzurum, Turkey (Dfb) during the summertime using Prisma solar glass combined with PCM and low-e glass in TG windows. In summer, the solar transmittance of the south-facing TG system was reduced by 100% compared to winter. They also observed that the PCM wall with Prisma solar glass did not warm throughout the summer.

Later, Souayfane et al. (2018) undertook a numerical and experimental investigation to assess the thermal performance of a super-insulated translucent wall (a triple glazing (TG) system) made of Prisma solar glass, silica aerogel, glass bricks filled with a fatty acid, and eutectic PCM. Figure 1.12 displays the translucent wall for the solid and liquid states of PCM. The experiment took place over the course of seven consecutive summer and winter days. The authors examined five distinct climates, including those of Madrid, Spain (Csa), Paris, France (Cfb), Chicago, USA (Dfa), Ottawa, Canada (Dfb), and Kiruna, Sweden (Dfc). Utilizing Prisma solar glass as opposed to conventional glasses has proven to be highly beneficial, since it eliminates the overheating issue in summer and maintains the system's benefits in winter. In addition, they assessed the necessity for ventilation systems and shade devices in the regions under consideration. Another method to avoid overheating is using laminated glasses. In a numerical and experimental investigation, Maduru and Shaik (2022) examined the thermoeconomic and optical analyses of various laminated glazing for buildings. The authors used Ethylene vinyl acetate (EVA) films coated with a variety of tints, including transparent film, cooling film, scarlet red film, fabric film, Tiffany Blue film, Mist Rose film, and reflective film, as an interlayer between two transparent glass sheets, as shown in Figure 1.13. The reflective film laminated glass demonstrated the greatest solar heat gain reduction, annual cost savings, and CO<sub>2</sub> emission reduction. Additionally, the payback period of EVA films was studied, and it was determined that all had an initial payback cost of less than two years. The authors also evaluated the average daylight factor of the EVA films, indicating that it was above the minimum recommended level (0.625% in Indian standards), and that the EVA films allowed daylight into the buildings without glare.

Table 1.3 Summary of PCM-incorporated multilayered GUs

| Ref.                | PCM Type (MT °C)          | Climate Code | Study Type | Envelope Element | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                                                                                   |
|---------------------|---------------------------|--------------|------------|------------------|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Goia et al., 2013) | RT35 paraffin (35)        | Cfa          | E, N       | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>On cloudy days, the performance of the two technologies (PCM-DGU and conventional DGU) is similar regarding thermal comfort, while the efficacy of PCM-DGU increases as solar irradiation rises.</li> <li>The presence of a PCM in the facade can also positively influence visual comfort, as it may prevent glare.</li> </ul> |
| (Goia et al., 2014) | RT35 paraffin (35)        | Cfa          | E          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>The use of PCM in summer is promising while, its application in winter faces some challenges that need further research as the direct solar gain decreases dramatically.</li> <li>They suggested control measures such as night ventilation to improve the system's performance.</li> </ul>                                     |
| (King et al., 2022) | RT35 paraffin (29–36)     | Aw           | E          | DGW              | Cooling             | <ul style="list-style-type: none"> <li>The PCM-DG window reduces energy usage by 3.76%, temperature fluctuations from 21 °C to 11 °C, and interior air temperature by 9 °C.</li> </ul>                                                                                                                                                                                 |
| (Liu et al., 2018)  | Paraffin wax (18, 26, 32) | -            | E          | DGW              | Cooling             | <ul style="list-style-type: none"> <li>Considering PCM's volume growth during the phase change, the researchers filled 97% of the total volume between the panes with PCM.</li> <li>The transmittance of the glazed unit is 50% when the PCM is liquid.</li> <li>PCM thickness in glazed unit shouldn't exceed 16 mm for optical performance.</li> </ul>               |

Table 1.3 Summary of PCM-incorporated multilayered GUs (continued)

| Ref.                          | PCM Type<br>(MT °C)                                                                                                                 | Climate<br>Code | Study<br>Type | Envelope<br>Element | Application            | Findings and Remarks                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|-----------------|---------------|---------------------|------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Tafakkori and Fattahi, 2021) | Paraffin,<br>MG29<br>(27)                                                                                                           | Bwh             | N             | DGW                 | Cooling                | <ul style="list-style-type: none"> <li>Using PCM-DGU system causes 20% reduction in energy consumption and a decrease in the Nusselt number by a factor of 4.</li> </ul>                                                                                                                                                                                                                                                                                   |
| (Musiał, 2020)                | RT28<br>paraffin<br>(28)                                                                                                            | Cfb             | E, N          | DGW                 | Cooling and<br>heating | <ul style="list-style-type: none"> <li>Instead of filling the cavity between DGU panes, a PCM thermal accumulator is used.</li> <li>Using PCM between the panes of the DGW caused 10% improvement in daily heat balance in heating seasons, while in cooling seasons, PCM accumulator had no significant impact on daily heat balance and experienced overheating.</li> </ul>                                                                              |
| (Musiał and Lichota, 2021)    | <i>n</i> -<br>octadecane<br>(25.05–<br>26.11)<br><i>n</i> -eicosane<br>(33.63–<br>35.64)<br><i>n</i> -docosane<br>(42.21–<br>43.15) | Dwa             | N             | Exterior            | Cooling and<br>heating | <ul style="list-style-type: none"> <li>44% reduction in cooling energy consumption and 34% improvement in thermal comfort are observed by using the proposed shading system.</li> <li>In such an application of PCM, the MT of PCM has a negligible impact on the energy consumption of the building.</li> <li>The system is not effective in winter and requires more research for PCM incorporated shading systems, according to the authors.</li> </ul> |

Table 1.3 Summary of PCM-incorporated multilayered GUs (continued)

| Ref.                            | PCM Type (MT °C)                         | Climate Code          | Study Type | Envelope Element | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                  |
|---------------------------------|------------------------------------------|-----------------------|------------|------------------|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Duraković and Mešetović, 2019) | RT27 paraffin (27)                       | Cfa                   | E          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>Using water instead of air in DGWs brings more temperature damping, but less favorable average temperature, which using PCM covers the latter issue.</li> </ul>                                                                                                |
| (Khetib et al., 2021)           | n-eicosane (37)                          | -                     | N          | DGW              | Cooling             | <ul style="list-style-type: none"> <li>PCM is placed between the frames of the DGW containing air between the panes.</li> <li>Expanding the air gap to 40mm decreases the Nusselt number by 44%.</li> <li>Decrease in heat transfer effectiveness was also observed due to PCM overheating</li> </ul> |
| (Gao et al., 2021)              | Different PCM variables (20, 30, 40, 50) | Warm, mixed, and cold | N          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>A DGU's inside glass is coated with solid-solid translucent PCM.</li> <li>3 mm PCM integration causes 9.4%, 6.7%, and 3.2% building energy savings reduction in warm, mixed, and cold climates, respectively.</li> </ul>                                       |
| (Yang et al., 2020)             | Paraffin wax                             | -                     | N          | Glazing window   | -                   | <ul style="list-style-type: none"> <li>TiO<sub>2</sub> nanoparticles in PCM for optical and thermal performance tests. Increasing nanoparticle diameter from 10 to 30 nm boosts nanoPCM scattering by 27.8 times.</li> </ul>                                                                          |

Table 1.3 Summary of PCM-incorporated multilayered GUs (continued)

| Ref.                          | PCM Type (MT °C)                  | Climate Code | Study Type | Envelope Element | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                                                                                                                                               |
|-------------------------------|-----------------------------------|--------------|------------|------------------|---------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Li et al., 2018)             | Paraffin MG29 (27–29)             | Cfa          | E, N       | TGW              | Cooling and heating | <ul style="list-style-type: none"> <li>• Triple-glazed window filled with PCM in the outside gap cavity space can avoid overheating phenomenon effectively.</li> <li>• In a typical sunny summer day, the PCM-TG window consumes 21.30% and 32.80% less energy than the PCM-DGW and hollow TGW, respectively</li> </ul>                                                                                                            |
| (Wieprzkowicz and Heim, 2020) | Paraffin wax (18, 22, 25, 28, 31) | Dfb          | E, N       | TGW              | Cooling             | <ul style="list-style-type: none"> <li>• PCM filled the outer cavity space of the glazing system, while Argon gas was used to fill the interior cavity space.</li> <li>• There is no optimum unit type of PCM for the system, and adopting PCMs with varying MTs is advantageous from an energy and optical standpoint, as liquid PCM provides a superb view of the sky and visual comfort, whereas solid PCM does not.</li> </ul> |
| (Liu et al., 2019)            | (25–28)                           | Dwa          | E, N       | FGW              | Heating             | <ul style="list-style-type: none"> <li>• As a trade-off between maximizing the thermal comfort enhancement and minimizing the solar transmittance reduction, PCM thickness should not be larger than 20mm.</li> </ul>                                                                                                                                                                                                              |



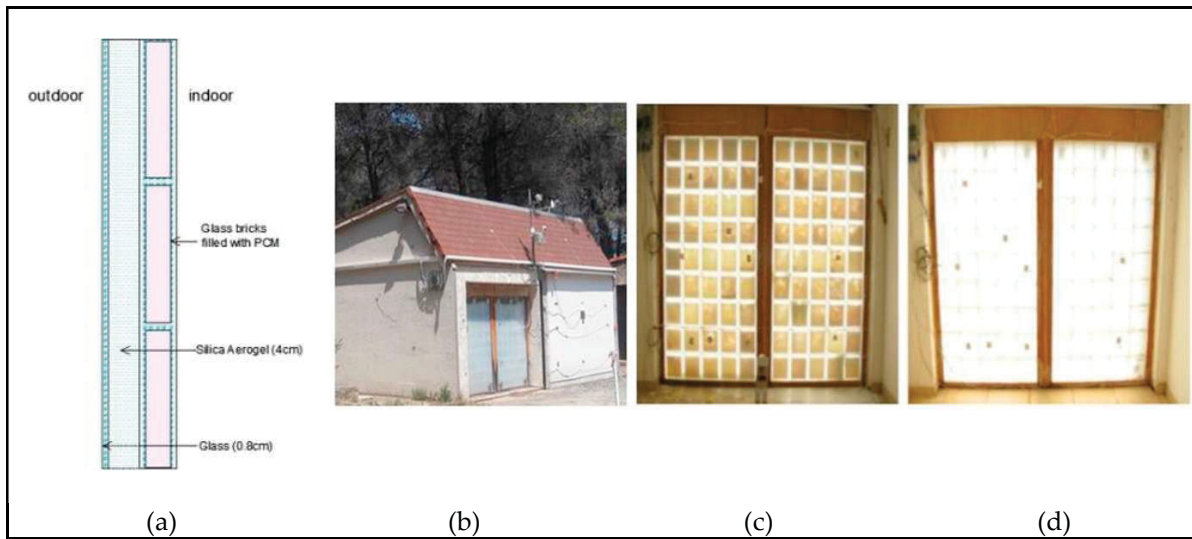


Figure 1.12 (a) Insulated translucent wall components, (b) outside view, and inside view in (c) solid and (d) liquid phases of the PCM taken from Souayfane et al. (2018, p. 392)

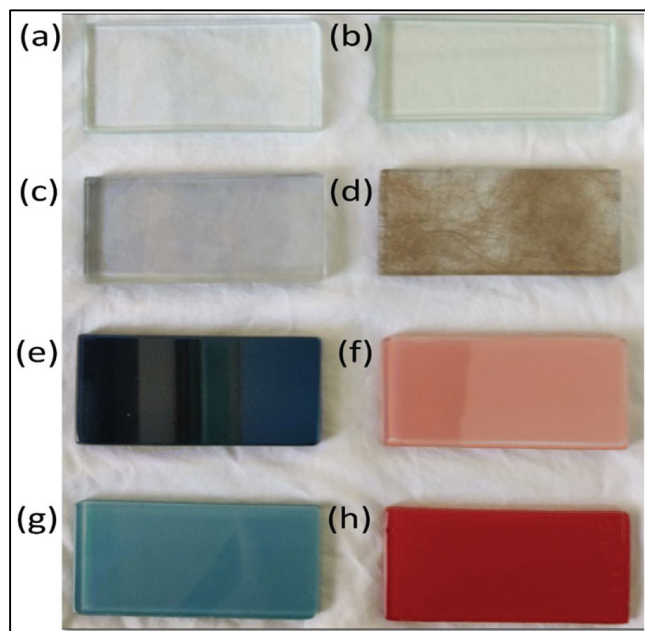


Figure 1.13 Laminated glass samples showing:  
 (a) monolithic clear glass (6 mm), (b) transparent film, (c) cooling film, (d) fabric film, (e) reflective film, (f) Mist Rose film, (g) Tiffany Blue film, and (h) scarlet red taken from Maduru and Shaik (2022, p. 14301)



Incorporating PCM-DGUs appears to be a potential technique for enhancing thermal comfort, reducing energy consumption, and decreasing temperature swings, however it reduces the glazing unit's optical performance or solar transmittance to the point where a trade-off is necessary. The thickness of the PCM should not exceed 16 to 20 mm as a result of such a trade-off by researchers. In regions with greater solar heat gain (like areas whose code ends with "a"), PCM performs better.

In addition, during the summer and when the sky is clear (which is more prevalent in areas whose code begins with "B"), PCM is more effective, whereas its performance in the winter and on cloudy days is questionable, necessitating the implementation of other passive and active techniques such as night ventilation. The volume expansion of the PCM during phase transition is an additional issue that must be considered. Another potential issue that has been discussed is the low solar transmittance of PCM solid phase compared to liquid phase. Utilizing solid-solid translucent PCM, which can also eliminate leakage and volume-changing difficulties, is one approach to circumvent this issue.

## 2) PCM-Incorporated Shading Systems of Gus

Using shade devices within and outside the fenestration system (e.g., window) and between the panes of a multi-layered GU is one method for blocking solar heat from entering the interior environment. Numerous researchers are interested in using PCMs to boost the thermal mass and heat storage of shading devices. As an example, the use of PCM on internal shading devices was studied by Helmut et al. (2011) as they compared the heating and cooling energy performance of an internal blind system incorporated PCM vs. the typical sun protection systems for a DG window in an experimental study conducted in Bayern, Germany (Cfb).

The blind system consisted of a hollow polycarbonate blind (12 mm gap) filled with encapsulated salt hydrate PCM with MT between 26 and 30 °C and sealed at the ends seen in Figure 1.14. The outcomes demonstrated that the PCM-integrated blind system significantly improves thermal comfort. The most significant issue, however, is the nighttime discharge of the PCM. Later, Wang and Zhao (2015) carried out a numerical parametric research of PCM embedded into the curtain of residential buildings in Shanghai, China (Cfa), during the

warmest days of the year. The air gap between the PCM curtain and the window was parameterized, as was the PCM MT. Consequently, other PCMs were evaluated, including paraffin with MTs of 28 °C, 29 °C, and 30 °C, and n-Eicosane with an MT of 37 °C. The scientists concluded that employing a 15 mm PCM layer with an MT of 29 °C reduces the average indoor heat transfer rate by 30.9%. In addition, the authors suggested a cascaded PCM layer with many MTs in a vertical orientation for future research to counteract the PCM curtain's disadvantage, which is the loss of window transparency due to the addition of an opaque layer.



Figure 1.14 Polycarbonate blinds filled with encapsulated salt hydrate PCM sealed at ends taken from Weinlaeder et al. (2011, p. 2469 and 2472)

The use of PCM on shutter windows was studied by Silva et al. (2015a) as they performed an experimental setup of window shutter (hollow aluminum blade) filled with PCM (macroencapsulated) in the Mediterranean climate of Aveiro, Portugal (Csb) during the winter season (ambient air temperature between 4.5 °C to 14 °C). The organic PCM of paraffin RT28HC with MT of 27–29 °C was utilized in this study. The authors also benefited from a thermal camera (Testo®875i) to identify the test room's thermal bridges and heat losses (Figure 1.15).

The obtained results proved that the maximum indoor temperature with PCM on shutter windows decreases by up to 30% compared to non-PCM shutter windows. Moreover, the energy efficiency enhancement and indoor spaces' thermal regulation were achieved by incorporating PCM into the DG window shutter blades. In a further experimental study, Silva et al. (2015b) examined the same issue during the summer (ambient air temperature ranging from 13 °C to 25 °C). The researchers determined an improvement of 18–22% in the thermal regulating capacity of interior temperature and a reduction of 6% and 11%, respectively, in the highest and minimum temperature peaks.

Another similar study was performed by Silva et al. (2016) to numerically simulate the thermal behavior of window shutters containing PCM (RT28HC) validated by real-scale test cells during the summer of 2013 (between the 2nd and 9th of August). The simulation was based on a 2D model analyzed with ANSYS Fluent software. Using a PCM-shutter window lessens the highest indoor temperature by up to 8.7% and increases the minimum indoor air temperature by 16.6% during the nighttime.



Figure 1.15 Test rooms outside view including shutter windows  
taken from Silva et al. (2015a, 2015b, 2016, p. 67)

Considering using external shading devices, Park et al. (2020) conducted numerical research in Seoul, South Korea (Dwa), to examine the energy performance and thermal comfort of an existing educational facility with a PCM-incorporated exterior shading system. As micro-packed PCMs for the shade system, the authors chose n-octadecane (NO) with an MT of 25.05–26.11 °C, n-eicosane (NE) with an MT of 33.63–35.64 °C, and n-docosane (ND) with an MT of 42.21–43.15 °C. Their technology reduced cooling energy consumption by 44% and increased thermal comfort hours by 34%. In addition, they argued that in such an application of PCM, the MT of PCM has a negligible impact on the energy consumption of the building. In addition, they underline the need for additional research on PCM-integrated shade devices, as they discovered that the system could not be defeated throughout the winter.

The application of PCM on the shading devices between the panes of multi-layered GUs was examined by Li et al. (2019) as they evaluated the thermal performance of a double skin facade (DSF) featuring a PCM-incorporated (as a microencapsulated coating) blind system between the two panes of the fenestration system using computational and empirical methods. Figure 1.16 depicts an experimental setting in Ningbo, China (Cfa). The simulations were carried out utilizing ANSYS Fluent software. The blind system incorporated the PX35 PCM with an MT of 35 °C. The results indicated that the air temperature in the DSF test cell did not exceed 39 °C for the entire day and was below 35 °C (the PCM's MT) before 10:00 and after 15:00, allowing the PCM blind system to undergo a complete solidification process. The researchers also argued that a decrease of 2.9 °C between the interior surface temperature of the DSF and its exterior surface temperature indicated a reduction in heat transfer through the building envelope.

As indicated in Figure 1.17, Hu et al. (2020) suggested a new fenestration system, incorporating a vented TG window with internal shade between the two inside panes and a PCM heat exchanger beneath the window for precooling and preheating purposes to conserve building energy. The research was carried out numerically with EnergyPlus software and experimentally in Denmark (Cfb). The authors opted for a PCM composed of fiber (50%) and paraffin wax (50%) with a freezing point of 20.7 °C. The proposed system increases energy

savings by 62.35% and 9.4% in the summer and winter, respectively. Table 1.4 provides a summary of the reviewed research on PCM-integrated shading solutions for GUs.

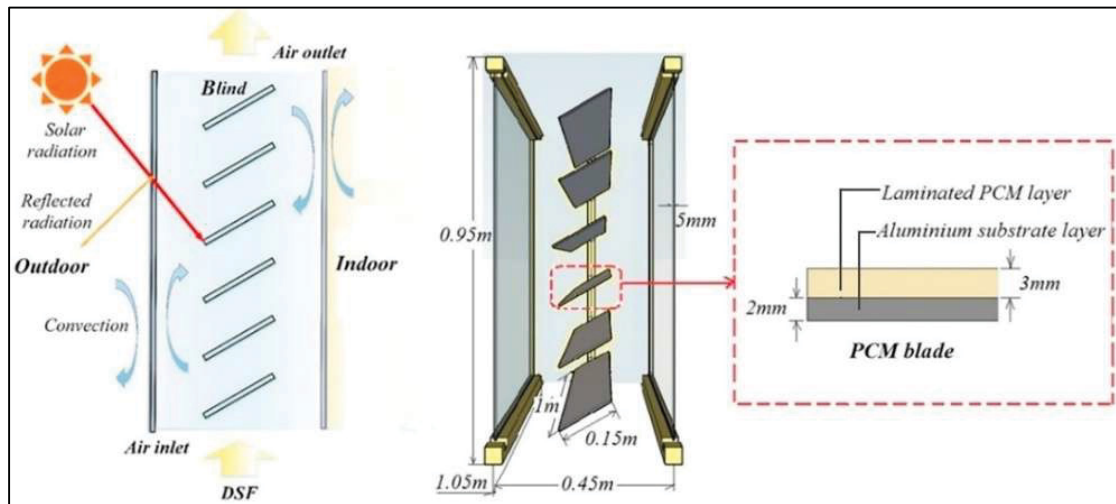


Figure 1.16 Schematic of experimental setup by taken from Li et al. (2019, p. 3)

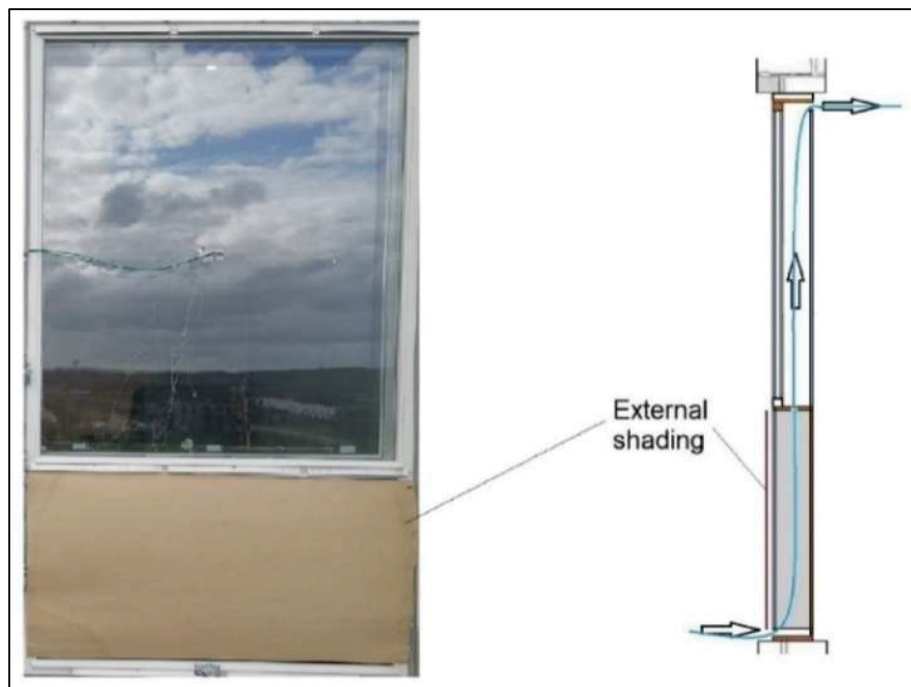


Figure 1.17 Outside view and components of the system proposed by taken from Hu et al. (2020, p. 139)

| Ref.                         | PCM Type<br>(MT °C)                            | Climate<br>Code | Study<br>Type | Shading<br>Position<br>of the<br>GU | Application            | Findings and Remarks                                                                                                                                                                                                                                                                                               |
|------------------------------|------------------------------------------------|-----------------|---------------|-------------------------------------|------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Weinlaeder<br>et al., 2011) | Salt hydrate<br>(26–30)                        | Cfb             | E             | Interior                            | Cooling and<br>heating | <ul style="list-style-type: none"> <li>A hollow polycarbonate blind (12 mm gap) was filled with PCM.</li> <li>The sun protection system improves thermal comfort. The most significant issue, however, is the nighttime discharge of the PCM.</li> </ul>                                                           |
| (Wang and<br>Zhao, 2015)     | Paraffin (28,<br>29, 30)<br>n-Eicosane<br>(37) | Cfa             | N             | Interior                            | Cooling                | <ul style="list-style-type: none"> <li>The average heat transfer rate is reduced by about 31% by using a 15 mm PCM layer on the hottest summer days.</li> <li>The authors suggested a cascaded PCM layer with many MTs to avoid the loss of window transparency due to the addition of an opaque layer.</li> </ul> |
| (Silva et al.,<br>2015a)     | Paraffin<br>RT28HC (27–<br>29)                 | Csb             | E             | Interior                            | Heating                | <ul style="list-style-type: none"> <li>Incorporating PCM into shutter window (hollow aluminum blade) increases 30% reduction in maximum indoor temperature compared to the system without PCM.</li> </ul>                                                                                                          |
| (Silva et al.,<br>2015b)     | Paraffin<br>RT28HC (27–<br>29)                 | Csb             | E             | Interior                            | Cooling                | <ul style="list-style-type: none"> <li>The PCM sun protection system causes an enhancement in the thermal regulating capacity of the indoor temperature by about 18%–22%.</li> </ul>                                                                                                                               |

Table 1.4 Summary of PCM-incorporated shading systems of GUs



Table 1.4 Summary of PCM-incorporated shading systems of GUs (continued)

| Ref.                 | PCM Type<br>(MT °C)                                                                                        | Climate<br>Code | Study<br>Type | Shading<br>Position<br>of the<br>GU | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                                                                                                        |
|----------------------|------------------------------------------------------------------------------------------------------------|-----------------|---------------|-------------------------------------|---------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Silva et al., 2016) | Paraffin<br>RT28HC (27–29)                                                                                 | Csb             | N             | Interior                            | Cooling             | <ul style="list-style-type: none"> <li>PCM-shutter window lessens the highest indoor temperature by up to 8.7% and increases the minimum indoor air temperature by 16.6% during the nighttime.</li> </ul>                                                                                                                                                                                   |
| (Park et al., 2020)  | <i>n</i> -octadecane (25.05–26.11)<br><i>n</i> -eicosane (33.63–35.64)<br><i>n</i> -docosane (42.21–43.15) | Dwa             | N             | Exterior                            | Cooling and heating | <ul style="list-style-type: none"> <li>44% reduction in cooling energy consumption and 34% improvement in thermal comfort are observed by using the proposed shading system.</li> <li>In such an application of PCM, the MT of PCM has a negligible impact on the energy consumption of the building.</li> <li>The system is not effective in winter and requires more research.</li> </ul> |
| (Li et al., 2019)    | PX35 as an organic PCM (35)                                                                                | Cfa             | E, N          | Between the panes                   | Cooling             | <ul style="list-style-type: none"> <li>The PCM shading system keeps the average temperature below 35 °C between the panes of the DGU during the summer, with testing showing subtle differences with ambient temperature.</li> </ul>                                                                                                                                                        |
| (Hu et al., 2020)    | mixture of fiber and paraffin (20.7)                                                                       | Cfb             | E, N          | Between the panes                   | Cooling and heating | <ul style="list-style-type: none"> <li>Using a PCM-contained chamber beneath the shading system for preheating and precooling purposes. 62.35% and 9.4% enhancement in energy saving is observed for the proposed system in summer and winter, respectively.</li> </ul>                                                                                                                     |

Different PCM types have been incorporated into the interior, between, and exterior shading systems of GUs. Utilizing blinds with PCM has been demonstrated to reduce energy consumption and improve thermal regulation, albeit with some limits. When the blind system is located on the interior side of the GUs (the majority of research are conducted in countries with temperate climatic conditions, where the code begins with “C”), the absorbed heat during the day must not be released to the inside, requiring nighttime ventilation. In winter, however, it absorbs heat during the day and releases it inside, which is a favorable effect, but it filters more sunlight during the day due to the addition of opaque material to the blind system.

To prevent the loss of sunlight, a cascaded PCM integration with several MTs is suggested. When the blind system is located on the outside side of the GUs, the MT of the PCM has a subtle influence on energy savings, which is beneficial in the summer but not in the winter, indicating the need for additional research. Using PCM between the panes exhibits promising thermal storage of the latent system during the summer’s hottest days. To potentially utilize the temperature regulation enhancing benefits of PCM-incorporated shading systems, this topic has been researched infrequently and requires additional investigation.

### 3) PCM/PV-Incorporated Multi-Layered GUs

Researchers have recently implemented the use of PCM materials as the sensible and latent heat storage and PV layer as the electricity generation in fenestration systems. Elarga et al. (2016) numerically evaluated the optical, electrical, and thermal performance of a PV-PCM in DSFs. These systems were tested in Venice, Italy (Cfa), Helsinki, Finland (Dfb), and Abu Dhabi, United Arab Emirates (Bwh). The authors utilized RT42-Organic PCM for Venice and Helsinki, RT55-Organic PCM for Abu Dhabi, and an a-Si (amorphous Silicon) thin-layer solar cell for the PV layer.

The combination of a PCM layer and a semi-transparent PV layer within the space cavity of the DSF raised monthly energy savings by 20–30%, independent of climate. The scientists observed that the selection of PCM material with the appropriate MT and a ventilation plan are the primary factors that have contributed to an efficient thermal and energy conversion system. Maintaining the PCM material at its mushy zone or phase transition allowed for the



greatest thermal performance. This can be accomplished by installing a ventilation system that protects the PCM from overheating and overcooling.

In a separate numerical work, Elarga et al. (2017) simulated and optimized (using a genetic multi-optimization technique) a forced-ventilated PV-PCM integration in DSF and TSF systems. For their numerical simulations, they employed a 1D model and the finite difference method. In the DSF system, the PV module was placed in the cavity area between the panes, but in the TGF system, the PCM was placed on the outside surface of the middle pane and the PV module was placed on the outer surface of the PCM. The optimal scenario reduces thermal loads by 26.4%. The authors suggested 2D simulations to capture the likely occurrence of stratification effect in the higher altitude façade and energy cost as part of the optimization strategy for the PV-PCM DSF system for further research.

Ziasistani and Fazelpour (2019) assessed the thermal and energy performance of a building with various glazing types of a DSF combined with a PV layer coated on the outside skin and inserting PCM to the walls using the DesignBuilder. These researchers evaluated six varieties of glazing, including single and double layers. As the PV layer, they chose monocrystalline silicon PVs. All major building orientations were evaluated in six Iranian cities: Tehran (Bwh), Tabriz (Bsk), Shiraz (Bwh), Esfahan (Bwh), Bandar Abbas (Bwh), and Yazd (Bwh). They demonstrated that west- and north-facing DSF result in the highest energy usage and the lowest cooling load, respectively. With the exception of Bandar Abbas (Bwh), the highest yearly electricity generation was also found with an orientation of 180 degrees in all cities.

Heydari and Khoshkhoo (2022) analyzed the energy performance of a six-story structure in four Iranian cities, namely Rasht (Cfa), Tabriz (Bsk), Yazd (Bwh), and Bandar Abbas (Bwh), by adopting DSF with PV layer on the external pane and PCM on the walls. The investigation was numerically simulated using the software package DesignBuilder. They demonstrated that the air cavity depth in DSF has a slight impact on the cooling and heating loads of buildings in every city tested. The overall energy production by the PV module for all orientations in Yazd, Bandar Abbas, Tabriz, and Rasht was reported to be 52.56, 44.49, 36.87, and 33.48 MWh, respectively. Using PCM in the walls had a negligible impact on energy consumption, as the PCM's phase change cycle did not occur throughout the study period (from 7:00 to 19:00).

Ahmed et al. (2020) incorporated four technologies for sliding smart windows, including air-gap, PCM, PV, and vacuum glazing for the climatic condition of Kuwait city (Bwh) in Kuwait. Figure 1.18 shows the glazing systems modelled by the authors. The researchers demonstrated that the presence of PCM in fenestration systems alters the PV system's safe operation and the peak indoor heat gain. The full example (Figure 1.18e) with a mechanically forced ventilation system was determined to be the optimal scenario for the efficient functioning and thermal insulation of the PV system. Future efforts proposed by the authors include long-term simulations involving the observation of the phase change cycle the PCM undergoes in a 24-h period, as well as varying weather conditions.

Ke et al. (2022) presented a multi-layer ventilated window with a PV layer (cadmium telluride or CdTe cell) combined with a PCM layer, with MT of 27–29 °C and 18–20 °C for summer and winter seasons, respectively, in the middle layer for Hefei, China's climatic conditions (Cfa). Using PCM, they determined an improvement in the electrical efficiency of the PV window and an increase in the thermal comfort of the interior. Among climatic parameters, it was discovered that the thermal and electrical performance of the system is most sensitive to ambient temperature and solar heat gain. In addition, the authors recorded a 1246.87 kWh reduction in air conditioning demand.

Figure 1.19 depicts the PCM-PV multi-layer ventilated window in summer and winter modes. Table 1.5 provides a summary of the reviewed research on PCM-integrated shading solutions for GUs. Using a PV layer in conjunction with a PCM layer in the glazing units appears to be a promising technology that requires further investigation to fully exploit the utilization of combined PCM-PV technology.

The PCM ensures the safe operation of the PV module, which improves the thermal performance of the smart glazing system. In addition, establishing a ventilation system to prevent PCM from overheating or overcooling is suggested. As the PV layer restricts sunlight transmittance, it might be utilized to prevent the PCM from overheating in addition to producing electricity. In these systems, ambient temperature and solar heat gains influence thermal and electrical performance the most.

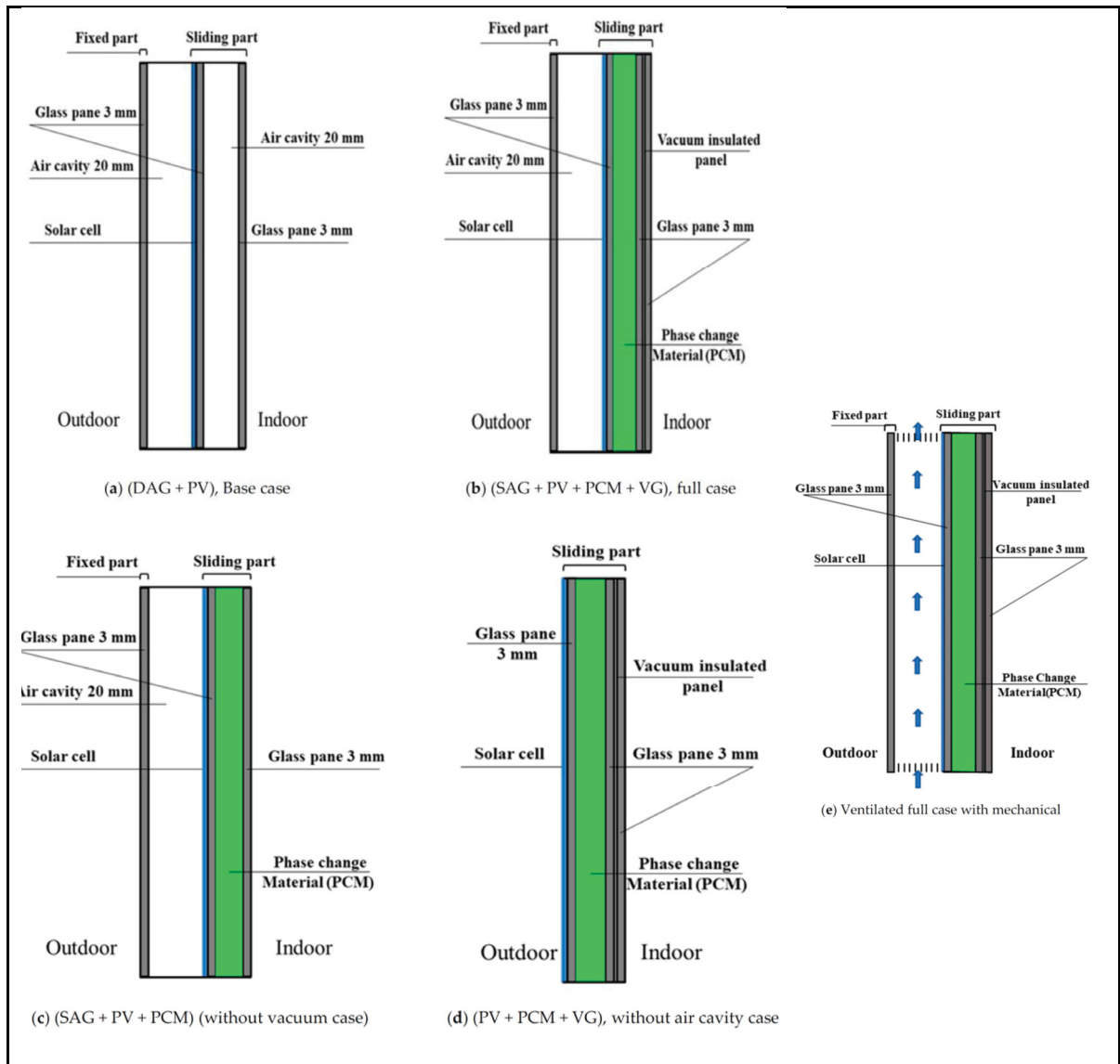


Figure 1.18 Different proposed windows showing: (a) base case, (b) full case, (c) without vacuum case, (d) without air cavity case, and (e) mechanical ventilated full case taken from Ahmed et al. (2020, p. 5)

Table 1.5 Summary of PCM/PV-incorporated multi-layer GUs

| Ref.                             | PCM Type (MT °C)       | Solar Cell Type         | Climate Code    | Study Type | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                                       |
|----------------------------------|------------------------|-------------------------|-----------------|------------|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Elarga et al., 2016)            | RT42 (42)<br>RT55 (55) | a-Si                    | Cfa, Dfb<br>Bwh | N          | Cooling and heating | <ul style="list-style-type: none"> <li>The proposed system causes a 20–30% increase in the monthly energy saving, regardless of the climate.</li> <li>Installing a ventilation system along with an appropriate MT for PCM is necessary to maintain the PCM in mushy zone to avoid overheating and overcooling.</li> </ul> |
| (Elarga et al., 2017)            | RT35 (35)              | a-Si                    | -               | N          | Cooling and heating | <ul style="list-style-type: none"> <li>PV-only layer is applied to a DGU, and PV-PCM layer is applied to a TGU.</li> <li>The optimum case leads to a 26.4% reduction in thermal loads.</li> </ul>                                                                                                                          |
| (Ziasistani and Fazelpour, 2019) | BioPCM - M182/Q25 (25) | monocrystalline silicon | Bwh<br>BSk,     | N          | Cooling and heating | <ul style="list-style-type: none"> <li>PV layer is applied to a DGU, and PCM is applied to the walls.</li> <li>West-faced and north-faced DSF lead to maximum energy consumption and minimum cooling load, respectively.</li> </ul>                                                                                        |

Table 1.5 Summary of PCM/PV-incorporated multi-layer GUs (continued)

| Ref.                                   | PCM Type (MT °C)                        | Solar Cell Type | Climate Code  | Study Type | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                                                                                                                              |
|----------------------------------------|-----------------------------------------|-----------------|---------------|------------|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Heydari and Haghighi Khoshkhoo, 2022) | BioPcm-Q23 (23)                         | a-Si            | Cfa, Bsk, Bwh | N          | Cooling and heating | <ul style="list-style-type: none"> <li>PV layer is applied to a DGU, and PCM is applied to the walls.</li> <li>Air cavity depth in DSF has a subtle effect on the cooling and heating loads of the buildings in all studied cities.</li> <li>From 7 am to 7 pm, the use of PCM in walls has an insignificant effect on energy consumption as during the hours, the phase change cycle is not complete.</li> </ul> |
| (Ahmed et al., 2020)                   | RT35HC (34–36)                          | Silicon wafer   | Bwh           | N          | Cooling             | <ul style="list-style-type: none"> <li>The presence of PCM in the fenestration systems causes the PV module to operate safely and the peak indoor heat gain to be shifted.</li> </ul>                                                                                                                                                                                                                             |
| (Ke et al., 2022a)                     | (27–29) for cooling (18–20) for heating | CdTe            | Cfa           | N          | Cooling and heating | <ul style="list-style-type: none"> <li>1246.87 kWh saving in the air-conditioning load is reported.</li> <li>Thermal and electrical performance of the system is mainly sensitive to ambient temperature and solar heat gain among the weather factors.</li> </ul>                                                                                                                                                |

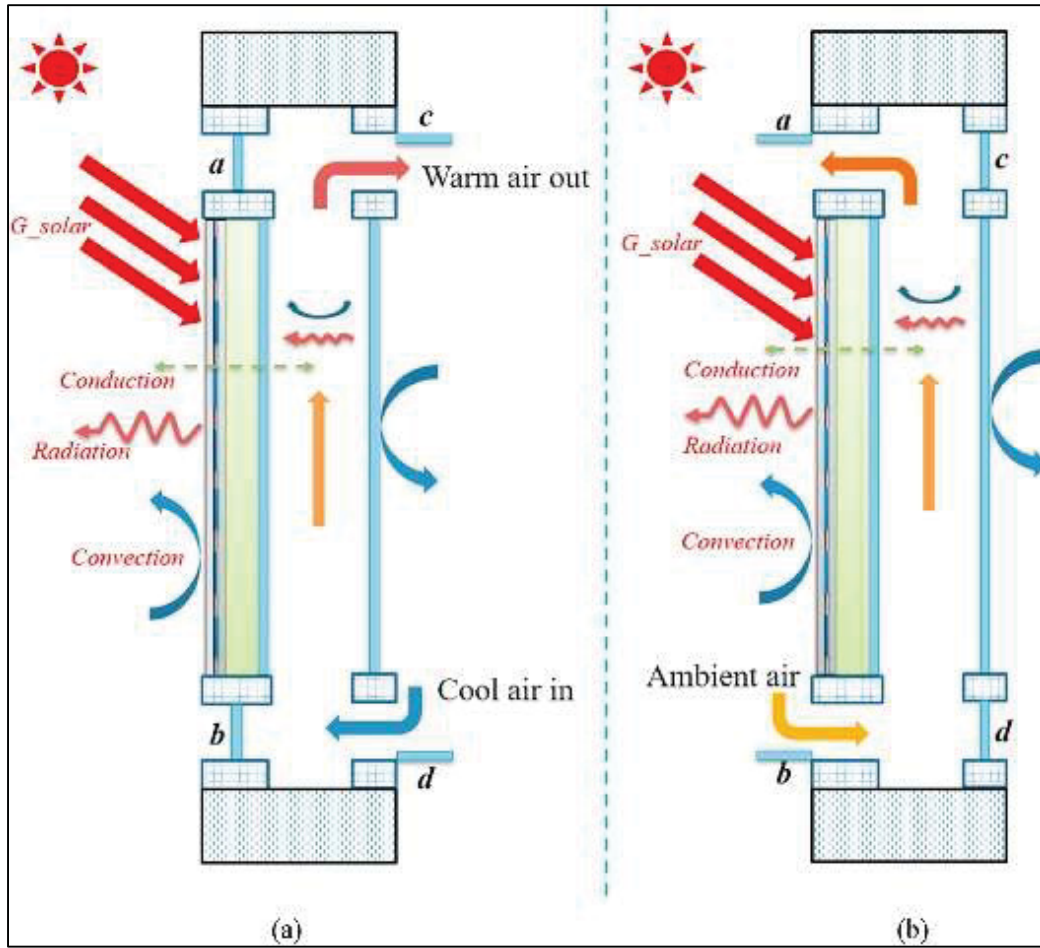


Figure 1.19 Energy flow and operating modes of the PCM-PV multi-layer ventilated glazing system in (a) winter mode and (b) summer mode, listed as vents taken from Ke et al. (2022, p. 1309)

### 1.1.3.2 Technologies of GUs with PCM Utilization

#### 1) Photovoltaic (PV) Window

The sole use of the PV layer in fenestration systems, often known as a PV-window, has recently captured the interest of numerous researchers. Cuce et al. (2016) developed a multi-functional glazing technology known as high insulation solar glass (HISG), which can not only generate electricity like conventional PV panels by having an amorphous silicon PV module, but can

also provide thermal and acoustic insulation, energy savings, and self-cleaning due to the presence of a nano-coating known as  $\text{TiO}_2$ .

The test rooms were done in Taiwan (Cfa), as shown in Figure 1.20. The authors calculated that the HISG delivers 100% UV blockage, which is beneficial to human health. HISG generates 16% more electricity than conventional PV glazing due to the nanolayer reflective film included therein. In addition, the HISG shading coefficient was reported to be 0.136, indicating an almost 80% reduction in solar heat gain compared to standard glass. In addition, the energy savings for heating and cooling seasons employing HISG were observed to be 38% and 48%, respectively.

Sharma et al. (2021) designed a PV-TSF by adding a perforated metallic sheet into the cavity space of a PV-DSF system in order to remove the heat from the pans' space cavity with minimal restriction of sunlight entering the building and to benefit from natural ventilation in the cavity. Figure 1.21 depicts the inside and exterior perspectives of the window system used by the authors. In an experiment done in Jaipur, India (Bsh), the authors also evaluated the system's thermal and electrical performance. The researchers concluded that applying the perforated sheet with 60% perforation decreases the solar heat gain coefficient by approximately 14.7% compared to the PV-DSF system with a cavity distance of 200 mm. In general, they determined that PV-TSF is superior to PV-DSF because the former does not require a wide air gap between the panes.

Tang et al. (2022) suggested a new DG-PV curtain wall system paired with an air handling unit based on exhaust cooling and heating recovery, as seen in Figure 1.22, in order to evaluate its electrical and thermal performance. A numerical simulation was conducted for a typical summer week operating in Hefei, China (Cfa). Using the proposed PV system for the curtain wall reduced the building's total energy consumption by 19.26%. Furthermore, it was discovered that a 0.08 m depth for the air cavity and a greater PV coverage ratio resulted in a greater energy-saving potential, making the system a viable choice for green technology.

Luo et al. (2017) studied the energy performance of a double skin façade (DSF) using PV-blinds (PVBs) as a shading device placed to the façade inside surface of a south-facing wall

through a numerical and experimental analysis. They utilized amorphous silicon (a-Si) for the PVB system's solar cell. The PVB-DSF system generates power, mitigates solar transmittance, and provides adjustable daylighting management. The experimental site was constructed during frigid winters and hot summers in Changsha, China (Cfa), which has a climate that is warm and moderate. The angle and space of PVB were investigated using a parametric model. In comparison to a typical DSF without shading devices and one with shading devices, their proposed system might save around 12.16 and 25.57 percent of energy during the summer months. They also proposed that the PV-DSF system must use natural ventilation mode throughout the summer.

Tan et al. (2022) explored a four-layer PV-integrated DGU, commonly known as vacuum-PV glazing, using numerical and experimental methods. To enhance the power generation of the PV module, the authors positioned the CdTe laminate and DG on the external and indoor sides, respectively. The vacuum PV glazing unit has a U-value of  $0.89 \text{ W/m}^2\text{K}$ , according to the researchers' numerical findings. The study was conducted in various Chinese cities, including Harbin (Dwa), Beijing (Dwa), Changsha (Cfa), Guangzhou (Cwa), and Kunming (Cwb), where the proposed PV-window produced average yearly power outputs of  $47 \text{ kWh/m}^2$ ,  $48 \text{ kWh/m}^2$ ,  $34 \text{ kWh/m}^2$ ,  $36 \text{ kWh/m}^2$ , and  $45 \text{ kWh/m}^2$ , respectively. The components of the PV glazing system utilized by the authors are illustrated in Figure 1.23.

Uddin et al. (2022) presented PV combined hybrid vacuum glazing as a new technique in comparison to PV combined vacuum glazing, which has been less investigated. Figure 1.24 depicts the CdTe-based semitransparent PV window system construction. According to reports, the U-value of the proposed system is 1.145. The authors investigated the energy performance of the suggested glazing system in five climate conditions in China, namely Hohhot, Inner Mongolia (Bsk), Tianjin, Tianjin (Dwa), Hefei, Anhui (Cfa), Kunming, Yunnan (Cwb), and Xiamen, Fujian (Cwa). The authors noted that the suggested glazing system lowers energy consumption by roughly 59.5% and 40% in cold climate regions and 76.5% and 74% in hot climate regions when compared to single clear glazing and DG windows, respectively.

Wang et al. (2021) carried out a numerical and experimental study to examine the annual energy performance of a ventilated DGW integrated with CdTe PV cells. They showed 25%



to 30% of the annual electrical loss was attributable to the extinction and reflection of the glass. It was also found that increasing the PV coverage proportion causes the net energy consumption of the three cities (i.e., Hefei (Cfa), Harbin (Dwb), and Haikou (Cwa) in China) to initially fall and subsequently rise. Optimum PV coverage proportion for minimum net energy consumption was reported as 50%, 60%, and 70% for Harbin, Hefei, and Haikou, respectively.

Alrashidi et al. (2022) performed an experimental study to assess the daylight control, energy saving, and power generation of PV-DGW using CdTe solar cells in Penryn, UK (Cfb). It was found that PV glass with the least amount of transparency can decrease solar heat gain by 96% and cooling energy by 23.2% when applied in a south-west orientation in comparison to standard clear glazing.

Zhang et al. (2022) numerically and experimentally examined the thermal and electrical performance of ventilated PV-DGW using CdTe solar cells in Hefei, China (Cfa). According to their results, the WWR and PV coverage of ventilated PV-DGW had a significant effect on the heat transmission and electrical output of the glazing system. Changes in the emissivity of low-e coating had no effect on the window's performance. Numerous researchers have recently demonstrated the potential application of PV layer in glazing systems (Castillo et al., 2022; Musameh et al., 2022; Yu et al., 2021), with cadmium telluride (CdTe) solar cells being the most prevalent in PV windows (Qiu and Yang, 2022; Su et al., 2021; Wang, et al., 2021; Wang et al., 2022). Su et al. (2022) examined the energy and electrical performance of PVB systems by adopting four solar cells, including amorphous silicon (a-Si), cadmium telluride (CdTe), dye-sensitized solar cell (DSSC), and perovskite solar cell (PSC). The CdTe PV cell had the best performance among the four solar cells examined. Table 1.6 provides a summary of the relevant studies on PV window systems.

According to the aforementioned literature, the use of solar cells to generate electricity from sunlight is a viable technology used to GUs to boost energy savings. It can be concluded that places with a greater amount of sunlight, such as those whose second letter code is “w”, give greater energy savings through the use of PV layers in GUs. It is because certain places encounter less cloudy days in a year and more sunlight may reach the solar cell. Since PV-

window technology alone has been employed more frequently than in collaboration with other smart glazing technologies and has demonstrated promising energy-saving performance, it might be integrated with other passive technologies to improve the thermal performance of smart glazing technology.



Figure 1.20 Example of high insulation solar glass system's outside view taken from Cuce et al. (2016, p. 371)



Figure 1.21 Inside and outside views of fenestration system proposed by taken from Sharma et al. (2021, p. 319)

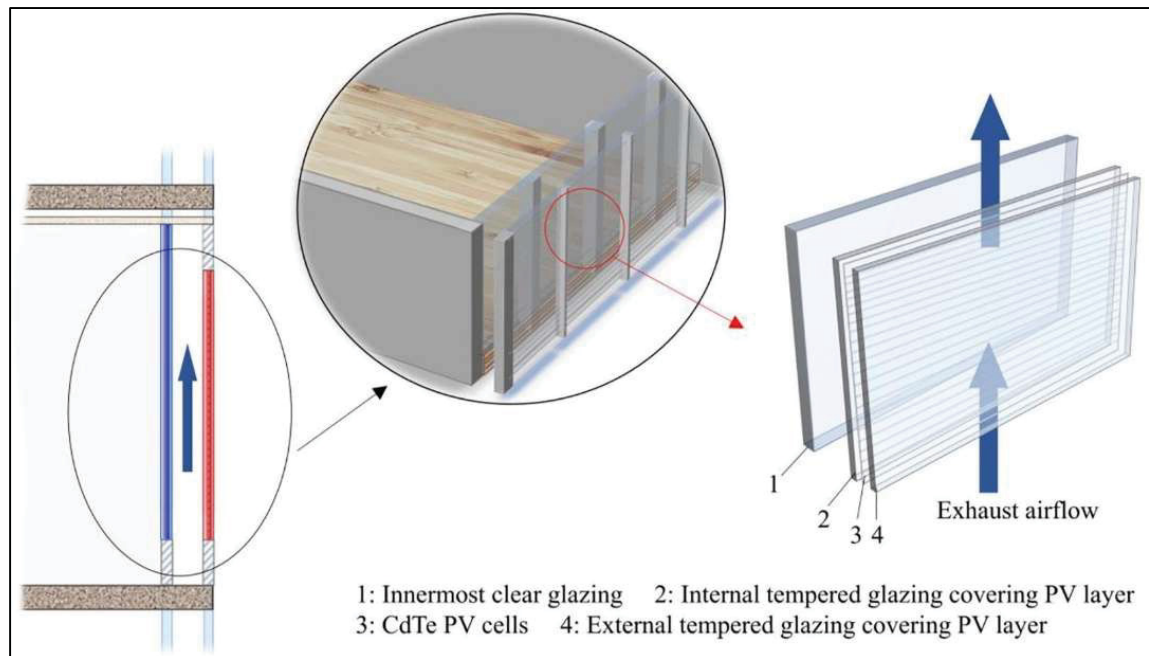


Figure 1.22 Proposed PV-incorporated DGU system by Tang et al. (2022, p. 3)

| Ref.                  | Solar Cell Type                      | Climate Code | Study Type | Envelope Element | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                                                                                    |
|-----------------------|--------------------------------------|--------------|------------|------------------|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Cuce et al., 2016)   | a-Si + TiO <sub>2</sub> nano-coating | Cfa          | E          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>The glazing system is self-cleaning due to the nano-coating and 100% UV protection.</li> <li>80% reduction in solar heat gain is reported compared to standard glass.</li> <li>The energy savings for heating and cooling seasons employing the proposed glazing system are observed to be 38% and 48%, respectively.</li> </ul> |
| (Sharma et al., 2021) | CdTe                                 | Bsh          | E          | DGW + a sheet    | Cooling             | <ul style="list-style-type: none"> <li>Implementing of the perforated sheet with 60% perforation reduces the solar heat gain coefficient by about 14.7% compared to the PV-DSF system with pane cavity distance of 200 mm.</li> </ul>                                                                                                                                   |
| (Tang et al., 2022)   | CdTe                                 | Cfa          | N          | DGW              | Cooling             | <ul style="list-style-type: none"> <li>19.26% reduction in the overall energy consumption using the proposed PV system for the curtain wall.</li> </ul>                                                                                                                                                                                                                 |

Table 1.6 Summary of PV window systems

Table 1.6 Summary of PV window systems (continued)

| Ref.                 | Solar Cell Type | Climate Code            | Study Type | Envelope Element | Application         | Findings and Remarks                                                                                                                                                                                                                                                       |
|----------------------|-----------------|-------------------------|------------|------------------|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Luo et al., 2017)   | a-Si            | Cfa                     | E, N       | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>Energy saving in summer is about 12.16% and 25.57% compared to a conventional DSF without and with shading devices, respectively.</li> </ul>                                                                                        |
| (Tan et al., 2022)   | CdTe            | Dwa, Cfa, Cwa, Cwb      | E, N       | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>Average annual power output was reported as about 47 kWh/m<sup>2</sup>, 35 kWh/m<sup>2</sup>, and 45 kWh/m<sup>2</sup> for climates with the classification codes Dwa, Cfa, and Cwb, respectively.</li> </ul>                       |
| (Uddin et al., 2022) | CdTe            | Bsk, Dwa, Cfa, Cwa, Cwb | E, N       | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>The proposed glazing system saves energy consumption by about 59.5% and 40% in cold dominate climate regions and 76.5% and 74% in hot dominant climate regions versus single clear glazing and DG windows, respectively.</li> </ul> |

| Ref.                     | Solar Cell Type       | Climate Code  | Study Type | Envelope Element | Application         | Findings and Remarks                                                                                                                                                                                      |
|--------------------------|-----------------------|---------------|------------|------------------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Wang et al., 2021)      | CdTe                  | Cfa, Dwb, Cwa | E, N       | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>Optimum PV coverage proportion for minimum net energy consumption is reported as 50%, 60%, and 70% for Dwb, Cfa, and Cwa, respectively.</li> </ul>                 |
| (Alrashidi et al., 2022) | CdTe                  | Cfb           | E          | DGW              | Cooling             | <ul style="list-style-type: none"> <li>PV glass decreases solar heat gain by 96% and cooling energy by 23.2% when applied in a south-west orientation in comparison to standard clear glazing.</li> </ul> |
| (Zhang et al., 2022)     | CdTe                  | Cfa           | E, N       | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>WWR and PV coverage of ventilated PV-DGW had a significant effect on the heat transmission and electrical output of the glazing system.</li> </ul>                 |
| (Su et al., 2022)        | CdTe, a-Si, DSSC, PSC | -             | N          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>CdTe PV cell is reported as the best performance among the four studied solar cells.</li> </ul>                                                                    |

Table 1.6 Summary of PV window systems (continued)

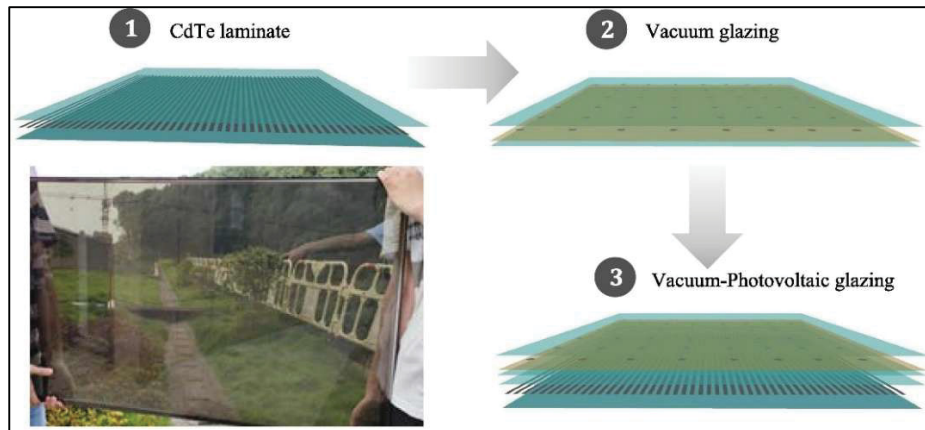


Figure 1.23 Example of PV-GU system components taken from Tan et al. (2022, p. 4)

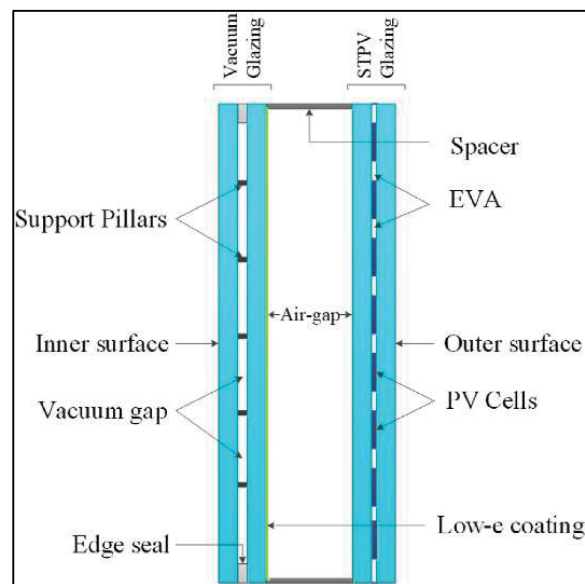


Figure 1.24 Example of PV combined hybrid vacuum glazing system Uddin et al. (2022, p. 3)

## 2) Shading Systems (without PCM)

Various shading methods for indoor thermal comfort have been integrated into the window system to improve energy efficiency. Due to the use of external shading devices, Touma and Ouahrani (2017) conducted an annual energy-saving research of brise soleil and venetian



blinds applied to the outer face of a DGW on both north- and south-facing facades using EnergyPlus and experimentally validated their findings. The examination rooms were fully glazed offices in Doha, Qatar (Bwh). It was discovered that brise soleil and fixed blinds with 90° save energy consumption by 18.6% and 20.6% annually in south-facing facades and 7.7% and 9.0% annually in north-facing facades. It was proved that the shading devices reduce glare risks on the south façade while eliminating the glare risks entirely on the north façade. Finally, they demonstrated that shade control can reduce energy use by 26.1%.

Dutta et al. (2017) presented a sun-path-based autonomous movable outside shade device with multiple orientations for an annual energy-saving performance evaluation. In tropical wet and dry weather (Aw), the heat transfer from the sun to the window was greatest in the South, followed by the East, West, and North. Maximum energy savings in June were 14.9% and average annual savings were 9.8%, respectively. The authors also claimed six months of financial payback for their proposed shading device.

Fedorczak-Cisak et al. (2019) examined the overheating risk reduction of highly glazed office rooms in Kraków, Poland (Dfb), during the transition season (spring) of a temperate environment, when air conditioning units are typically not operating. According to these studies, exterior shading blinds with a 45° angle reduce discomfort hours during working hours by 92% compared to a fenestration system without venetian blinds. Kuczyski et al. (2021) compared the thermal performance of three passive cooling approaches, including night ventilation, thermal mass, and external blinds, in a building with a temperate climate in central-western Poland (Cfb). The authors discovered that night ventilation and an increase in thermal mass do not considerably reduce the number of hours in which the maximum temperature is exceeded, however closing the exterior blinds eliminates the problem.

Carlier et al. (2022) performed a numerical analysis of the annual energy performance of residential structures with switchable insulation systems (SIS) applied to windows as shades and outside walls as dynamic simulation. The climatic data for Brussels (Cfb), Oostende (Cfb), and St. Hubert (Cfb) in Belgium and Barcelona (Csa) in Spain were established for two types of homes, namely a single-family home and an apartment. The researchers argued that SIS-integrated windows eliminate the need for mechanical cooling and reduce heating energy



consumption by 44% in Belgium. It was also noted that Belgium and Spain, with their milder temperatures, could profit from such a system, particularly in terms of energy savings for heating. The orientation of the windows and the behavior of the inhabitants were also identified as critical factors in SIS energy performance.

The internal use of shading devices also drew the interest of researchers. Wang et al. (2021) presented a movable shade curtain inside and outside of a single-layer window in Beijing, China (Dwa) to numerically evaluate and experiment with its energy-saving performance throughout the year. They demonstrated that during the winter, the movable curtain may be rolled down at night to reduce heat loss and raised during the day to maximize solar heat gain through the window openings. They evaluated the position of the curtain (inside and outside), whether it was rolled up or down, the air gap distance between the window and curtain, the heat transfer coefficient, and the size of the window-to-wall ratio. The optimal example was determined to be one with a window-to-wall ratio of 0.26 and a heat transfer coefficient of  $1.02 \text{ W/m}^2$ , resulting in a 75% increase in annual energy savings. Additionally, the authors demonstrate that the suggested insulated windows result in more desired indoor temperatures, less heating, cooling, and annual loads, and a possible price-to-load ratio compared to existing energy-saving windows.

Using infrared thermography images and building simulation, Cho et al. (2020) studied the energy and hygrothermal performance of retrofitting a cultural property with various energy efficiency measure packages. The construction site was in Seoul, Korea (Dwa). Using EnergyPlus and WUFI models, energy and hygrothermal simulations of a building were simulated. The package of technologies, which included the replacement of TG windows with low-e coating, the addition of insulation, the improvement of airtightness, the installation of internal blinds, and the replacement of incandescent lighting with LEDs, reduced heating energy consumption by 72% and total energy consumption by 60%, respectively.

Tan et al. (2022) conducted a numerically and experimentally validated annual energy study of internal venetian blinds in residential structures. Positioned on the interior surface of a DG window as depicted in Figure 1.25, they evaluated various blind angles and shade states, namely fully opened, partly opened, and fully closed. This study utilized typical meteorological

years for Houston (Cfa) and Minneapolis (Dfa) in the United States. According to the results, the results showed that the two most influential parameters on annual energy performance are (i) solar transmittance, (ii) solar reflectance, and (i) thermal infrared transmittance, (ii) inner emissivity for cooling-dominated and heating-dominated climates, respectively. It was stated that cooling and heating energy savings might be reduced by 44% and 65%, respectively. Additionally explored were shading devices between multi-layered windows.

Zhang et al. (2018) experimentally studied and dynamically modelled a TG exhaust air window, combining adjustable venetian blinds within the window. As illustrated in Figure 1.26, the blinds were positioned between the external and middle panes to be fully opened in summer mode and entirely closed in winter mode. In addition to movable shades, they profited from switchable components that facilitated the summer and winter modes' exhaust air flow. On a typical summer day in Wuhan, China (Cfa), which has a humid subtropical climate, the effects of airflow velocity within the TG window and blinds angles on the system thermal performance were examined. The authors say that the switchable exhaust air window is suitable in both newly constructed and retrofitted buildings since it greatly reduces cooling and heating loads, as well as peak loads, resulting in lower beginning costs for air-conditioning systems. Table 1.7 provides a summary of the researched literature on shading systems without PCM.

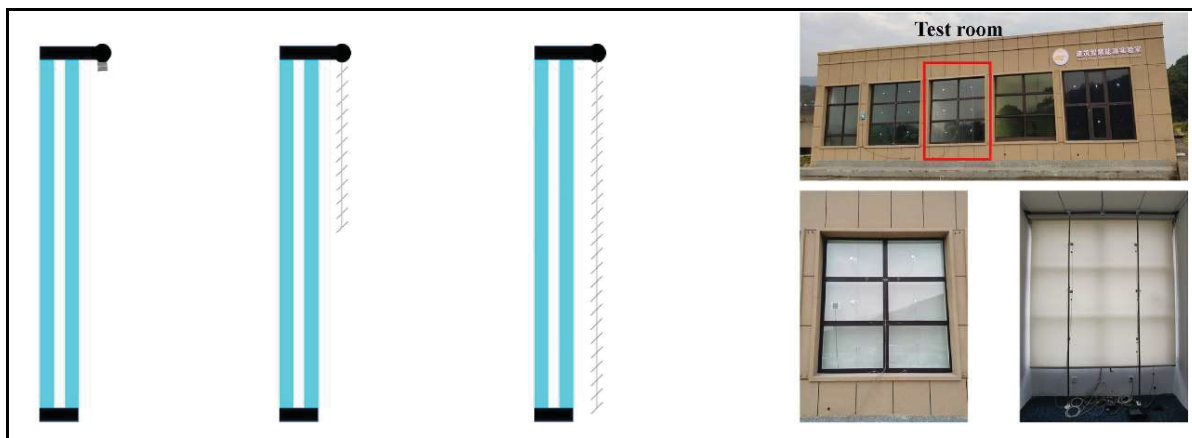


Figure 1.25 The outside view of the test room, along with the position of the shading devices taken from Tan et al. (2022, p. 4 and 5)

Table 1.7 Summary of shading systems (without PCM)

| Ref.                           | Climate Code | Study Type | Shading Position of the GU | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                                                   |
|--------------------------------|--------------|------------|----------------------------|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Touma and Ouahrani, 2017)     | Bwh          | E, N       | External                   | Cooling and heating | <ul style="list-style-type: none"> <li>South-facing facades with shading devices reduce energy usage more than north-facing ones. Utilizing shade control has been shown to reduce energy consumption by 26.1%.</li> </ul>                                                                                                             |
| (Dutta et al., 2017)           | Aw           | E, N       | External                   | Cooling and heating | <ul style="list-style-type: none"> <li>14.9% and 9.8% energy savings were reported as the maximum savings in June and for an average annual saving, respectively. The authors also claimed six months of financial payback for their proposed shading device.</li> </ul>                                                               |
| (Fedorczak-Cisak et al., 2019) | Dfb          | E          | External                   | Cooling spring      | <ul style="list-style-type: none"> <li>External shading blind with an angle of 45° results in 92% reduction in discomfort hours during working hours compared to a fenestration system without venetian blinds.</li> </ul>                                                                                                             |
| (Kuczyński et al., 2021)       | Cfb          | E          | External                   | Cooling             | <ul style="list-style-type: none"> <li>Night ventilation and an increase in thermal mass do not considerably reduce the number of hours in which the maximum temperature is exceeded, however closing the exterior blinds eliminates the problem.</li> </ul>                                                                           |
| (Carlier et al., 2022)         | Csa, Cfb     | N          | External                   | Cooling and heating | <ul style="list-style-type: none"> <li>Using switchable insulation systems applied to windows as shades causes no use of mechanical cooling and 44% decrease in heating energy end-use in Belgium (Cfb).</li> <li>The studied regions could profit from such a system, particularly in terms of energy savings for heating.</li> </ul> |

| Ref.                 | Climate Code | Study Type | Shading Position of the GU | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                                                                                                                           |
|----------------------|--------------|------------|----------------------------|---------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Wang et al., 2021)  | Dwa          | E, N       | Internal                   | Cooling and heating | <ul style="list-style-type: none"> <li>The optimum case is the one with window to wall ratio of 0.26 and heat transfer coefficient of 1.02 W/m<sup>2</sup>, resulting in 75% enhancement of the annual energy saving.</li> </ul>                                                                                                                                                                               |
| (Cho et al., 2020)   | Dwa          | E, N       | Internal                   | Cooling and heating | <ul style="list-style-type: none"> <li>The package containing all the studied technologies including installing internal blinds decreases 72% and 60% of the heating energy and total energy consumption, respectively.</li> </ul>                                                                                                                                                                             |
| (Tan et al., 2022)   | Cfa, Dfa     | E, N       | Internal                   | Cooling and heating | <ul style="list-style-type: none"> <li>The two most influential parameters on annual energy performance are (i) solar transmittance, (ii) solar reflectance, and (i) thermal infrared transmittance, (ii) inner emissivity for cooling-dominated and heating-dominated climates, respectively.</li> <li>The proposed system causes 44% and 65% energy saving for cooling and heating, respectively.</li> </ul> |
| (Zhang et al., 2018) | Cfa          | E, N       | Between the panes          | Cooling and heating | <ul style="list-style-type: none"> <li>The proposed switchable exhaust air TG window is applicable in a newly constructed building and retrofitting due to its energy-saving enhancement and peak load reduction benefits.</li> </ul>                                                                                                                                                                          |

Table 1.7 Summary of shading systems (without PCM) (continued)

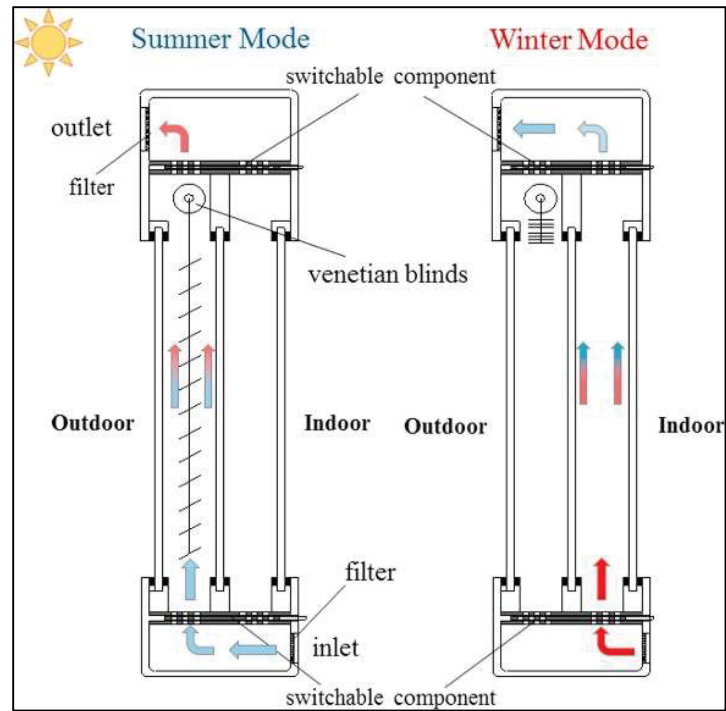


Figure 1.26 Example of blind position and air flow in winter and summer modes taken from Zhang et al. (2018, p. 74)

According to the above literature review, the smart shading system is a passive approach employed in GUs to improve thermal comfort and saving energy. The use of active strategies to optimize the operation of shade systems throughout the year has been discussed. The performance of such devices is strongly affected by the behavior of the occupants. However, further study is required to incorporate such systems with other passive techniques in order to achieve the desired energy savings.

### 3) Chromogenic (Thermotropic and Thermochromic) Materials in GUs

Chromogenic materials, including thermotropic and thermochromic materials, are valuable design tools for dynamically controlling solar energy heat transmission. Thermotropic materials change their light transmittance behavior reversibly from extremely transparent to light scattering, sometimes referred to as a turbid state, when the majority of light reflects outside at a temperature threshold known as lower critical solution temperature (LCST). As

the temperature increases, the outer material alters its behavior to prevent sunlight transmission and overheating. Thermotropic effects studied in the solar control field can be induced by a phase separation process, a phase transition between an isotropic and an anisotropic (liquid-crystalline) state, and by very differing temperature dependences of the refractive indices of domains and matrices. Polymer mixtures and polymeric hydrogels have been widely researched. Thermochromic materials alter their visible optical characteristics as a function of temperature. Consequently, the integration of a sensor or actuator into the material itself is made possible. If the thermochromic material absorbs more light as the temperature rises, also known as positive thermochromism or inverse thermochromism, smart windows may be a viable use. This effect of moving from a transparent, low-hued, or colorless state to a brightly colored one has already been proven by laboratory prototypes. In addition, the public has been shown samples of products that are ready for sale (Seeboth et al., 2010).

Pertaining to the use of thermotropic materials in smart glazing systems, Yao and Zhu (2012) numerically investigated thermotropic windows of a typical six-story residential building located in Hangzhou, China (Cfa) to increase the energy efficiency, daylighting, and thermal performance of building envelopes. The researchers conducted their numerical calculations using the building modelling software DeST. The authors reported a 70% and 50% reduction in extremely uncomfortable indoor heat conditions when utilizing thermotropic DG west-facing windows as compared to DG windows and tinted DG windows, respectively. It was also discovered that the performance of the window system can be improved on east- and south-facing facades by selecting a thermotropic material with a lower LCST and a higher NaCl content. Therefore, the researchers suggested thermotropic material-based windows for thermal comfort, energy savings, and daylighting in hot summer and cold winter climatic building envelopes.

Goia et al. (2014) carried out an experiment to ascertain the energy performance of a south-facing TGU with a PCM layer and a thermotropic layer (n-alkane mixture) in Torino, Italy (Cfa), during the summer. According to researchers, inserting the PCM layer into the innermost cavity space of the TGU causes the PCM to remain longer in the mushy zone, resulting in a greater utilization of latent heat and a consequent improvement in the energy performance of

the window system. The authors also demonstrated that the energy performance of the proposed glazing system is enhanced by the employment of thermotropic and PCM layers, as well as the simultaneous use of both technologies, and that inserting PCM at the innermost layer can accommodate a PCM layer with a lower nominal MT.

Figure 1.27 demonstrates that Connelly et al. (2017) utilized a thermotropic layer called Hydroxypropyl cellulose (HPC) polymer in a DGU, alongside a PV layer of an office building located in London, UK (Cfb). The authors investigated HPC concentrations ranging from 1% to 6%. The threshold temperature or transition temperature for 1 weight percent HPC and 6 weight percent HPC was reported to be approximately 44 °C and 40 °C, respectively. Below the transition temperature, the thermotropic material is in a translucent state (Figure 1.27a) with a reported reflectance of approximately 10%, whereas above the threshold temperature, the material is in a transparent state (Figure 1.27b) with a reported reflectance of approximately 70%. In general, the authors indicated that the HPC is a potential thermotropic material for the application of smart windows based on their empirical findings.

Sun et al. (2021), presented a numerical and experimental investigation to evaluate the energy and optical performances of a south-facing DG smart window employing transparent parallel slat insulation as a thermotropic material. The research was conducted in London (Cfb), Rome (Csa), Stockholm (Dfb), and Singapore (Af) under diverse environmental circumstances. The impact of the optical properties and transition temperature of the thermotropic material on the energy performance of buildings was evaluated. The authors reported a 27.1% increase in annual energy savings due to the usage of thermotropic material in the DGW against a standard DGW. Figure 1.28 depicts the thermotropic material with DGW incorporation in both its clear and translucent forms. In a separate study, Sun et al. (2021) used the same smart glazing unit to quantitatively evaluate the thermal and optical performance of the unit on an energy building located in London, UK (Cfb). On the basis of the geometric features, i.e., slat spacing and slat tilt angle, and the thermotropic layer properties, i.e., temperature transient and optical properties, the thermal and optical performances of the building were analyzed. They determined that the suggested GU improves the building's energy performance by up to 22% in comparison to standard DGWs.

Regarding the use of thermochromic materials, Long et al. (2014) deployed a standard thermochromic material called vanadium dioxide ( $\text{VO}_2$ ) coated into transparent portions and paraffin wax PCM into non-transparent parts of a building envelope to experimentally study the energy performance of a structure in Shanghai, China (Cfa). The phase change temperature of  $\text{VO}_2$  thermochromic material was  $41.3^\circ\text{C}$ , and the peak phase change temperature of the PCM was  $38.8^\circ\text{C}$ . During the cooling period, the synergistic combination of PCM and  $\text{VO}_2$  materials resulted in a higher level of thermal comfort than passive techniques alone, while simultaneously enhancing energy efficiency. Moreover, a negative ESI was achieved during the heating period, indicating a bad decision between using  $\text{VO}_2$  alone and  $\text{VO}_2$  and PCM together in cold regions.

Then, Jin et al. (2022) investigated the thermal performance of three passive approaches, including  $\text{VO}_2$  thermochromic material, PCM, and low-e coating in DG and TG systems (shown in Figure 1.29) implemented in a building envelope in Shanghai, China (Cfa) using ANSYS Fluent software. The authors concluded that during the summer, the TG system with the three passive methods decreases the total heat gain compared to traditional DG windows by up to 32% on a sunny day and 40% on a cloudy day, whereas during the winter, the proposed system is not as effective as DGW due to the blockage of desirable solar energy.

Ke et al. (2022) developed a PCM-based aesthetic thermochromic window inspired by tetra-fish to improve the energy efficiency and aesthetics of a building. They utilized photonic co-doped  $\text{VO}_2$  as the thermochromic layer exhibiting angle-dependent bright colors resembling the skin of tetra fishes. An office building in Beijing (Dwa), Hong Kong (Cwa), Bangkok (Aw), and Kuala Lumpur (Af) saved an additional  $35.7\text{ kWh/m}^2$  of energy annually, according to the results obtained.

Tao et al. (2022) conducted a CFD study in Shanghai, China (Cfa), to evaluate the optical and energy performance of six thermochromic materials with varying switching temperatures ranging from  $20^\circ\text{C}$  to  $42.5^\circ\text{C}$ . As the maximum value for threshold temperatures between  $25^\circ\text{C}$  and  $35^\circ\text{C}$ , they observed a solar heat gain savings of 20.9%. Furthermore, the authors inferred that the optimal performance of thermochromic smart glazing occurs in places with long summer days and significantly lower solar radiation in winter days. Compared to



thermotropic smart glazing, thermochromic smart glazing is of greater interest to the authors, and the majority of researchers have chosen  $\text{VO}_2$  as the thermochromic layer (Aburas et al., 2021; Arnaoutakis and Katsaprakakis, 2021; Arnesano et al., 2021; Hong et al., 2021; Lin et al., 2021; Teixeira et al., 2022; Wang, et al., 2021). Table 1.8 provides a summary of the research conducted on chromogenic materials.

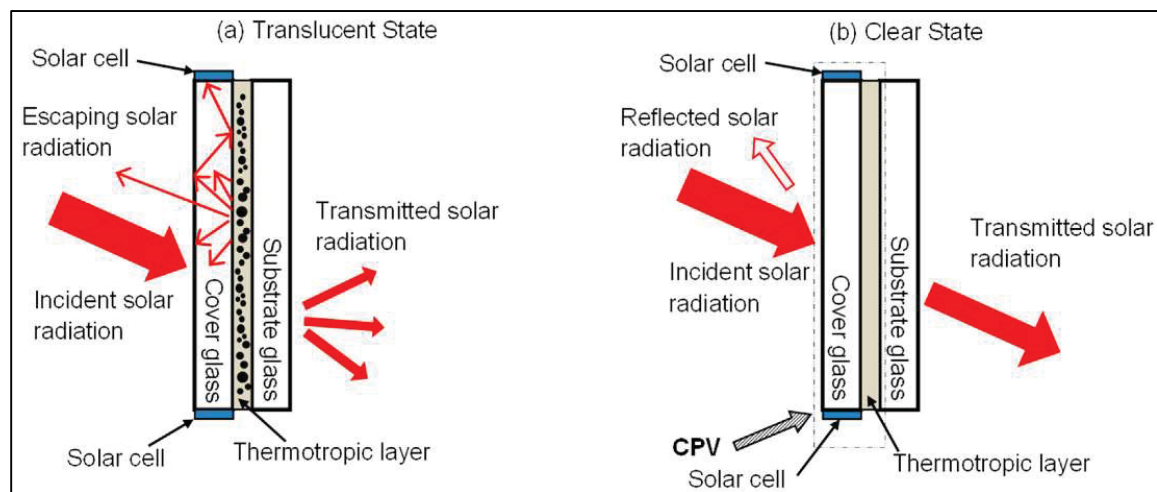


Figure 1.27 The thermotropic smart glazing along with PV layer in (a) translucent and (b) clear states taken from Connelly et al. (2017, p. 2)

Regarding the use of thermochromic materials, Long et al. (2014) deployed a standard thermochromic material called vanadium dioxide ( $\text{VO}_2$ ) coated into transparent portions and paraffin wax PCM into non-transparent parts of a building envelope to experimentally study the energy performance of a structure in Shanghai, China (Cfa). The phase change temperature of  $\text{VO}_2$  thermochromic material was  $41.3^\circ\text{C}$ , and the peak phase change temperature of the PCM was  $38.8^\circ\text{C}$ . During the cooling period, the synergistic combination of PCM and  $\text{VO}_2$  materials resulted in a higher level of thermal comfort than passive techniques alone, while simultaneously enhancing energy efficiency. Moreover, a negative ESI was achieved during the heating period, indicating a bad decision between using  $\text{VO}_2$  alone and  $\text{VO}_2$  and PCM together in cold regions. Then, Jin et al. (2022) investigated the thermal performance of three passive approaches, including  $\text{VO}_2$  thermochromic material, PCM, and low-e coating in DG and TG systems (shown in Figure 1.29) implemented in a building envelope in Shanghai,

China (Cfa) using ANSYS Fluent software. The authors concluded that during the summer, the TG system with the three passive methods decreases the total heat gain compared to traditional DG windows by up to 32% on a sunny day and 40% on a cloudy day, whereas during the winter, the proposed system is not as effective as DGW due to the blockage of desirable solar energy. Ke et al. (2022) developed a PCM-based aesthetic thermochromic window inspired by tetra-fish to improve the energy efficiency and aesthetics of a building. They utilized photonic co-doped VO<sub>2</sub> as the thermochromic layer exhibiting angle-dependent bright colors resembling the skin of tetra fishes. An office building in Beijing (Dwa), Hong Kong (Cwa), Bangkok (Aw), and Kuala Lumpur (Af) saved an additional 35.7 kWh/m<sup>2</sup> of energy annually, according to the results obtained. Tao et al. (2022) conducted a CFD study in Shanghai, China (Cfa), to evaluate the optical and energy performance of six thermochromic materials with varying switching temperatures ranging from 20 °C to 42.5 °C. As the maximum value for threshold temperatures between 25 °C and 35 °C, they observed a solar heat gain savings of 20.9%. Furthermore, the authors inferred that the optimal performance of thermochromic smart glazing occurs in places with long summer days and significantly lower solar radiation in winter days. Compared to thermotropic smart glazing, thermochromic smart glazing is of greater interest to the authors, and the majority of researchers have chosen VO<sub>2</sub> as the thermochromic layer (Aburas et al., 2021; Arnaoutakis and Katsaprakakis, 2021; Arnesano et al., 2021; Hong et al., 2021; Lin et al., 2021; Teixeira et al., 2022; Wang, et al., 2021). Table 1.8 provides a summary of the research conducted on chromogenic materials.

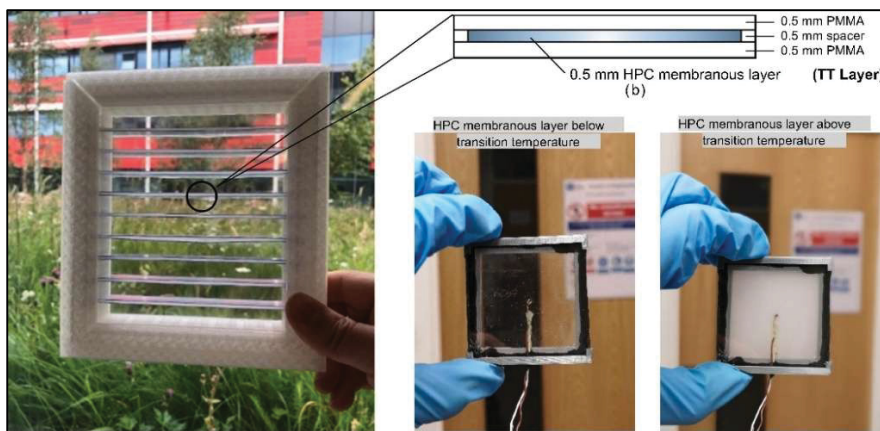


Figure 1.28 Photos of the DGW-incorporated thermotropic material in clear and translucent states taken from Sun et al. (2021, p. 3)

Table 1.8 Summary of chromogenic (thermotropic and thermochromic) materials in GUs

| Ref.                    | Chromogenic Material | Climate Code      | Study Type | Envelope Element | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                                                                                                  |
|-------------------------|----------------------|-------------------|------------|------------------|---------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Yao and Zhu, 2012)     | NaCl + HPMC + Water  | Cfa               | N          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>70% and 50% reduction in peak undesired indoor temperature is reported versus conventional DGWs and tinted DGWs, respectively.</li> </ul>                                                                                                                                                                                                      |
| (Goia et al., 2014)     | n-alkane mixture     | Cfa               | E          | TGW              | Cooling and heating | <ul style="list-style-type: none"> <li>PCM and thermotropic layers are used at the same time. It is suggested to place PCM and thermotropic layers in the innermost and outermost cavity spaces, respectively.</li> </ul>                                                                                                                                                             |
| (Connelly et al., 2017) | HPC polymer          | Cfb               | N          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>Glazing system reflectance above and below threshold temperature of the thermotropic layer is reported as 70% and 10%, respectively. Authors also used a PV layer in the DGW.</li> <li>Hydroxypropyl cellulose polymer is a potential thermotropic material for the application of smart windows based on their empirical findings.</li> </ul> |
| (Sun et al., 2021a)     | parallel slat        | Cfb, Csa, Dfb, Af | E, N       | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>27.1% enhancement in annual energy saving is reported by the use of thermotropic material in a DGW compared to a conventional DGW.</li> </ul>                                                                                                                                                                                                  |

| Ref.                | Chromogenic Material                 | Climate Code     | Study Type | Envelope Element | Application         | Findings and Remarks                                                                                                                                                                                                                                                                                            |
|---------------------|--------------------------------------|------------------|------------|------------------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| (Sun et al., 2021)  | parallel slat                        | Cfb              | N          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>22% enhancement in building energy performance is reported by the use of thermotropic material in a DGW compared to a conventional DGW.</li> </ul>                                                                                                                       |
| (Long et al., 2014) | VO <sub>2</sub>                      | Cfa              | E          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>The synergetic use of PCM and VO<sub>2</sub> materials showed better indoor thermal comfort than sole passive methods in the cooling period.</li> </ul>                                                                                                                  |
| (Jin et al., 2022)  | VO <sub>2</sub>                      | Cfa              | N          | DGW, TGW         | Cooling and heating | <ul style="list-style-type: none"> <li>The proposed system decreases the total heat gain versus the traditional DGWs by up to 32% and 40% for a sunny and cloudy day, respectively, while during winter, the proposed system is not as sufficient as DGW due to the block of desirable solar energy.</li> </ul> |
| (Ke et al., 2022)   | Tetra-fish-inspired layer            | Cwa, Aw, Dwa, Af | E          | SGW              | Cooling and heating | <ul style="list-style-type: none"> <li>35.9 kWh/m<sup>2</sup> enhancement in annual energy saving of an office building is reported for the three studied different climatic conditions.</li> </ul>                                                                                                             |
| (Tao et al., 2022)  | Six different thermotropic materials | Cfa              | N          | DGW              | Cooling and heating | <ul style="list-style-type: none"> <li>The best performance of thermochromic smart glazing occurs in regions with long summer days and substantially lower solar radiation in winter days.</li> </ul>                                                                                                           |

Table 1.8 Summary of chromogenic (thermotropic and thermochromic) materials in GUs (continued)

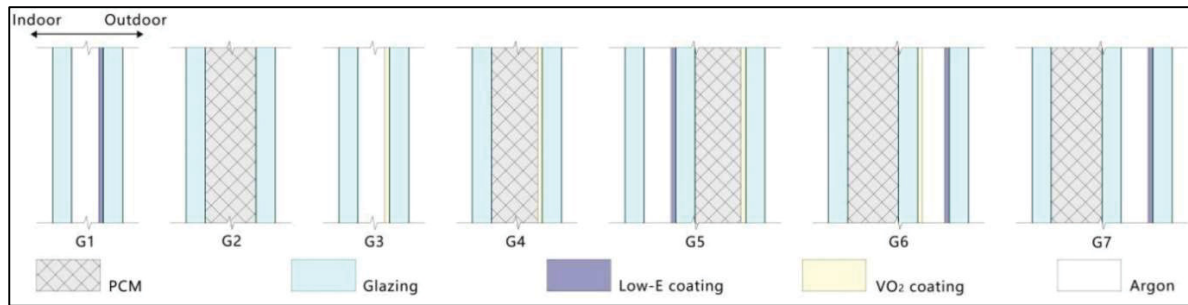


Figure 1.29 Different DG and TG systems used by taken from Jin et al. (2022, p. 3)

The last potential passive technology for smart glazing discussed in this article is chromogenic materials. The objective is to evaluate the viability of combining these materials with other passive technologies in order to achieve the desired energy performance in GUs. There are several individual applications of chromogenic materials, but only a few use them in combination with other smart glazing techniques. Using their dynamic control of the sunlight entering buildings, PCM overheating may be prevented, and other technologies can work in a safer environment. They function better in locations with warm summers (climatic code ending in “a”).

#### 1.1.4 *Summary and Conclusions*

The transparent parts in the building envelopes are responsible for the most energy losses. The initial sources of these energy losses came from burning fossil fuels. As such, the heat losses from building envelopes also contribute to global warming and CO<sub>2</sub> emissions. Increasing demand for the use of fully glazed façade systems makes it essential to optimize the energy performance of these systems. This study reviewed the potential active and passive methods, focusing on phase change materials (PCMs) as latent energy storage material for energy enhancement of fenestration systems while providing a desirable optical view, as well as enough sunlight for the occupants. Other technologies were also reviewed for smart glazing combined with PCM, including shading systems, solar cells (photovoltaic), and chromogenic (thermotropic and thermochromic). Since the climatic condition has been identified as the most influential factor for choosing the appropriate technology for smart glazing systems, almost all

reviewed studies in this paper were designated by a Köppen-Geiger climate classification code.

The main observations of this review study are as follows:

- PCM performs better in places where solar heat gain is greater. In addition, PCM is more successful in the summer and on clear days, whereas its efficacy in the winter and on overcast days is uncertain, necessitating the use of other passive and active approaches such as night ventilation.
- The PCM's volume expansion during phase transition is an additional factor that must be considered. Another potential problem that has been discussed is the reduced solar transmittance of PCM solid phase in comparison to liquid phase. Using solid–solid translucent PCM, which can also remove leakage and volume-changing issues, is one way to avoid this problem.
- During the summer, when the PCM-integrated blind system is on the interior side of the GUs, the absorbed daytime heat must not be vented inside, necessitating nighttime ventilation. On the other hand, during winter it collects heat during the daytime and releases it to the inside, which is a beneficial effect, but it filters more sunlight during the day as additional opaque material has been added to the blind system. To minimize losing sunlight, cascaded PCM integration with multiple MTs is recommended.
- Combining a PV layer and a PCM layer in the glazing units appears to be a promising technique that requires additional research to be fully exploited. The PCM enables the PV module to operate safely, which improves the thermal performance of the smart glazing system. As the PV layer blocks sunlight transmittance, it might be employed to keep the PCM from overheating while also producing electricity.
- Since PV-window technology alone has been used more frequently than in combination with other smart glazing technologies, and has demonstrated a promising energy-saving performance, it could be combined with other passive technologies to achieve a higher thermal performance for smart glazing technology. In addition, solar cells show better performance in regions with less cloudy days.

- There are numerous individual utilizations of chromogenic materials, but only a few use them in combination with other passive techniques. Using their dynamic control of the sunlight entering buildings, PCM overheating may be prevented, and other technologies can work in a safer environment. They function better in locations with warm summers.

As per this review study, the scientific gaps for future work would include the following:

- An unsteady state analysis of the use of PCMs, along with other glazing technologies, over a long period of time is missing in the literature, as the available studies were mainly conducted on typical days in summer and winter.
- The hysteresis analysis for a large number of cycles for PCMs, as well as PV and chromogenic layers, is missing in the literature.
- A hygrothermal analysis and risk of mold growth due to using PCM combined with other technologies in the glazing systems is missing in the literature.
- The use of various technologies in smart glazing and identifying the optimum case for each climatic condition is also less studied in the literature.
- Incorporating Prisma glasses with other technologies to enhance the energy performance of the glazing units needs to be expanded to cover various operating conditions.
- The economic viability of incorporating PCMs in smart glazing is not justified in previous studies.

Optical characteristics of smart glazing are of vital importance and need to be studied more deeply.

## 1.2 Solid-solid phase change materials

Most individuals spend the majority of their time inside buildings. As living standards have improved, the role of buildings in global energy use has grown substantially, now accounting for nearly 40 percent of total consumption and up to 35 percent of greenhouse gas emissions, both of which contribute directly to climate change (Németh et al., 2021). In response to this issue, global sustainability agendas advocate for immediate efforts to address climate impacts. Various technological and design-based solutions have emerged to improve indoor thermal conditions. These range from passive architectural strategies and enhanced cooling methods to energy-efficient air conditioning systems and renewable energy integration (National Research Council Canada (NRC), 2020).

The building envelope, which functions as the interface between internal spaces and external weather conditions, is responsible for over half of the total energy consumption in buildings (Sadineni et al., 2011). Ensuring thermal stability indoors requires careful envelope design. Traditionally, this was accomplished by incorporating heavy construction materials to boost the building thermal mass and inertia. However, the widespread adoption of lightweight construction systems has resulted in many buildings underperforming in terms of thermal efficiency (Roberz et al., 2017). Consequently, improving envelope performance has become a key focus of recent studies.

The building envelope consists of opaque and transparent components, each playing a distinct role in thermal performance. Opaque elements include walls, roofs, and floors, while transparent parts comprise windows, curtain walls, and skylights. Among these, fenestration systems are particularly critical, as they are responsible for the majority of heat loss (up to 60 percent) thereby significantly affecting the overall energy efficiency of buildings (Ming et al., 2024). A promising passive solution to this challenge is the incorporation of PCMs into glazing systems. Our recent research (Arasteh et al., 2023), extensively reviewed the integration of PCMs into glazing systems, demonstrating their potential to enhance thermal performance while reducing visual transparency



Moghaddam et al. (2023) reviewed glazing solutions for nearly zero-energy buildings and proposed an approach for selecting optimal systems. They found that considering energy performance, thermal comfort, cost, and environmental impact together enable informed glazing choices, and future studies could include glare and visual comfort. Ceviz et al. (2023) found that adding phase change material in horizontal double-glazing improves energy storage and thermal comfort, with a 30 percent area ratio of PCM to double-glazed test elements providing the best balance between cooling duration and light transmittance.

Lu et al. (2023) evaluated double-layer and multilayer phase change material glazing and found that the optimal configurations depend on climate, improving thermal regulation and energy savings. Nsaif et al. (2024) found that adding phase change material along with blinders in triple-glazed windows reduced interior temperatures and increased time lag, though PCM solidification leakage remains a challenge. Uribe et al. (2024) developed and validated a heat transfer model for double-clear PCM glazing and integrated it into EnergyPlus (U.S. Department of Energy, 2017). They found that PCM glazing increases the thermal inertia, and reduces the cooling energy consumption by up to 9.1 percent and the cooling peak loads by up to 10.5 percent.

Shaik et al. (2024) tested double-pane glazing filled with organic phase change materials and found that the 30-degree liquid mixture best reduced heat gain, energy costs, and carbon emissions while allowing natural daylight, whereas the solid-state mixtures blocked daylight. Hu et al. (2024) found that 10 mm PCM glazing reduced temperature fluctuations, delayed peak temperatures, and maintained adequate daylighting, while thicker layers (15 and 20 mm) lowered energy storage and daylight performance.

Yuan et al. (2025) showed that triple-glazed windows with PCM and silica aerogel improve thermal regulation and energy savings subjected to cold and tropical climates. The cold climates benefit from reduced heat loss, while tropical climates achieve up to 74.8 percent energy savings. Future work should address durability, PCM stability, and extreme climate performance. Zhang et al. (2025) showed that the optical properties of PCM glazing units are strongly affected by the thermal parameters and layer thickness of the PCMs. They indicated that the common assumption in previous studies that optical properties are independent of

thermal parameters is not valid, and the design strategies for such glazing units should be revised accordingly.

In another study by Zhang et al. (2025), they showed that during phase change, the transmittance and reflectance of PCM glazing units vary linearly, with most changes occurring in the solid-liquid stage and notable changes in the solid-solid stage. Also, they have showed that an optimized radiative transfer model based on their findings reduced calculation errors compared to previous models. Mandev (2025) found that integrating PCM in double-glazed windows improved the thermal regulation but reduced the natural light. A 45 percent area ratio of PCM to window cut light transmittance by about one-third highlighting a trade-off between thermal comfort and visual transparency.

As provided above, the use of PCMs can regulate heat transfer through phase changes, either from solid to liquid, referred to as SLPCMs, or from solid to solid, referred to as SSPCMs. The present study adopts SSPCMs in glazing configurations due to their distinct advantages over SLPCMs. These advantages include low subcooling effects, reduced material degradation, consistent optical behavior, the ability to be applied without encapsulation, absence of leakage, minimal phase segregation, small volumetric changes, and high thermal stability.

Unlike SLPCMs, SSPCMs remain in a solid state throughout the phase transition and can be directly applied to the surface or pane of a multi-glazed window at a defined thickness. This configuration allows the low thermal conductivity of the intermediate air or inert gas layer to be preserved, maintaining the insulating function between indoor and outdoor environments. In contrast, SLPCMs, when used to fill the air gap, reduce the system thermal resistance due to their relatively higher thermal conductivity.

Although encapsulation can address this drawback by stabilizing the SLPCM in a solid state, the performance still depends on containment and material compatibility. SSPCMs undergo a phase transition between a semi-crystalline (opaque) and an amorphous (transparent) state, wherein only the soft segments melt while the hard segments (polymeric backbones with significantly higher melting temperatures) retain structural stability. This transition allows the material to remain solid as the soft segments undergo phase change, anchored by the hard

segments. Detailed descriptions of the SSPCM phase transition mechanism are available in (Fallahi et al., 2017).

SSPCMs experience a phase transition between opaque (semi-crystalline) and transparent (amorphous) states, wherein only the soft segments melt, supported by the hard segment (polymeric backbone) with a significantly higher melting temperature. Consequently, the SSPCM remains solid during phase transition by melting and freezing the soft segments, which are anchored by the hard segments. The illustration for the phase transition mechanism of Polymeric Graft SSPCM (Gao et al., 2021) and the transparency during phase transitioning (Wang et al., 2023) are depicted in Figure 1.30. Figure 1.31 presents the phase transition temperatures and enthalpies for the primary types of SL-PCMs and SS-PCMs. As shown in this figure, the SS-PCMs generally display lower phase transition enthalpies and transition at lower temperatures in relation to the SL-PCMs. The lower enthalpy can be explained by the restricted mobility within SS-PCMs, which hinders crystallization and limits packing efficiency (Fallahi et al., 2017).

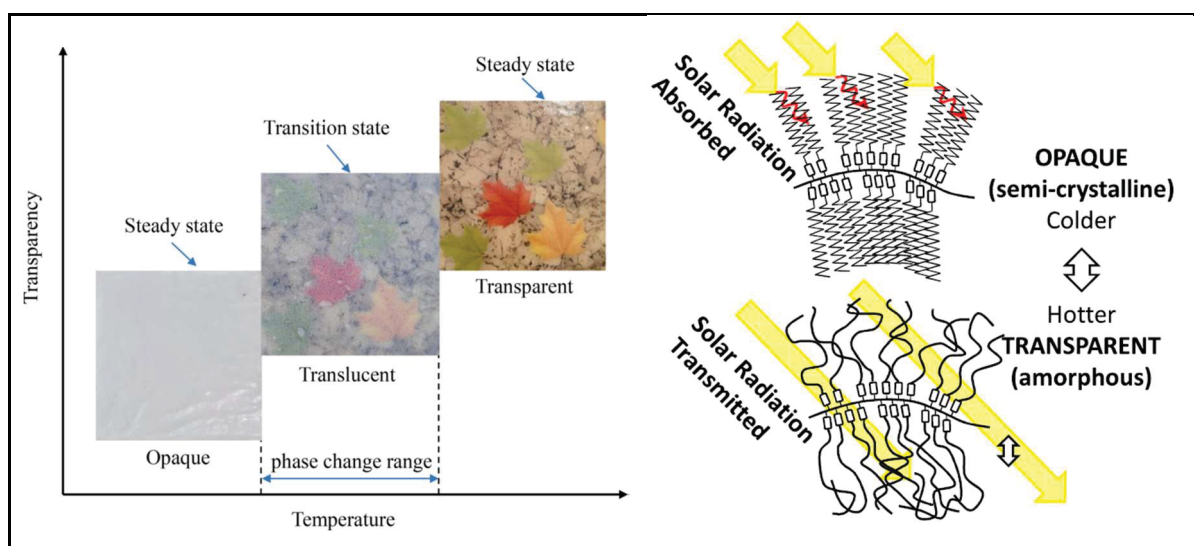


Figure 1.30 Schematics for the principal operation of SSPCM: (a) phase transition process of Polymeric Graft SSPCM (Gao et al., 2021) and (b) transparency of a SSPCM's phase transitioning taken from Wang et al. (2023, p. 4)

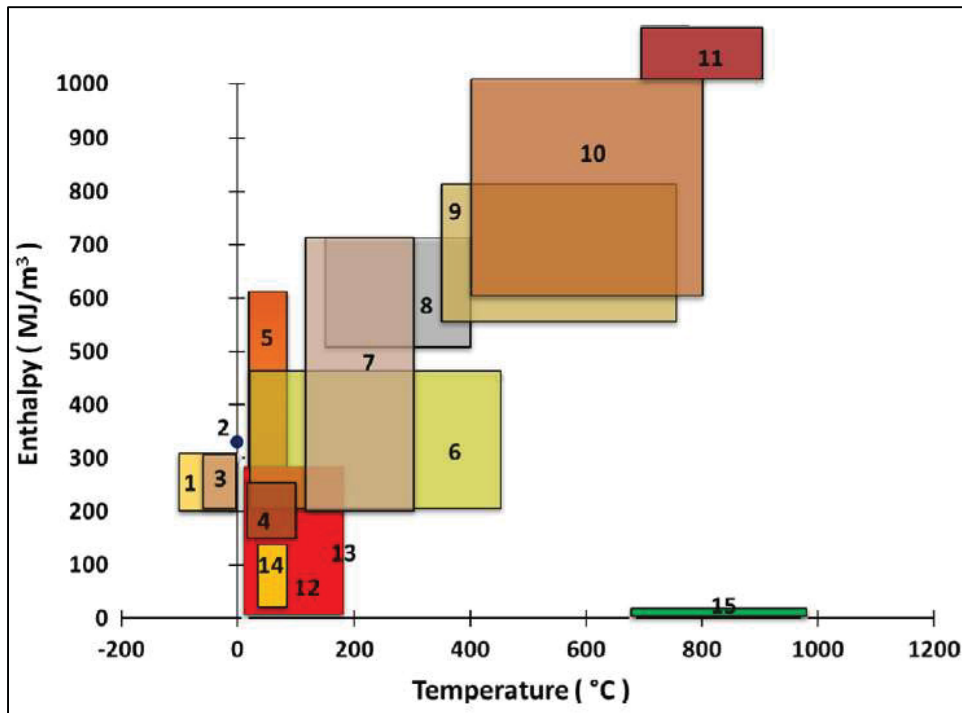


Figure 1.31 Enthalpy and temperature ranges for SL-PCMs and SS-PCMs;  
 L-PCMs: (1) Water-salt solutions; (2) Water; (3) Clathrates; (4) Paraffins;  
 (5) Salt hydrates; (6) Sugar alcohols; (7) Nitrates; (8) Hydroxides;  
 (9) Chlorides; (10) Carbonates; (11) Fluorides; (12) Polymeric; SS-PCMs:  
 (12) Polymeric; (13) Organics (Polyols); (14) Organometallics;  
 (15) Inorganics (Metallics) taken from Fallahi et al. (2017, p. 1431)

Although numerous studies have examined the application of SLPCMs in glazing systems, research focusing on SSPCMs in smart glazing remains limited. Raj et al. (2020) presented a review that outlined the development of SSPCMs and recent progress in their thermophysical properties. The study provided an extensive compilation of organic, polymeric, organometallic, and commercially available SSPCMs, including data on phase transition temperatures, melting points, molecular structures, and thermal behavior. This compilation serves as a valuable reference for professionals exploring SSPCM integration across a range of thermal energy applications. Another review (Fallahi et al., 2017) examined the relationship between molecular configurations, phase transition mechanisms, and thermal characteristics of SSPCMs. The study categorized SSPCMs into four primary groups: polymeric, organic,

organometallic, and inorganic. It also offered guidelines for material selection based on specific thermal, mechanical, and physical requirements, supported by detailed listings within each category.

Guldentops et al. (2018) evaluated the performance of SSPCMs in a passive building enclosure system installed on the south-facing facade of a structure in central Massachusetts. The analysis, conducted through a finite element model, considered both summer and winter scenarios to identify optimal seasonal configurations. The study emphasized the importance of refining extinction coefficients and phase transition temperatures to ensure year-round effectiveness. In a separate investigation, Gao et al. (2021) conducted a numerical study involving a thin SSPCM layer integrated on the interior surface of a double-glazed window. Since EnergyPlus could not directly simulate latent thermal storage, an equivalent model was developed. Results indicated that a 3 mm SSPCM layer improved energy performance in warm, mixed, and cold climates, offering better results than conventional low-emissivity glazing.

Ma et al. (2022) investigated a composite glazing system combining silica aerogel with SSPCM for use in extremely cold regions of China. EnergyPlus was used for thermal analysis and Radiance for daylighting assessment. As with previous studies, an equivalent SSPCM model was required. Key influencing parameters identified through sensitivity analysis included transition temperature, latent heat, absorption coefficient, and refractive index. The study recommended a 10 mm aerogel layer to achieve energy savings while meeting daylighting requirements.

Wang et al. (2023) developed an inverse modeling approach to determine temperature-dependent equations for extinction coefficients and refractive indices of SSPCMs in the translucent phase. Constant values were used for the opaque and transparent phases, and the optical parameters derived were used in the current analysis.

More recently, Zhang et al. (2024) investigated SSPCM glazing windows as an alternative to SLPCM to avoid liquid leakage issues. Through a parametric study in cold weather, they found that the melting temperature and latent heat of the PCM strongly affect thermal performance,

energy saving potential, and inner surface temperature, while optical properties such as absorption coefficient and refractive index have smaller effects. Optimal values yielded the highest energy saving efficiency of 15.38 percent. Also, their study highlights guidelines for SSPCM design, noting that longer-term evaluations are needed for practical applications.

### **1.3 Research gap**

Transparent components in building envelopes are responsible for the largest portion of energy losses, which, in turn, contribute to global warming and CO<sub>2</sub> emissions. With the increasing demand for fully glazed façades, optimizing the energy performance of these systems has become essential. PCMs have been widely investigated as latent heat storage materials to enhance the energy performance of glazing units while maintaining adequate daylighting and occupant comfort. SLPCMs have been integrated with various smart glazing technologies such as shading systems, photovoltaic layers, and chromogenic materials to improve energy efficiency and dynamic control of solar gains.

Previous studies on SLPCMs in glazing systems highlighted several limitations. SLPCMs are most effective in climates with high solar heat gain and on clear summer days, while their performance during winter or overcast conditions is uncertain, often necessitating additional active or passive strategies such as night ventilation. Moreover, SLPCMs face challenges related to volume expansion during phase transition, leakage, and reduced solar transmittance in the solid phase. Strategies such as interior-blind integration, cascaded PCM layers, and combination with photovoltaic or chromogenic technologies have been proposed, yet critical aspects remain underexplored, including unsteady-state performance over extended periods, hysteresis effects over multiple cycles, hygrothermal risks, optical characteristics, and the economic feasibility of these systems.

These challenges motivated the transition from SLPCMs to SSPCMs for glazing applications. SSPCMs retain the latent heat storage benefits of conventional PCMs while avoiding issues associated with liquid-phase formation, including leakage, volume change, and moisture-related risks within the building envelope. However, despite these advantages, the application of SSPCMs in glazing systems remains underexplored. Most existing studies rely on simplified

numerical approaches, such as EnergyPlus simulations that cannot fully capture phase transition behavior, or two-dimensional models that assume complete SSPCM occupancy in the air gap. Consequently, there is a need for three-dimensional modeling approaches that can accurately represent heat transfer—including conduction, radiation, and natural convection—within SSPCM-integrated double-glazed units, while also evaluating optical performance under realistic operating conditions.

This thesis addresses these gaps by developing a three-dimensional CFD model using the finite volume method to investigate the energy and optical performance of double-glazed windows incorporating SSPCMs. The SSPCM layer is positioned on the interior-facing glass surface, allowing it to maintain elevated temperatures and remain transparent throughout the year. By capturing all relevant modes of heat transfer and considering realistic boundary and operational conditions, this study aims to provide a comprehensive understanding of SSPCM-based glazing systems across diverse climatic scenarios, offering insights that extend beyond the capabilities of prior SLPCM-based solutions.

## **1.4 problem statement**

Fenestration systems remain among the most energy-sensitive components of the building envelope because they combine relatively low thermal resistance with high solar transmittance, leading to disproportionate heat losses and gains that drive heating and cooling demand. The increasing adoption of highly glazed façades in contemporary buildings further highlights the need for glazing technologies that can reduce energy demand without compromising daylight availability or visual clarity.

Latent thermal energy storage using phase change materials has been widely explored as a passive approach to increase thermal inertia in glazing systems. However, maintaining satisfactory optical performance during operation remains a persistent limitation. SSPCMs are particularly attractive for glazing integration because they avoid leakage, minimize volume-change issues, and can be implemented as thin layers while preserving the low thermal conductivity of the air or inert-gas cavity. This makes them a promising alternative to

conventional SLPCMs, which are more prone to leakage, reduced solar transmittance, and complex volume changes.

Despite these advantages, the technical and scientific basis for robust SSPCM-glazing design remains incomplete. The performance of SSPCM-enhanced glazing is highly climate- and weather-dependent: the same system may yield energy savings under certain conditions but cause energy penalties under others. The underlying mechanisms are strongly coupled and transient: radiative exchange drives solar charging, phase-transition dynamics control thermal storage and release, and heat transfer in glazing cavities can be affected by natural convection.

Existing SSPCM-glazing studies are limited compared with the broader literature on SLPCM glazing, and experimental evidence for SSPCM integration remains scarce. These gaps create uncertainty in material selection (transition temperature and range), in the reliability of optical transparency during occupied hours, and in the validity of simplifying assumptions such as neglecting natural convection. Consequently, a validated, physics-based modeling framework is needed to quantify energy and optical performance, assess the benefits of SSPCM integration under realistic operating conditions, and provide actionable guidance for climate-responsive smart fenestration design. In this study, a three-dimensional CFD approach is developed to address these challenges and provide a comprehensive evaluation of SSPCM-enhanced double-glazed windows.

## **1.5 Research objectives**

The overall objective of this thesis is to provide a rigorous, physics-based evaluation of multi-layer glazing systems incorporating SSPCM layers, with an emphasis on simultaneous assessment of energy performance and optical transparency under realistic boundary conditions. To achieve this objective, the thesis pursues the following specific objectives:

1. Establish a validated numerical modelling framework capable of resolving transient heat transfer, radiative transport, and SSPCM phase-transition behaviour in glazing systems using computational fluid dynamics and finite-volume discretization, with



radiation treated via the discrete ordinates model and phase change captured using an enthalpy-based approach.

2. Quantify energy performance across representative climates and weather conditions by evaluating SSPCM-enhanced double glazing against a reference configuration under hottest and coldest days, and under sunny and cloudy conditions, to determine the climate dependence of benefits and penalties.
3. Determine the influence of SSPCM thermophysical design parameters (notably transition temperature and transition range) on energy outcomes and phase-transition completeness, and identify parameter sets that maximize performance within each climatic context.
4. Assess optical performance and transparency during occupied hours by analysing SSPCM transparency behaviour under transient climatic forcing and by identifying configurations that preserve visual clarity while enabling effective latent heat storage.
5. Clarify the role of natural convection in glazing cavities and determine when it can be neglected without compromising accuracy, and when it materially alters phase-transition dynamics and energy performance.
6. Deliver quantitative design guidance for SSPCM-enhanced glazing systems that links climate conditions, glazing orientation, and SSPCM selection to expected energy and optical outcomes, thereby supporting climate-responsive smart fenestration development.



## CHAPTER 2

### 3D NUMERICAL MODELING TO ASSESS THE ENERGY PERFORMANCE OF SOLID-SOLID PHASE CHANGE MATERIALS IN GLAZING SYSTEMS

Hossein Arasteh <sup>a</sup>, Wahid Maref <sup>a</sup>, Hamed H. Saber <sup>b</sup>

<sup>a</sup> Department of Construction Engineering, École de technologie supérieure,  
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C1K3

<sup>b</sup> Deanship of Research and Industrial Development, and Mechanical Engineering  
Department at Jubail Industrial College, Royal Commission of Jubail and Yanbu, Jubail  
Industrial City, 31961, Saudi Arabia

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#### Abstract

This research investigates the energy efficiency of a novel double-glazing system incorporating solid-solid phase change materials (SSPCMs), which offer significant advantages over traditional liquid-solid phase change materials. The primary objective of this study is to develop a 3D numerical model using the finite volume method, which will be followed by a parametric study under real climatic boundary conditions. A proposed double-glazing setup featuring a 2 mm layer of SSPCM applied on the inner glass pane within the air gap is modeled and analyzed. The simulations consider various transient temperatures and ranges of the SSPCM to evaluate the energy performance of the system under different weather conditions of Miami, FL, during the coldest and hottest days of the year, both in sunny and cloudy conditions. The results demonstrate a notable improvement in energy performance compared to standard double-glazing windows (DGW), with the most efficient SSPCM configuration exhibiting a phase transition temperature and range of 25 °C and 1 °C, respectively. This configuration achieved energy savings of 24%, 26%, and 23% during summer sunny, winter sunny, and winter cloudy days, respectively, relative to DGW during cooling and heating degree hours. However, a 3% energy loss was observed during summer cloudy days. Overall,

the findings of this study have shown the potential for energy savings by incorporating SSPCM with suitable thermophysical properties into double-glazing systems.

**Keywords:** Carbon Neutrality; Building Energy; Solid-Solid Phase Change Material; Glazing System; Zero Energy Buildings; Computational Fluid Dynamics; Finite Volume Method

## 2.1 Introduction

According to the International Energy Agency (IEA) and its current projections on energy efficiency, achieving carbon neutrality in buildings by 2050 is anticipated to be challenging (*International Energy Agency, Tracking Buildings*, 2022). Notably, approximately one-third of the world's final energy consumption and nearly 15% of direct CO<sub>2</sub> emissions (comprising 40–48% of both direct and indirect CO<sub>2</sub> emissions) stem from the combined sectors of residential and building construction (*International Energy Agency, Tracking Buildings*, 2022). The building envelope, specifically fenestration systems (e.g., windows, curtain walls, skylight devices), is identified as the primary source of heat loss in building constructions, responsible for approximately 60% of the overall heat loss (Wang et al., 2021). Consequently, research efforts have intensified in this area to alleviate the energy demand attributed to heating, ventilation, and air conditioning (HVAC) systems. Overall, advancements in enhancing the thermal performance of transparent components of the building envelope can be categorized into three main areas: solar control, thermal resistance, and thermal inertia (Araújo et al., 2023; Sun et al., 2021).

The improvement of solar control systems has been the subject of extensive research, involving the integration of smart glazing technologies such as chromogenic materials (thermochromism, thermotropism, etc.), photovoltaic modules (Radwan et al., 2020), switchable systems (Ke et al., 2022), coating techniques (such as low-e coatings, laminated coatings (Maduru and Shaik, 2022; Sorooshnia et al., 2025)), and so forth. Similarly, efforts to improve the thermal resistance of transparent components in building envelopes have resulted in reduced heat loss. Techniques such as the use of inert gases within the gap space of multi-glazing systems (Taleb and Antony, 2020) as well as the incorporation of low thermal conductivity materials like

aerogels and hydrogels (Mohamed et al., 2023; Soares et al., 2023) are recognized methods for enhancing thermal resistance. Another approach involves increasing the thermal mass of glazing systems by utilizing thermal energy storage materials such as phase change materials (PCMs), which can store and release heat during day and night, thereby improving not only energy savings but also indoor thermal management. These techniques have been extensively explored in recent research and were comprehensively reviewed in (Arasteh et al., 2023). Furthermore, nanoscale analysis of thermal storage materials is also of vital importance. Methods such as Molecular Dynamics and Monte Carlo simulations can provide deep insights into the nanoscale thermal capabilities of these materials (Fasano et al., 2017).

This research primarily focuses on enhancing thermal inertia/mass within glazing systems, specifically by employing phase change materials (PCMs). The PCMs undergo heat absorption and release through phase change cycles, which can occur as a solid-to-liquid transition, known as solid-liquid phase change material (SLPCM), or a solid-to-solid transition, known as solid-solid phase change material (SSPCM), as applicable in glazing systems. The SSPCMs offer several advantages over SLPCMs, including no leakage, less phase-segregation, low subcooling, small volume variation, encapsulation-free implementation, extended durability upon thermal cycling (high thermal stability), more consistent optical properties, and less material degradation (Fallahi et al., 2017). Furthermore, SSPCMs, remaining solid (except when reaching their melting temperature), can be directly adhered to a surface (such as the interior glass pane in the present study) with specific thickness, while the air or inert gas (possessing low thermal conductivity) remains between the indoor and outdoor environments. This arrangement is advantageous because when the SLPCM completely fills the air gap, it diminishes the thermal resistance of the glazing systems to some extent, as the thermal conductivity of SLPCM is higher than that of air unless it has been encapsulated which will act like a SSPCM. Despite extensive literature on SLPCM application in glazing units, studies on SSPCMs in smart glazing are limited. Additionally, to the best of the authors' knowledge, there is no direct experimental research incorporating SSPCMs into glazing systems (Gao et al., 2021).

As mentioned earlier, a limited number of studies have explored the application of SSPCMs in glazing systems. Fallahi et al. (2017) conducted a review study focusing on the molecular properties and thermal characteristics of SSPCMs for thermal energy storage. That study examined the relationship between molecular structure, phase transition mechanisms, and thermal properties of the four main categories of SSPCMs: polymeric, organic, organometallic, and inorganic. The authors provided guidance for selecting an appropriate SSPCM for various applications based on desired physical, thermal, and mechanical properties, offering a comprehensive list of SSPCMs within each main category. Another review study (Raj et al., 2020) discussed the applications of SSPCMs and recent advancements in their thermophysical properties. That study compiled a comprehensive list of organic, polymeric, organometallic, and commercial SSPCMs, along with their thermophysical properties, phase transition temperatures, melting temperatures, molecular characteristics, and thermal behavior. This review serves as a valuable resource for researchers and practitioners interested in utilizing SSPCMs in various applications.

Guldentops et al. (2018) proposed a building enclosure system employing SSPCMs to passively regulate the temperature of a south-facing building in a typical central Massachusetts four-season climate, considering both summer and winter conditions. They conducted an analysis of the energy performance of the system by creating a finite element model. The study identified different optimized systems beneficial for summer and winter seasons separately. However, it was noted that further refinement of extinction coefficients and transition temperatures of the SSPCM is necessary for the system to effectively function in both summer and winter conditions. In a related study, Gao et al. (2021) integrated a thin layer of SSPCM into the interior side of the inner glass of a south-facing double-glazing window (DGW) of an office room. They performed a numerical analysis to assess the annual energy savings achieved by the system. Utilizing the EnergyPlus for their numerical investigation, the authors encountered a limitation as the software lacked the capability to simulate latent energy storage materials undergoing phase transitions. The authors also mentioned that EnergyPlus cannot simulate transparent PCMs. Consequently, they developed an equivalent model to overcome this limitation. The study demonstrated that the implementation of a 3 mm SSPCM led to energy savings improvements in warm, mixed, and cold climates. Furthermore, the authors

argued that the energy savings achieved with the DGW equipped with SSPCM (DGW-SSPCM) outweighed those of low-emissivity windows.

Additionally, Ma et al. (2022) investigated the integration of both silica aerogel and SSPCM in a glazing system to assess its daylighting and energy performance in a severe cold region of China. For energy performance analysis, EnergyPlus (Tennakoon et al., 2024) was employed, while radiance software (Nazari and Matusiak, 2024) was utilized for daylighting analysis. Similar to Gao et al. (2021), the authors employed an equivalent model for SSPCM modeling due to EnergyPlus limitations. Through sensitivity analysis, they identified transient temperature, latent heat, absorption coefficient, and refractive index as the most influential parameters. Recommending a 10 mm thickness for silica aerogel in their glazing system, the authors aimed to achieve maximum energy savings while meeting daylighting design standards in China. Their findings suggested the viability of employing DGW-SSPCM in severe cold regions. Moreover, Zhang et al. (2024) investigated a similar glazing system containing silica aerogel within the outer gap space and SSPCM within the inner gap space, emphasizing the effectiveness of SSPCMs over SLPCMs. Through simulations conducted for a 24-hour real-time period in very cold climates in Anda City, China, they developed a model to predict the heat transfer of the glazing system. Their results highlighted the significant impact of SSPCM transition temperature and latent heat on heat transfer, while the absorption coefficient and refractive index had subtler effects.

Wang et al. (2023) developed an inverse approach, based on hybrid model, to represent useful expressions for the extinction coefficient and refractive index of SSPCMs as a function of temperature for the translucent phase and constant values for opaque and transparent phases. Their results for the optical properties of SSPCMs have been implemented in the current study. Recently, Zhang et al. (2024) implemented a two-dimensional numerical parametric study for the influence of optical and thermal properties of a triple glazed window containing SSPCM within the inner air gap and silica aerogel within the outer air gap using finite volume method. The study was performed to simulate 24 hours of severe cold weather conditions in a city of China. Their sensitivity analysis showed that the thermal efficiency of the glazed window is notably influenced by the melting temperature and the latent heat of PCM, whereas the

absorption coefficient and refractive index only have minor effects. In that study, the optimum melting temperature of the PCM was reported as 18 °C resulting in 15.4% energy saving rate.

Based on the literature review provided above as well our recent review (Arasteh et al., 2023), it is evident that there are few studies investigating the energy performance of SSPCMs in glazing systems using 3D modeling. The existing numerical models are either using EnergyPlus that has some limitations in capturing the phase transition phenomenon within the SSPCM, hence using an equivalent model has been inevitable or 2D models that assess the SSPCM behavior fully filled the air gap space of a triple-glazed window. Therefore, to bridge this gap, the main objective of this study is to develop a 3D model and use it to assess the energy performance of a DGW incorporating SSPCMs. The idea of placing the SSPCM onto the interior pane between the air gap has come up to keep the material's temperature as high as possible to yield an almost full transparent window throughout the whole year. Following model validation, a parametric study was conducted by varying the transient temperature and transient temperature range of a south-facing DGW-SSPCM over a 24-hour real-time period. The simulations were performed for sunny and cloudy days during the coldest and hottest days of the year 2022 in Miami.

## **2.2 Methodology**

### **2.2.1 Geometrical details**

The present study comprises two configurations: a double-glazing window (DGW) as a reference called “DGW-REF” and another DGW equipped with a SSPCM applied on the interior pane within the air gap, called “DGW-SSPCM”. Both DGW-REF and DGW-SSPCM consist of two panes with dimensions of 20 cm long, 20 cm wide, and 4 mm thick. The DGW-REF features a 1.6 cm air gap, as depicted in Figure 2.1a, while the DGW-SSPCM includes a 2 mm-thick SSPCM, having a mass of 844 grams, applied to the interior pane between the panes. This has resulted in a 1.4 cm air gap, as illustrated in Figure 2.1b.





Table 2.2 List of scenarios for the phase change temperature values and ranges

| Summer | Cases | Glazing system                                                      | Winter | Cases | Glazing system                                                      |
|--------|-------|---------------------------------------------------------------------|--------|-------|---------------------------------------------------------------------|
|        | 0     | DGW-REF                                                             |        | 0     | DGW-REF                                                             |
|        | 1     | $T_c = 20\text{ }^\circ\text{C}, dT_{pc} = 1\text{ }^\circ\text{C}$ |        | 1     | $T_c = 15\text{ }^\circ\text{C}, dT_{pc} = 1\text{ }^\circ\text{C}$ |
|        | 2     | $T_c = 20\text{ }^\circ\text{C}, dT_{pc} = 3\text{ }^\circ\text{C}$ |        | 2     | $T_c = 15\text{ }^\circ\text{C}, dT_{pc} = 3\text{ }^\circ\text{C}$ |
|        | 3     | $T_c = 20\text{ }^\circ\text{C}, dT_{pc} = 5\text{ }^\circ\text{C}$ |        | 3     | $T_c = 15\text{ }^\circ\text{C}, dT_{pc} = 5\text{ }^\circ\text{C}$ |
|        | 4     | $T_c = 25\text{ }^\circ\text{C}, dT_{pc} = 1\text{ }^\circ\text{C}$ |        | 4     | $T_c = 20\text{ }^\circ\text{C}, dT_{pc} = 1\text{ }^\circ\text{C}$ |
|        | 5     | $T_c = 25\text{ }^\circ\text{C}, dT_{pc} = 3\text{ }^\circ\text{C}$ |        | 5     | $T_c = 20\text{ }^\circ\text{C}, dT_{pc} = 3\text{ }^\circ\text{C}$ |
|        | 6     | $T_c = 25\text{ }^\circ\text{C}, dT_{pc} = 5\text{ }^\circ\text{C}$ |        | 6     | $T_c = 20\text{ }^\circ\text{C}, dT_{pc} = 5\text{ }^\circ\text{C}$ |
|        | 7     | $T_c = 30\text{ }^\circ\text{C}, dT_{pc} = 1\text{ }^\circ\text{C}$ |        | 7     | $T_c = 25\text{ }^\circ\text{C}, dT_{pc} = 1\text{ }^\circ\text{C}$ |
|        | 8     | $T_c = 30\text{ }^\circ\text{C}, dT_{pc} = 3\text{ }^\circ\text{C}$ |        | 8     | $T_c = 25\text{ }^\circ\text{C}, dT_{pc} = 3\text{ }^\circ\text{C}$ |
|        | 9     | $T_c = 30\text{ }^\circ\text{C}, dT_{pc} = 5\text{ }^\circ\text{C}$ |        | 9     | $T_c = 25\text{ }^\circ\text{C}, dT_{pc} = 5\text{ }^\circ\text{C}$ |

The extinction coefficient is commonly described by the optical thickness ( $d$ ) of a substance as shown in Equation (2.1) (*ANSYS FLUENT*, 2021). In this equation,  $s$  represents the actual thickness of the sample, which is set to 2 mm in this study for the SSPCM-DGW cases.

$$d = (\sigma_a + \sigma_s)s \quad (2.1)$$

In Equation (2.1),  $\sigma_a$  and  $\sigma_s$  represents the absorption and scattering coefficients, respectively. In this study, the scattering coefficient is considered isotropic. By using the Beer-Lambert's law for non-gaseous materials, the transmittance of the PCM can be calculated using Equation (2.2) as (Guldentops et al., 2018):

$$\tau_{PCM} = 10^{-d} \quad (2.2)$$

where  $\tau_{PCM}$  represents the transmittance of the PCM. Also, the absorption coefficient can be calculated using Equation (2.3) (Gowreesunker et al., 2013), then used to determine the scattering coefficient by Equation (2.1).

$$\sigma_a = \sigma_s \left[ \frac{\tau_{PCM,tr} - \tau_{PCM,op}}{1 - \tau_{PCM,op}} \beta + \frac{1 - \tau_{PCM,tr}}{1 - \tau_{PCM,op}} \right] \quad (2.3)$$

In Equations (2.1) to (2.3),  $\tau$  and  $\beta$  represent the transmittance and transparency fraction of the material, respectively. The Subscripts PCM, tr, and op represent the phase change material, transparent and opaque, respectively. The refractive index and extinction coefficient for the transparent phase (equal to 1.11 and 25.73 m<sup>-1</sup>, respectively (Wang et al., 2023)) and opaque phase (equal to 5.33 and 152.82 m<sup>-1</sup>, respectively (Wang et al., 2023)) of the SSPCM (Gao et al., 2021).

For the translucent phase Equations (2.4) and (2.5) (Wang et al., 2023) are used to provide the average optical property as function of the transparency fraction. This term is used to replace the term ‘liquid fraction’ as there is no liquid phase in the SSPCM that refers to the fraction of the material within the transparent phase. The value of  $\beta$  is equal to 0 when the SSPCM is totally opaque and 1 when the SSPCM is totally transparent. When the transparency fraction is 0, it means the SSPCM temperature is less than or equal its lower limit of the transient temperature range (opaqueus temperature) and it is in the opaque phase. Conversely, when it is 1, it means that the SSPCM temperature is greater than or equal its upper limit of the transient temperature range (transparentus temperature) and it is in the transparent phase. However, when the transparency fraction value is between 0 and 1, it indicates that the SSPCM is in the translucent phase, akin to the mushy zone in SLPCMs. Note that at the border between the opaque phase and translucent phase, the temperature is called “saturated-opaque temperature, T<sub>opaqueus</sub>”. While at border between the translucent phase and transparent phase, the temperature is called “saturated-transparent temperature, T<sub>transparentus</sub>”.

$$\sigma_{a,cell} = 33.8\beta + 25.73(1 - \beta) \quad (2.4)$$

$$\sigma_{s,cell} = 119.02(1 - \beta) \quad (2.5)$$

### 2.2.3 Governing equations

To model the SSPCM, the enthalpy-porosity model in FLUENT has been employed utilizing a very high viscosity value (equal to 250 Pa\*s that is much higher than honey viscosity range: 6.54 – 7.01 Pa\*s (Bambang et al., 2019)) for the SSPCM, resulting in nearly zero velocity within it. In this study, the results are represented by neglecting natural convection effects within the air gap of the DGW for all cases (i.e., DGW-SSPCM and DGW-REF), aiming to analyze the applicability and concept of using SSPCM in glazing systems. Utilizing the Miami climate as an illustrative example under natural climatic conditions, this approach seeks to investigate whether energy savings can be achieved in a glazing system equipped with SSPCM compared to the same system without SSPCM. The governing equations of the current study, considering the Discrete Ordinates (DO) model for radiation and a solidification/melting model for SSPCM, are as follows.

- Energy equation (*ANSYS FLUENT*, 2021):

$$\frac{\partial}{\partial t}(\rho H) = \nabla \cdot (k \nabla T) + S_h \quad (2.6)$$

In Equation (2.6), the enthalpy of the PCM,  $H$ , is calculated as the sum of the sensible enthalpy,  $h_s$ , and latent heat,  $\Delta H$  as:

$$H = h_s + \Delta H \quad (2.7)$$

where,

$$h_s = h_{s,ref} + \int_{T_{ref}}^T c_p dT \quad (2.8)$$

In Equation (2.7), the fractional latent heat of the PCM,  $\Delta H$ , can be expressed in terms of the PCM's latent heat of fusion,  $L$ . Note that  $\Delta H$  can vary between 0 (opaque phase),  $L$  (transparent phase), and values between 0 and  $L$  when  $T_{opaqueus} < T < T_{transparentus}$  (translucent phase).

$$\Delta H = \beta L \quad (2.9)$$

The transparency fraction,  $\beta$ , can be defined as:

$$\beta = \begin{cases} 0 & \text{if } T \leq T_{opaqueus} \\ 1 & \text{if } T \geq T_{transparentus} \\ \frac{T - T_{opaqueus}}{T_{transparentus} - T_{opaqueus}} & \text{if } T_{opaqueus} < T < T_{transparentus} \end{cases} \quad (2.10)$$

The term  $S_h$  in Equation (2.6) denotes the volumetric heat source/sink related to phase change, which is defined as:

$$S_h = -\frac{\partial(\rho\Delta H)}{\partial t} \quad (2.11)$$

- Radiation equation:

In this research, the DO model is utilized to simulate the radiation effects as it is the most detailed model for radiation in ANSYS FLUENT (*ANSYS FLUENT*, 2021). This model enables the simulation of radiation scattering and absorption across various optical thicknesses. The DO model addresses radiation heat transfer by converting the equation into a transport equation for radiation intensity, solving it for a finite number of discrete solid angles (*ANSYS FLUENT*, 2021). Consequently, although the simulation speed is diminished due to the additional equations of the DO model, precision is enhanced.

The radiative transfer equation for an absorbing, emitting, and scattering medium at position  $\vec{r}$  in the direction  $\vec{s}$  is (*ANSYS FLUENT*, 2021):

$$\frac{dI(\vec{r}, \vec{s})}{ds} + (\sigma_a + \sigma_s)I(\vec{r}, \vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \phi(\vec{s}, \vec{s}') d\Omega' \quad (2.12)$$

The DO model considers the radiative transfer equation in the direction  $\vec{s}$  as a field equation and is written as (*ANSYS FLUENT*, 2021):

$$\begin{aligned} & \nabla \cdot (I(\vec{r}, \vec{s})\vec{s}) + (\sigma_a + \sigma_s)I(\vec{r}, \vec{s}) \\ & = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \phi(\vec{s}, \vec{s}') d\Omega' \end{aligned} \quad (2.13)$$

In Equations (2.12) and (2.13),  $I$ ,  $n$ ,  $\vec{r}$ ,  $\vec{s}$ ,  $\vec{s}'$ ,  $\phi$ ,  $\Omega'$ , and  $\sigma$  represent radiation intensity, refractive index, position vector, direction vector, scattering direction vector, phase function, solid angle, and the Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ ), respectively.

#### 2.2.4 Weather conditions

The glazing system in this study represents a south-facing window situated in Miami, with a longitude and latitude of -84.63 (west) and 13.65 (north) degrees, respectively. The time zone of Miami is defined as -5 during Eastern Standard Time (EST) and -4 during Eastern Daylight Time (EDT). Four scenarios for ambient weather conditions have been selected for the coldest (occurred in January 30th) and hottest (occurred in August 18th) days of the year 2022, encompassing both sunny and cloudy conditions. The ambient weather conditions include hourly wind speed (*Weather History in Miami, 2022*), hourly ambient temperature (*Weather History in Miami, 2022*), hourly solar direct irradiation (*ANSYS FLUENT, 2021*), hourly solar diffuse irradiation (*ANSYS FLUENT, 2021*), and hourly x, y, and z beam direction vectors (*ANSYS FLUENT, 2021*) (equal to the negative value of sun direction vector) for the coldest and hottest days, as illustrated in Figures 2.2 to 2.4. The geometry's orientation is such that the +z axis points to the North and the -x axis points to the East, as depicted in Figure 2.5.

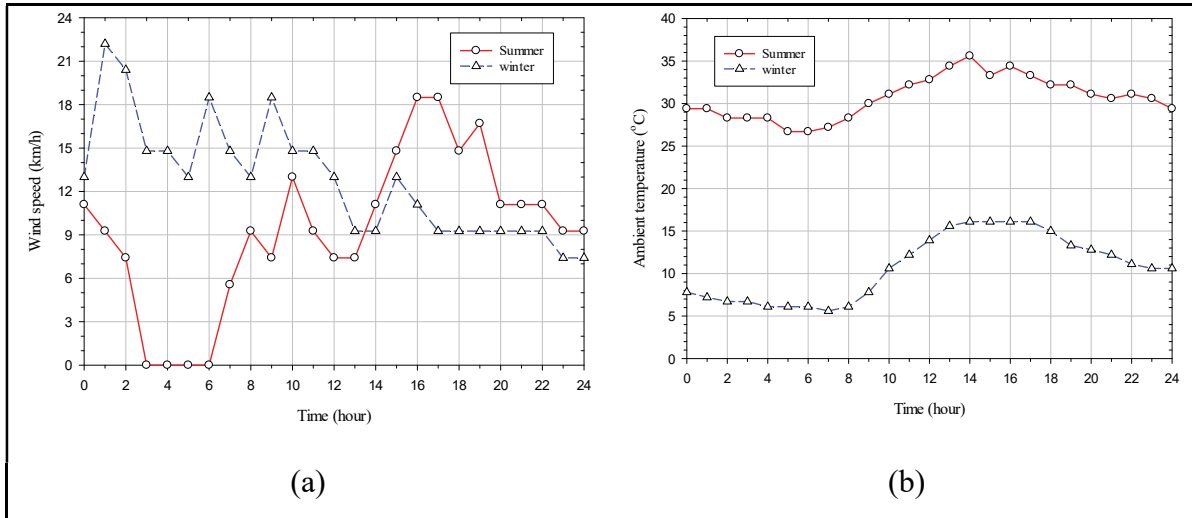


Figure 2.2 (a) Wind speed and (b) ambient temperature on January 30<sup>th</sup> and August 18<sup>th</sup> of the year 2022 in Miami (*Weather History in Miami, 2022*)

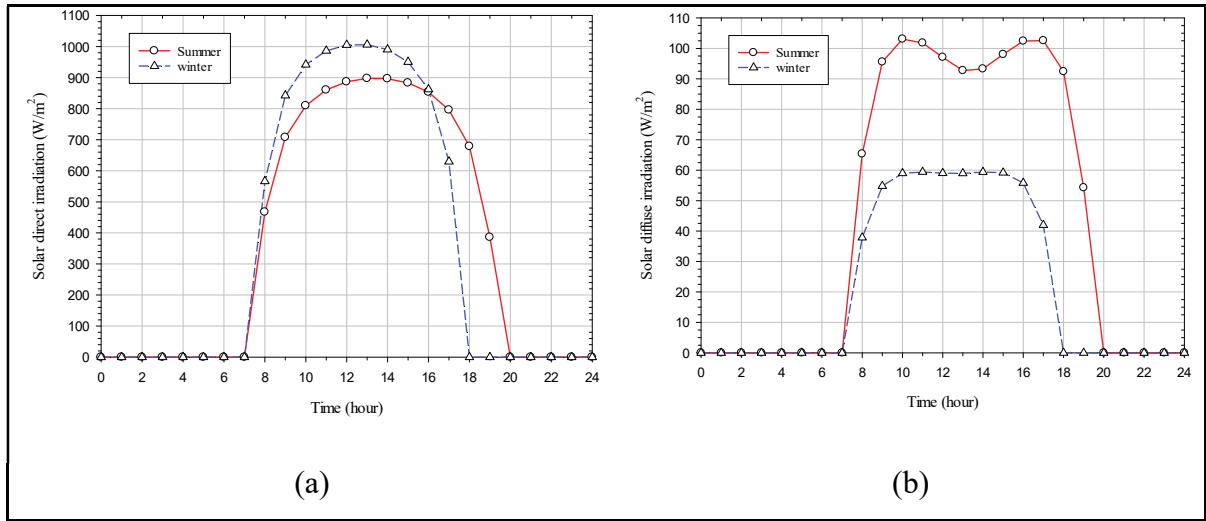


Figure 2.3 (a) Solar direct irradiation and (b) solar diffuse irradiation on January 30<sup>th</sup> and August 18<sup>th</sup> of the year 2022 in Miami (*ANSYS FLUENT*, 2021)

### 2.2.5 Initial and boundary conditions

The initial conditions for all parts of the DGW-REF and DGW-SSPCM are set to 26 °C and 24 °C during summer and winter, respectively.

The wall boundary conditions for the side (exterior top, bottom, front and back) surfaces of the window are set as thermally insulated or adiabatic. The mixed thermal boundary condition including both convection and radiation are set for the indoor and outdoor surfaces of the window. Hence, the parameters including heat transfer coefficient, free stream temperature, external emissivity, and external radiation temperature have to be determined for the indoor and outdoor surfaces. Moreover, the semi-transparent boundary condition is set for the radiation boundary condition of the indoor and outdoor surfaces of the window to account for the solar irradiation through the numerical domain. Therefore, the parameters including direct solar irradiation, diffuse solar irradiation, and x, y, and z beam direction vectors have to be determined for the indoor and outdoor surfaces. The external emissivity for the typical clear glasses is set to 0.89 for all boundaries. To represent a full sunny day, the sunshine factor is set to 1, while for a cloudy day, this value is set to 0, resulting in a direct solar irradiation value of 0.

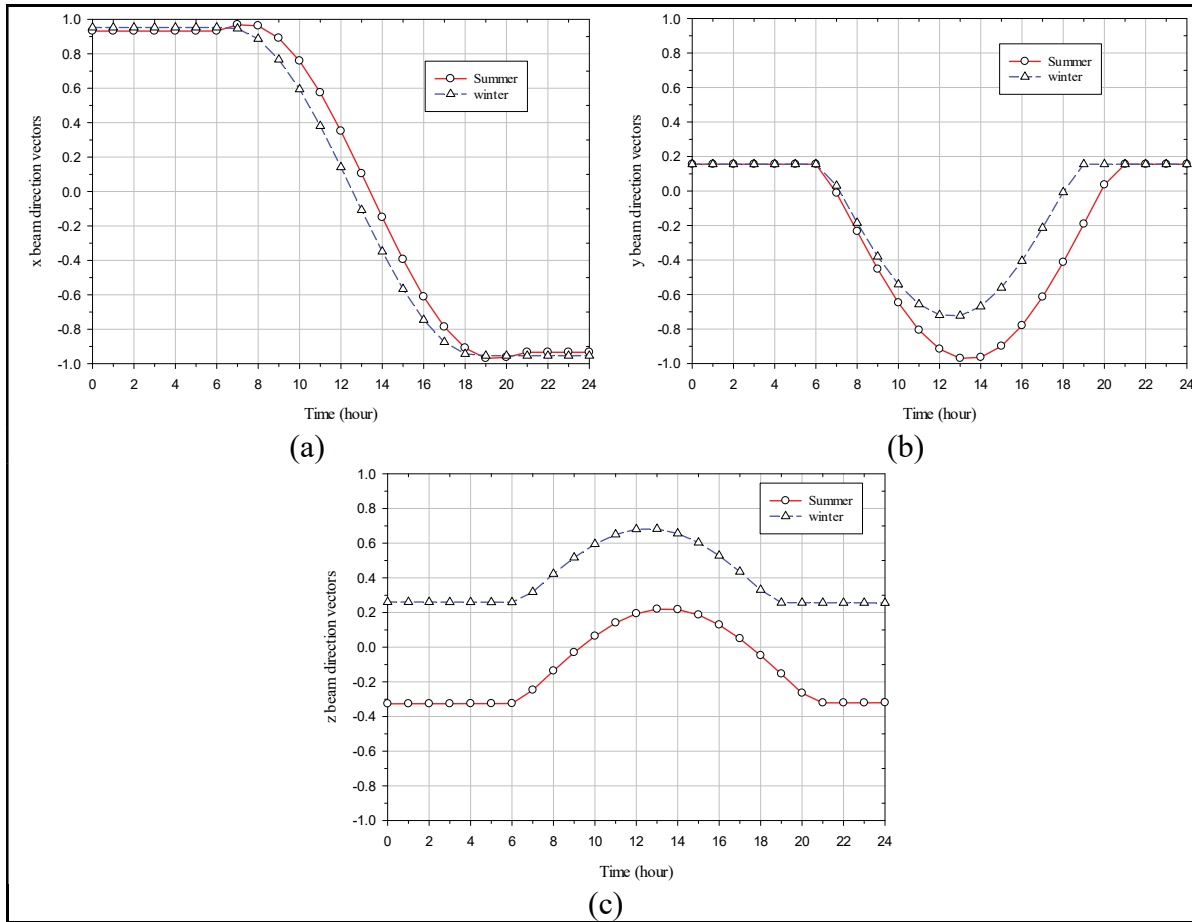


Figure 2.4 (a) x, (b) y, and (c) z beam direction vectors on January 30<sup>th</sup> and August 18<sup>th</sup> of the year 2022 in Miami (*ANSYS FLUENT*, 2021)

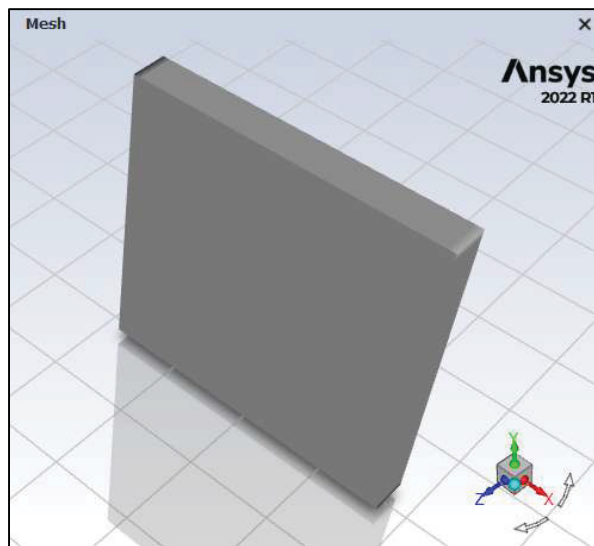


Figure 2.5 South-facing orientating DGW-SSPCM



Regarding the window's indoor surface thermal and radiation boundary conditions, the heat transfer coefficient is set to  $8.7 \text{ W/m}^2\text{K}$  (ASHRAE, 2021). Both free stream temperature and external radiation temperature are set to  $26^\circ\text{C}$  and  $24^\circ\text{C}$  during summer and winter, respectively. No solar irradiation is set for the indoor radiation boundary condition to obviously not model a direct or diffuse solar irradiation to the indoor surface.

Regarding the window's outdoor surface thermal and radiation boundary conditions, except the emissivity, all other boundary conditions are imported into ANSYS FLUENT via User Defined Functions (UDFs) written in C-programming compatible with the FLUENT library to simulate a full day (24 hours). The UDFs are written in piecewise linear functions for the available hourly weather conditions. The hourly ambient temperature is set for the free stream temperature in the thermal boundary condition. In addition, the hourly direct and diffuse solar irradiances as well as hourly x, y, and z beam direction vectors are set in the radiation boundary conditions. The hourly heat transfer coefficient as a function of wind speed and hourly external radiation temperature or sky temperature as a function of ambient temperature have been calculated using Equations (2.14) and (2.15) (Goia et al., 2012).

$$h_a = 5.62 + 3.9 v_{wind} \quad (2.14)$$

$$T_{sky} = 0.0552 T_{air,o}^{1.5} \quad (2.15)$$

## 2.3 Numerical procedure

### 2.3.1 Model description

To generate geometry and grid in this study, both Design Modeler and Ansys Meshing, respectively, were used. The commercial CFD code in ANSYS FLUENT (version 2022 R1), which is based on finite volume method, is employed for the 3D numerical simulations in this study. The finite volume method implemented in ANSYS FLUENT discretizes the computational domain into control volumes and applies conservation laws for energy

(Equation (2.8)) to these volumes. The resulted algebraic equations are solved iteratively within each control volume, considering boundary conditions and turbulence models as needed. This approach enables the simulation of fluid flow and heat transfer. In this study, the semi-implicit method for pressure linked equations (SIMPLE) algorithm is used for the velocity–pressure coupling. Additionally, the second order upwind scheme is employed for discretization of pressure, momentum, and energy while first order upwind is used for Discrete Ordinates (DO) and first order implicit for transient formulation. In this study, the DO model is used with one iteration for energy per radiation iteration. The theta and phi divisions are set to 2, while the theta and phi pixels are set to 1. Additionally, the solar calculator is utilized to derive the hourly direct and diffuse solar irradiation for various climatic conditions. These values are then incorporated into a UDF file. Thereafter, the UDF file is imported into the software. The solidification and melting model are also employed to model the Solid-Solid Phase Change Material (SSPCM). The material properties added to this model, namely the absorption and scattering coefficients, are imported into the software using a UDF file. Additionally, the energy model is used to yield the temperature profile in the numerical domain. Finally, the desired outcome parameters are defined in the report definitions to save the data at each iteration for post-processing purposes. The convergence criteria were set to be less than  $10^{-6}$ ,  $10^{-6}$ ,  $10^{-6}$ ,  $10^{-6}$ ,  $10^{-9}$ , and  $10^{-9}$  for mass conservation, x-velocity, y-velocity, z-velocity, energy and DO-intensity, respectively. Before using the model to assess the energy performance of the glazing systems considered in this study, it was validated as described next.

### **2.3.2 Model validation**

In this study, the same model used for SLPCMs has been applied to SSPCMs using the solidification/melting model. The key distinction lies in the absence of natural convection effects in SSPCMs, as the liquid phase of SLPCM melts. Neglecting gravity effect and due to the quite high viscosity for the liquid phase of SLPCM allows it to behave similarly to SSPCM.

To validate the numerical model comprising the Discrete Ordinates (DO) model and solidification/melting model in glazing systems, transient numerical results obtained over a simulation period of 12000 seconds have been compared with experimental data reported by Gowreesunkera et al. (2013) for the transmittance of PCM-filled glazing units over time. In

that study, the researchers devised an experimental setup in order to quantify the changes in radiation effects within the mushy phase, a task that cannot be achieved using a spectrophotometer alone, and to depict the radiation behavior of the PCM within an actual PCM-glazed system, providing a more realistic understanding of its performance. They positioned the entire setup within an environmental chamber where they could control the air temperature. The light source utilized was a 150 W metal halide lamp, emitting a diffuse light of neutral white color. The regular double glazing had dimensions of 20 cm × 20 cm, with a total thickness of 24 mm, comprising sequentially of 4 mm glass, a 16 mm air cavity, and another 4 mm glass layer. In contrast, for the PCM-filled glazing configuration, the air within the cavity was substituted with RT27. Irradiation level and air/initial PCM temperature were set to 950 W/m<sup>2</sup> and 13 °C, respectively.

Figure 2.6 illustrates that the transmittance values derived from the simulation closely match the experimental results, with differences falling within the margin of error. In fact, the overall transmittance was defined by the ratio of radiation flux between the front and back faces. Furthermore, the observed transmittance trends exhibit similarity between the simulation results and the experimental data. Since the numerical results are in good agreement with the experimental data within acceptable margins of error, the model is valid and can be used with confidence in this study.

### 2.3.3 *Grid sensitivity*

To find the optimum grid size that leads to mesh independent solution, various grid sizes ranging from finer to coarser have been generated over the numerical domain of a DGW-SSPCM. The average total heat flux over 24 hours, as defined in Equation (2.16), on the interior surface of the inner glass pane has been selected as the criterion to assess grid independence. In this equation,  $q''$  defines the transmitted heat flux on the interior pane of the glazing system.

$$\overline{q''} = \frac{1}{t} \int_0^t q'' dt \quad (2.16)$$

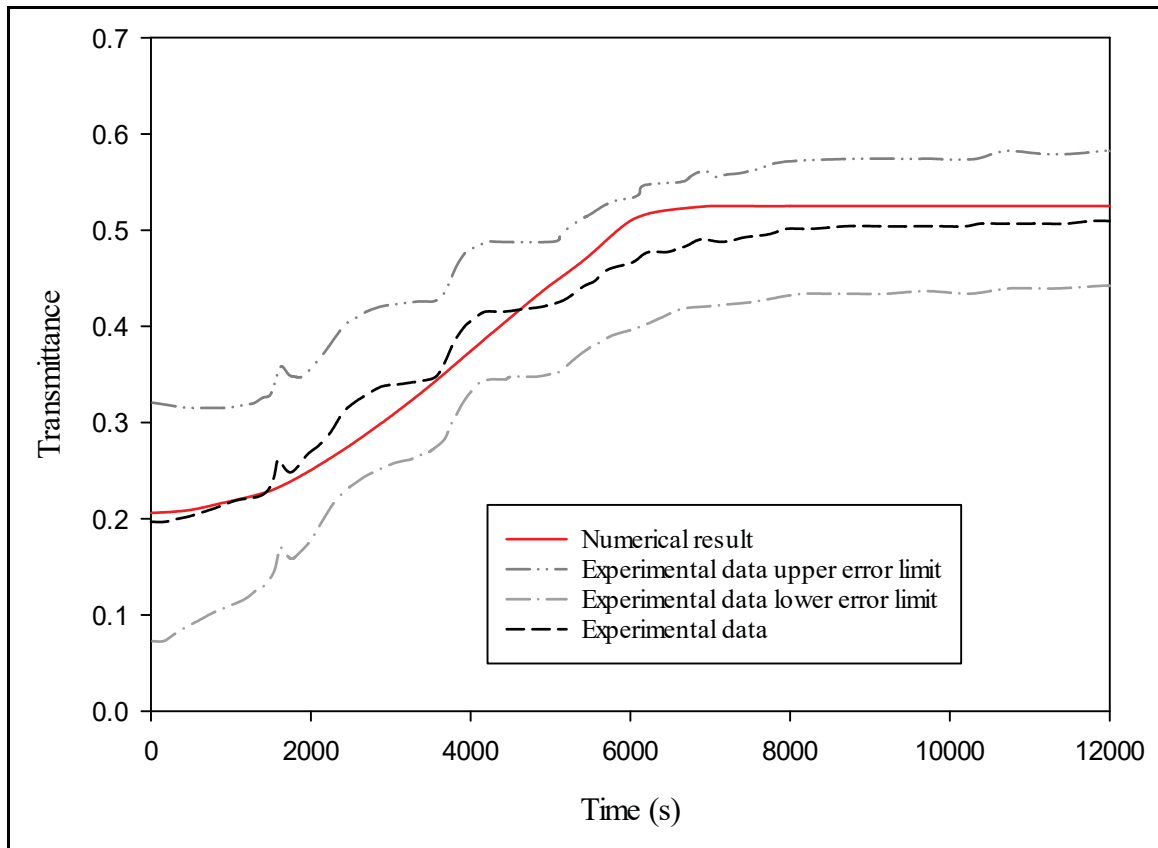


Figure 2.6 Current numerical model validation study against the experimental data (Gowreesunker et al., 2013)

The obtained results are shown in Table 2.3. As shown in this table, the number of elements of 82,369 yields to approximately optimum grid size as its relative error is less than 1%. Thus, the number of elements of 82,369 was used in this study.

Table 2.3 Grid sensitivity analysis

| Case | Number of elements | $\overline{q''}$ | Error (%) |
|------|--------------------|------------------|-----------|
| 1    | 288923             | 15.47104         | -         |
| 2    | 158661             | 15.5293          | 0.376595  |
| 3    | 82369              | 15.58556         | 0.740245  |
| 4    | 27440              | 15.71381         | 1.569181  |
| 5    | 11025              | 15.8746          | 2.608495  |
| 6    | 4050               | 16.1296          | 4.25671   |

### 2.3.4 Time step sensitivity

The goal of the time step sensitivity analysis is to find the highest time step size that results in an accurate result. The same procedure as in the previous section was used, where the average total heat flux over 24 hours on the interior surface of the inner glass pane, has been selected to find the optimum time step size (i.e., the largest time step that would be used to minimize the CPU time). Table 2.4 shows the results for different time step sizes and it can be inferred that the time step size 5 min would result in a relative error less than 1% and is suitable to be used for simulations.

Table 2.4 Time-step sensitivity analysis

| Case | Time step size | $\overline{q''}$ | Error (%) |
|------|----------------|------------------|-----------|
| 1    | 10 sec         | 15.73079         |           |
| 2    | 30 sec         | 15.72085         | 0.06315   |
| 3    | 1 min          | 15.70591         | 0.15812   |
| 4    | 2.5 min        | 15.66088         | 0.44443   |
| 5    | 5 min          | 15.58556         | 0.92319   |
| 6    | 10 min         | 15.43214         | 1.89849   |
| 7    | 20 min         | 15.11929         | 3.88729   |
| 8    | 30 min         | 14.82675         | 5.74694   |

## 2.4 Results and discussion

Numerical simulations are conducted for a DGW incorporating a 2 mm layer of SSPCM adhered to the inner pane within the gap space. The simulations are carried out over a period of 24 hours in real time, encompassing both sunny and cloudy days during the coldest and hottest days of the year 2022 in Miami.

As shown in Table 2.2, numerical simulations were performed for transient temperatures of 10, 15, and 20 °C, along with transient temperature ranges of 1, 3, and 5 °C in winter, and transient temperatures of 20, 25, and 30 °C, and transient temperature ranges of 1, 3, and 5 °C in summer. It is noteworthy to say that the transient temperature represents the central temperature within the temperature range. For example, with a transient temperature of 20 °C

and a transient temperature range of 5 °C, the opaqueus (equivalent to the term solidus in SLPCM) and transparentus (equivalent to the term liquidus in SLPCM) temperatures are 17.5 °C and 22.5 °C, respectively. The study analyzes the effects of these parameters on the transparency fraction, interior surface temperature, and energy savings.

As provided next, the numerical results are represented in four sections, each of which containing the parametric study results for one parameter including transparency fraction, interior surface temperature, total heat flux on the interior surface, and energy savings.

#### **2.4.1 Transparency fraction**

In this section, the variations of the transparency fraction of the SSPCM during summer and winter for the hottest sunny and cloudy days, as well as the coldest sunny and cloudy days, are analyzed.

Figure 2.7 shows the dependence of the transparency fraction on time for the studied scenarios during summertime in sunny and cloudy days. In Figure 2.7a, it is observed that when the SSPCM transient temperature is 20 °C, it remains opaque throughout the day; however, it partially transitions to a translucent state between 12 pm and 4 pm. Conversely, at a transient temperature of 25 °C, a complete phase transition cycle occurs, highlighting the significant influence of transient temperature on the phase transition behavior of the SSPCM and consequently, the thermal behavior of the glazing system. With the initial temperature of the glazing system set equal to the indoor temperature (26 °C), the transparency fraction of SSPCM decreases from values near 1 during the night as solar radiation is absent at low outdoor temperature. As shown in Figure 2.7a, the gradient of transparency fraction increases with lower transient temperature ranges, with the transparency fraction transitioning from 1 to 0 in about 3.5 hours for a transient temperature range of 1 °C, and nearly 4.25 hours for a transient temperature range of 3 °C. However, for a transient temperature range of 5 °C, the SSPCM does not transition to the opaque phase, and its transparency fraction reduction gradient is lower than that for the other two conditions above. The gradients are consistent across the three different transient temperature ranges. Around 8:00, as solar radiation starts to take place, the temperature of the glazing system starts to rise, leading to an increase in transparency fraction. All three SSPCMs with different transient temperature ranges reach the transparent phase,

remain transparent for a couple of hours, and then start to transition back to a translucent state due to the temperature and solar irradiation reductions. For SSPCMs with a transient temperature of 30 °C, the transparency fraction never decreases, indicating that the SSPCM remains transparent throughout the day and its temperature never exceeds the opaque temperature.

Figure 2.7b provides the results for the summertime on a cloudy day. The transparency fraction variations before sunrise (around 8:00) are identical to those in Figure 2.7a, as expected. The lack of direct solar irradiation at the presence of diffuse solar irradiation causes less overall solar irradiation resulting in lower temperature rise of the system and hence lower transparency fraction increment gradient during the daytime. It is also evident from this figure that for all transient temperature ranges, the transparency fraction remains at 0 and 1 for transient temperatures of 20 °C and 30 °C, respectively. As shown in Figure 2.7b, although the SSPCM with transient temperature range of 1 °C goes through a full phase transition cycle and remains transparent for couple of hours, it is not the case for the SSPCM with transient temperature range of 3 °C and 5 °C as they do not reach the transparent phase. Overall, lower transient temperature ranges have facilitated full phase transition cycles of the SSPCM, allowing the system to fully utilize its latent heat energy storage capacity. Furthermore, the longer the SSPCM remains in its transparent phase, the longer it provides the best visual view for the occupants.

Figure 2.8 depicts the variations in SSPCM transparency fraction for the studied scenarios during winter, considering both sunny and cloudy days. It is evident from this figure that the presence of direct solar irradiation on a sunny day greatly affects both the SSPCM temperature and its transparency fraction. Specifically, when the SSPCM transient temperature is 15 °C, on both sunny and cloudy days, the SSPCM remains transparent throughout the entire day. At a transient temperature of 25 °C, the glazing system can utilize the latent heat storage of the SSPCM during sunny days, as the SSPCM undergoes partial phase changes, whereas this is not observed during cloudy days, where the SSPCM remains opaque throughout the day. When the SSPCM transient temperature is set to 20 °C, it undergoes a full phase transition cycle on

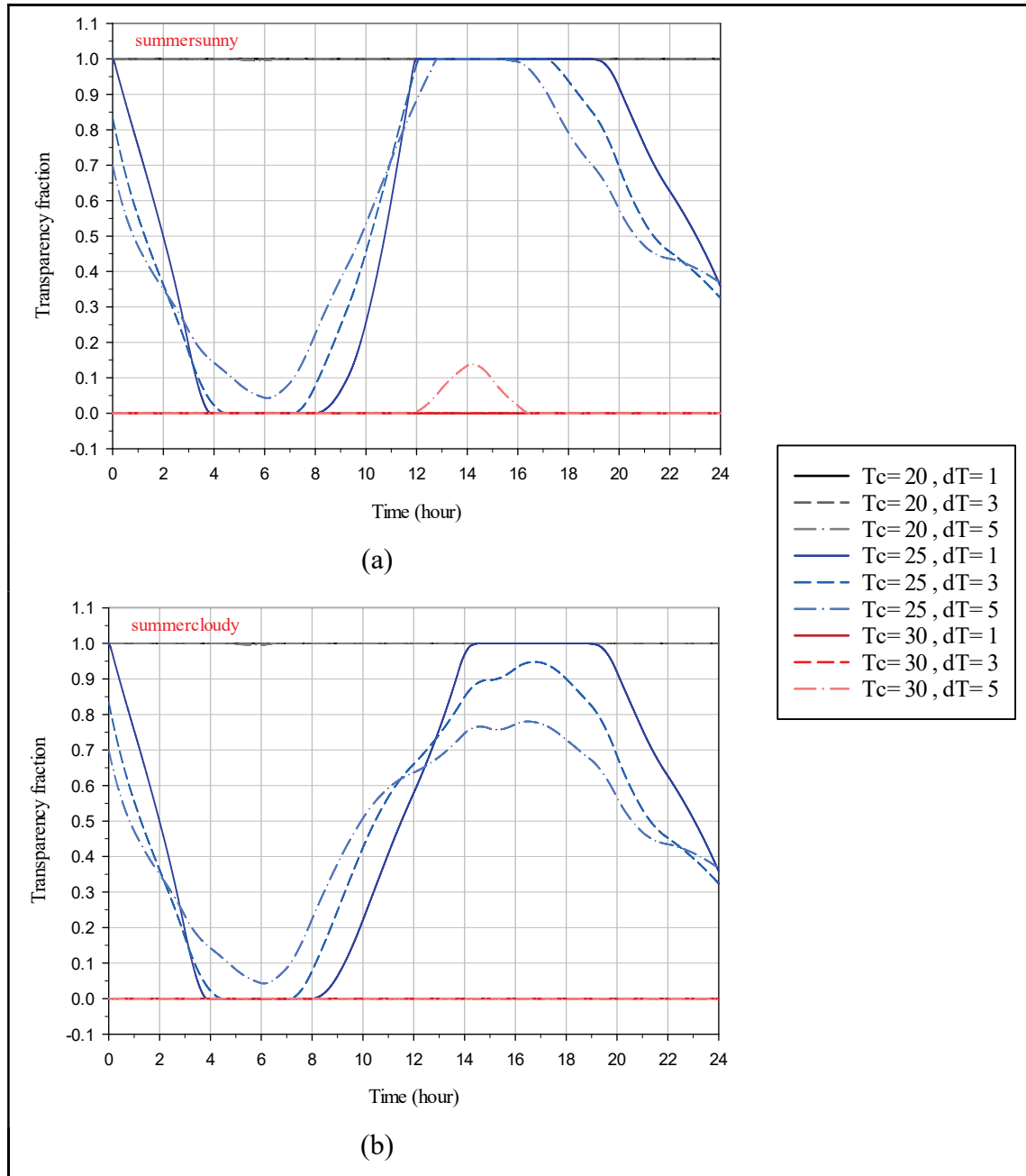


Figure 2.7 Variations of transparency fraction over time in the cases of  
(a) summer sunny and (b) summer cloudy

sunny days, but only a partial phase transition on cloudy days, failing to reach its transparent phase. Figure 2.8 also shows that the effect of transient temperature range on the SSPCM transparency fraction is lower during winter sunny days compared to winter cloudy days. Regarding the provision of a visual view for the occupants, during sunny days in winter, a



visual view can be provided during the daytime, whereas on cloudy days, the view would mostly be translucent during the daytime.

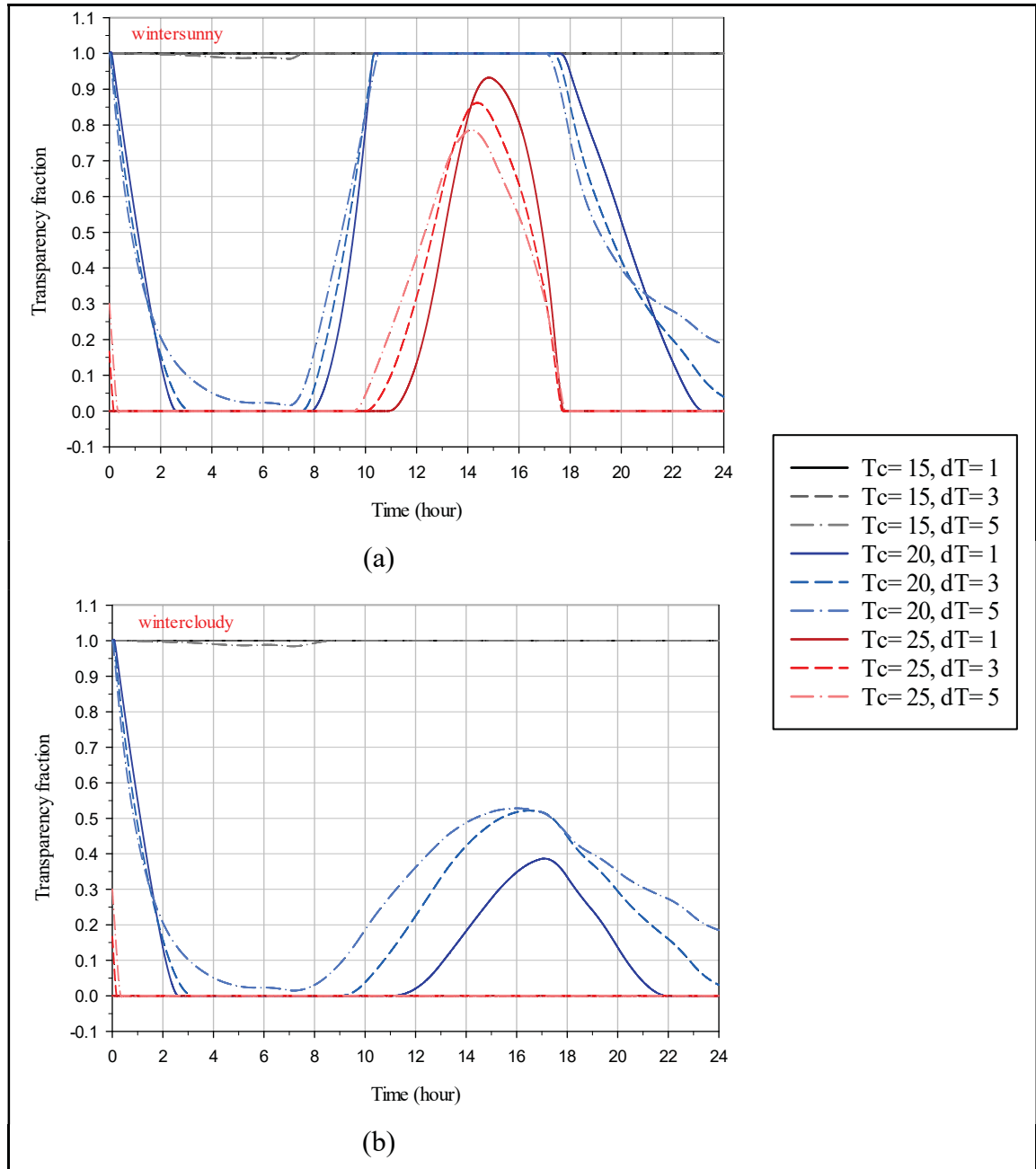


Figure 2.8 Variations of transparency fraction over time in the cases of (a) winter sunny and (b) winter cloudy

### 2.4.2 *Interior surface temperature*

In this section, the simulation results related to the variations of the interior surface temperature of the glazing system during the hottest summer and coldest winter days in sunny and cloudy sky conditions are discussed.

Figure 2.9 depicts the interior surface temperature distribution during the summer sunny and cloudy days for the studied scenarios of the DGW-SSPCM as well as the DGW-REF (Table 2.2). During the summertime, this figure shows that the lower the interior surface temperature is the better the thermal performance of the system is. Also, the interior surface temperature for the cases with transient temperature of 20 °C and 30 °C are approximately the same and the trend is the same for both sunny and cloudy days. This is because in these transient temperatures the SSPCM has not gone through any phase transition, and thus the glazing system cannot benefit from its latent heat storage advantage. In addition, the case with 20 °C transient temperature results in higher inner temperature as it stays in the transparent phase as opposed to the case with 30 °C transient temperature. Moreover, in these two cases, the transient temperature range has a subtle impact on the interior temperature due to the lack of SSPCM phase change. Regarding these two cases (i.e., transient temperatures of 20 °C and 30 °C), the thermal performance of the system is different in sunny and cloudy days. In sunny days, even when the SSPCM phase transition does not occur, the thermal performance of the DGW-SSPCM (comparing to DGW-REF) has been increased during the daytime and it has been decreases during the nighttime due to the blockage of the direct solar irradiation.

In cloudy days, Figure 2.9 shows that the thermal performance of the DGW-SSPCM is lower than the DGW-REF in most of the hours of the day. On the other extreme of the rope, the SSPCM with transient temperature 25 °C yields different temperature distributions as the phase transition occurs. It is visible that during the daytime, the interior surface of the DGW-SSPCM is lower than the DGW-REF and at nights it is reversed. During the day, as the solar irradiation comes to light, the SSPCM absorbs heat using its high latent heat advantage and behaves as a promising insulation material by preventing solar irradiation to heat up the interior surface. At night this absorbed heat is released as the ambient temperature drops resulting in higher interior

temperature at nights. At this transient temperature (i.e., 25 °C), the influence of the transient temperature range becomes substantial. Finally, in both sunny and cloudy days, the transient temperature range effects on the interior surface temperature are visible, as the lower this value is the greater the temperature gradients are.

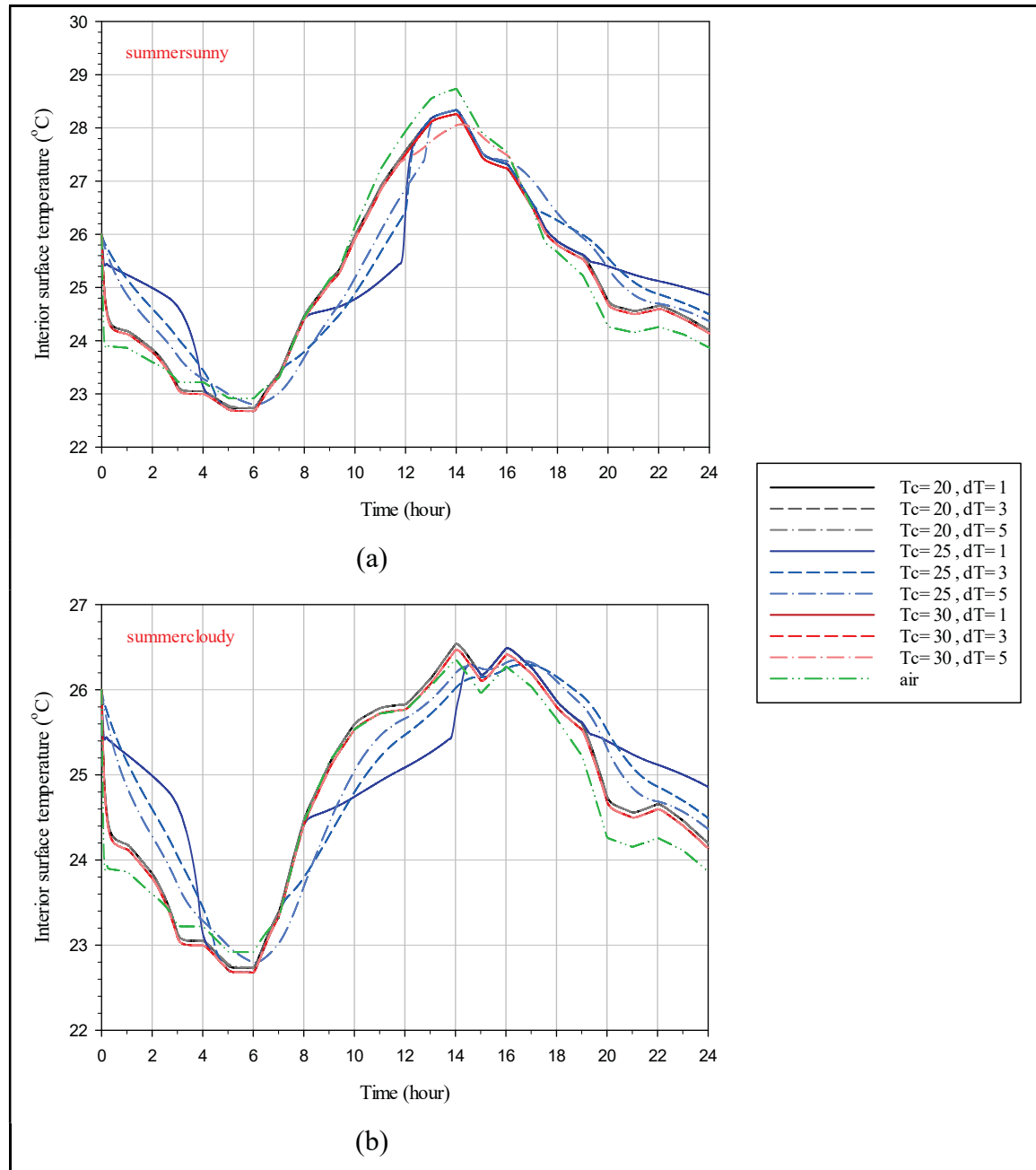


Figure 2.9 Variations of the interior surface temperature over time in the cases of (a) summer sunny and (b) summer cloudy

Figure 2.10 displays the variations in interior surface temperature for the DGW-SSPCM and DGW-REF throughout the day in winter, for both sunny and cloudy conditions. Higher interior surface temperature during winter indicates better thermal performance of the system. Referring to Figure 2.8a, In sunny conditions depicted in Figure 2.10a, the SSPCM undergoes phase transition at transient temperatures of 20 °C and 25 °C, resulting in differences in interior surface temperature between the DGW-SSPCM and DGW-REF. The presence of SSPCM leads to lower interior temperatures during the day due to its latent absorption and solar direct irradiation blockage, which is released at night when ambient temperatures drop. However, when the SSPCM does not complete a full phase transition cycle, as seen with the transient temperature of 20 °C, the released heat during the night contributes to the low sensible heat storage capacity of the material. In contrast, at a transient temperature of 25 °C, where the full phase transition cycle occurs, higher interior temperatures at night indicate improved thermal performance of the system using the higher latent heat storage capacity of the material.

In cloudy conditions, demonstrated in Figure 2.10b, only the transient temperature of 25 °C results in beneficial temperature distributions, providing higher interior temperatures during the night. Overall, the transient temperature is a critical parameter for optimizing the thermal performance and energy savings potential of the DGW-SSPCM system compared to the DGW-REF. Incorrect selection of the transient temperature can lead to reduced thermal performance and energy efficiency of the system.

#### **2.4.3      *Total heat flux on the interior surface***

The numerical results for the dependence of the interior surface heat flux on time for the glazing system during the hottest summer and coldest winter days in sunny and cloudy sky conditions are discussed. In Figures 2.11, 2.12 and 2.13, the negative values for the total heat flux represent the heat flux direction from outside to the inside that contributes to the cooling energy loads.

On the contrary, the positive values for the total heat flux represent the heat flux direction from inside to the outside that contribute to heating loads.

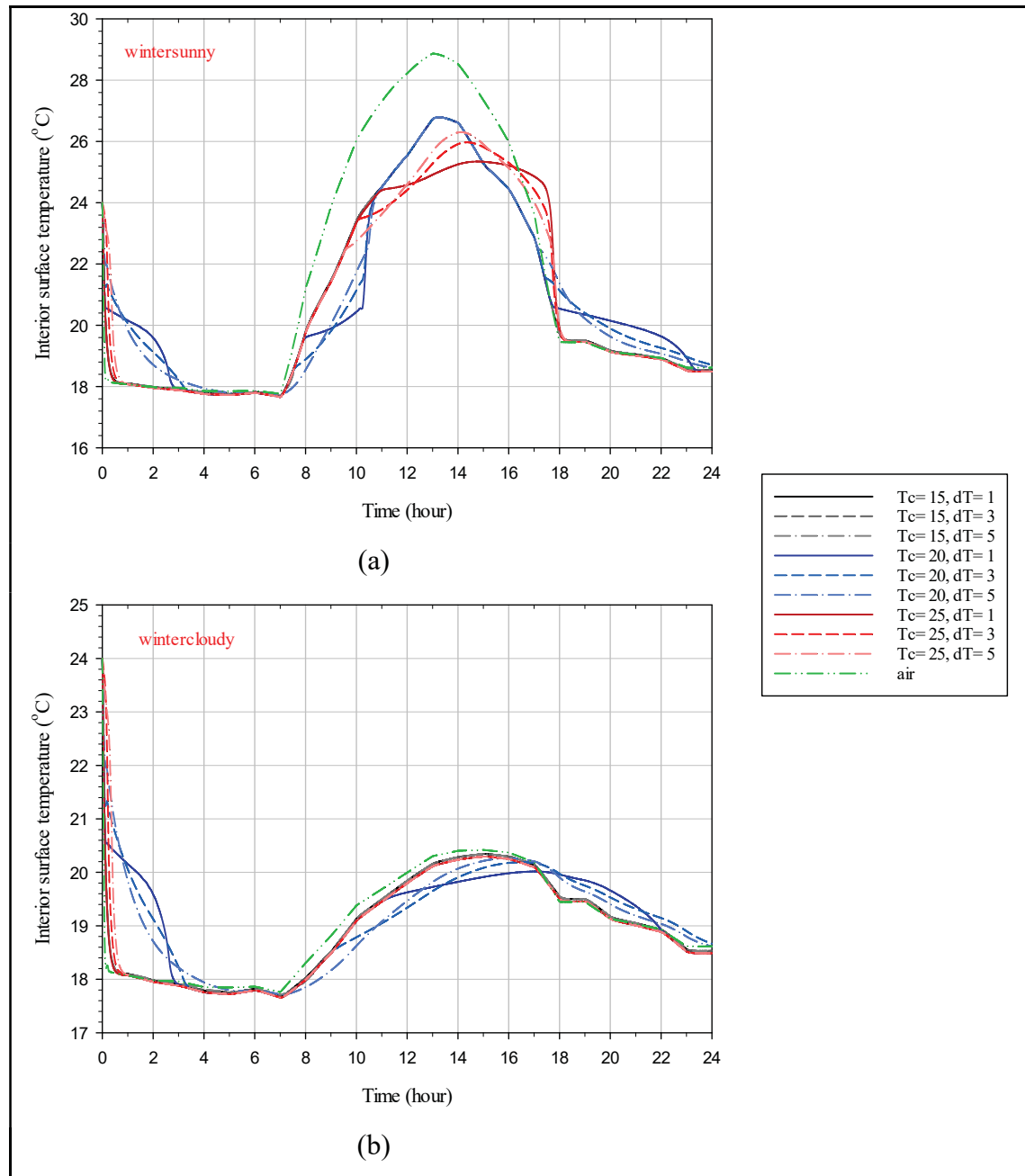


Figure 2.10 Variations of the interior surface temperature over time in the cases of (a) winter sunny and (b) winter cloudy

In Figure 2.11, for the DGW-REF case, the heat flux is observed to flow from outside to inside during the night, while during the day, it reverses direction, flowing from inside to outside. On sunny days, using SSPCM results in reduced heat flux entering the interior during the day due to blocking of solar direct irradiation. However, during the night, heat flux continues to enter

the interior as a result of heat release from the SSPCM, which was absorbed during the day. Even on cloudy days, heat release from the SSPCM to the interior is evident during the night, but the heat entering the interior during the day is approximately similar for both DGW-SSPCM and DGW-REF, due to the absence of direct solar irradiation. Interestingly, SSPCMs that have not gone through a phase transition still exhibit heat release to the interior during the night, attributed to sensible heat energy storage. However, SSPCMs with a transient temperature of 25 °C, which experience a phase transition during the day, show higher heat flux entering the interior during the night. Comparing different transient temperature ranges reveals that for cases with a transient temperature of 25 °C, lower transient temperature ranges correspond to higher heat flux entering the interior during the night and lower heat flux exiting during the day.

In Figure 2.12, the interior surface total heat flux distribution during the day is depicted for both the DGW-SSPCM and DGW-REF. During winter, the SSPCM can influence the heat flux dynamics, resulting in less overall heat flux being released to the outside during the day, contributing to energy savings. However, it also reduces the amount of heat entering the interior from direct solar irradiation. Figure 2.12a shows that less heat enters the interior in the DGW-SSPCM compared to the DGW-REF during the day, while the amount of heat flux escaping from the interior in the DGW-SSPCM is also reduced compared to the DGW-REF. Due to the absence of direct solar irradiation, the heat flux throughout the day is directed outside, and the SSPCM contributes positively by reducing the heat flux escaping from the interior to the outside, leading to energy savings (see Figure 2.12b).

#### **2.4.4      *Energy savings***

To quantify the energy savings with the DGW-SSPCM in relation to DGW-REF, the definition of the energy savings given by Equation (2.18) is used and depicted in Figure 2.13 for different scenarios investigated in this paper. Figure 2.13 shows that the energy savings during cooling and heating degree hours (i.e., the hours during which both cooling and heating are needed) defined as the interior surface temperature of the inner glass pane is above 26 °C in summer

and below 24 °C in winter in the DGW system as compared to the reference system (i.e., the DGW-SSPCM system).

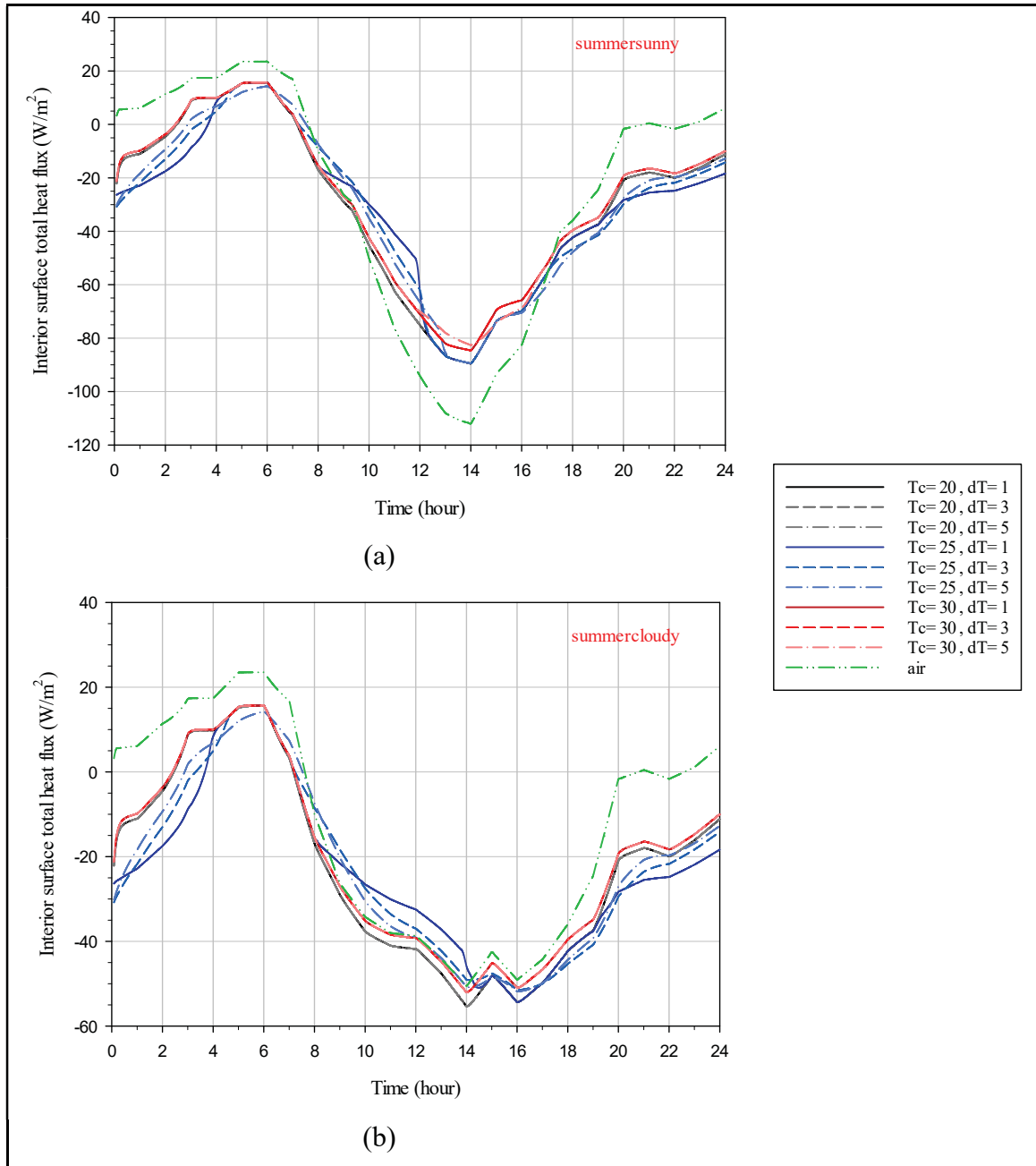


Figure 2.11 Variations of the interior surface total heat flux over time in the cases of (a) summer sunny and (b) summer cloudy

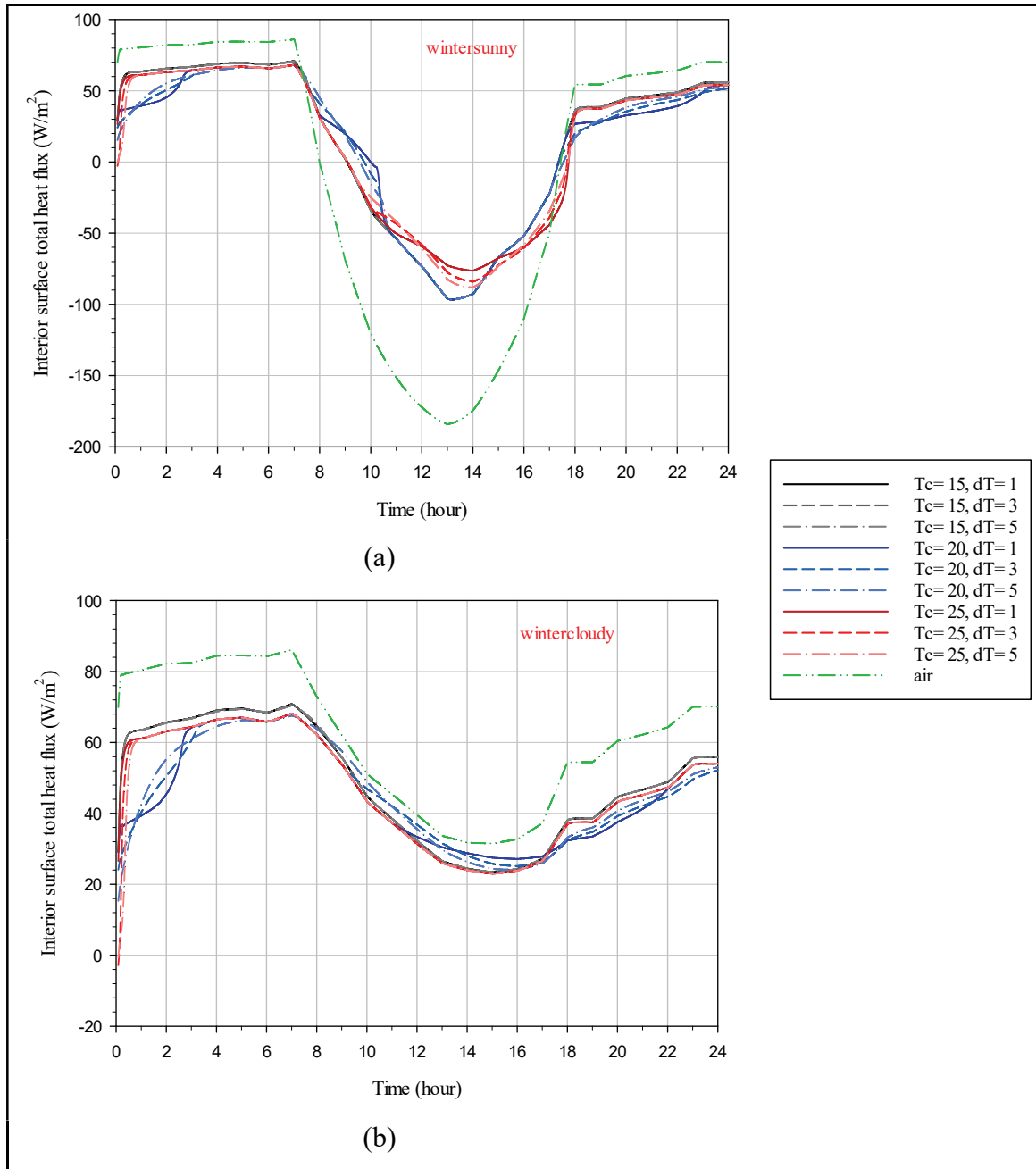


Figure 2.12 Variations of the interior surface total heat flux over time in the cases of (a) winter sunny and (b) winter cloudy

$$E = \overline{q''} \times t \times A \quad (2.17)$$

$$\Delta E = E_{final} - E_{ref} \quad (2.18)$$



Figure 2.13. displays the heat energy of the studied cases (as determined in Table 2.2) over the peak load hours defined above. Furthermore, Table 2.5 is provided to summarize the energy savings of all studied cases for various climatic conditions.

During summer, the SSPCM absorbs solar heat radiation, leveraging its high latent heat energy storage capacity during heating and cooling degree hours. For the summer sunny day, over the cooling degree hours occurring between 9:55 and 17:20, the DGW-SSPCM system exhibits lower heat energy entering the building compared to DGW-REF due to the blockage of direct solar irradiation by the SSPCM. The energy savings of the cases 1 to 9 (defined in Table 2.2) versus DGW-REF case in summer sunny days are 17.4, 17.4, 17.4, 24.2, 22.5, 21.1, 22.1, 22.1, and 21.9 percent, respectively. Hence, the highest energy savings of the DGW-SSPCM system versus DGW-REF in summer sunny weather conditions occur in case 4, where the transient temperature value and range are 25 °C and 1 °C, resulting in a 24.2 percent energy savings. However, for the summer cloudy day (over the cooling degree hours occurring between 12:55 and 17:05), the DGW-SSPCM system experiences energy loss compared to the DGW-REF system. The energy loss of the cases 1 to 9 (defined in Table 2.2) versus DGW-REF case in summer cloudy days are 10.9, 10.9, 10.9, 3.1, 1.4, 6.3, 4.1, 4.1, and 4.1 percent, respectively. Hence, the lowest energy loss of the DGW-SSPCM system versus DGW-REF in summer cloudy weather conditions occur in case 4, where the transient temperature value and range are 25 °C and 1 °C, resulting in a 3.1 percent energy loss.

During winter, the SSPCM retains warm air inside the building and prevents it from escaping. For the winter sunny day, over the heating degree hours occurring between 16:55 and 9:00, the DGW-SSPCM system demonstrates higher energy savings compared to the DGW-REF system. The energy savings of the cases 1 to 9 (defined in Table 2.2) versus DGW-REF case in winter sunny days are 14.6, 14.6, 14.6, 14.6, 14.6, 14.6, 26.3, 25.4, and 24.0 percent, respectively. Case 7, with a transient temperature value and range of 25 °C and 1 °C, exhibits the best energy savings among other cases, at 26.3 percent. Conversely, for the winter cloudy day, where the temperature remains below 24 °C throughout the day, the entire day is considered as heating degree hours. The energy savings of the cases 1 to 9 (defined in Table 2.2) versus DGW-REF case in winter cloudy days are 20.4, 20.4, 20.4, 26.2, 26.0, 25.3, 23.1,

23.6, and 24.0 percent, respectively. Case 4, with a transient temperature value and range of 20 °C and 1 °C, demonstrates the most energy-efficient system, achieving a 26.2 percent energy savings. While case 7 shows slightly lower energy savings (23.1 percent), it still performs significantly better compared to the DGW-REF system.

Overall, the best SSPCM for the studied south-facing glazing system in Miami is one with a transient temperature value and range of 25 °C and 1 °C, respectively. Choosing an SSPCM with appropriate thermophysical properties and a small thickness applied to the inner glass pane of a DGW within the air gap, resulting in full phase transition cycles along with a lower temperature transient range, could lead to a more energy-efficient glazing system. Despite slightly less energy efficiency during summer cloudy days, the overall energy performance enhancement in other day types during winter and summer compensates for this loss.

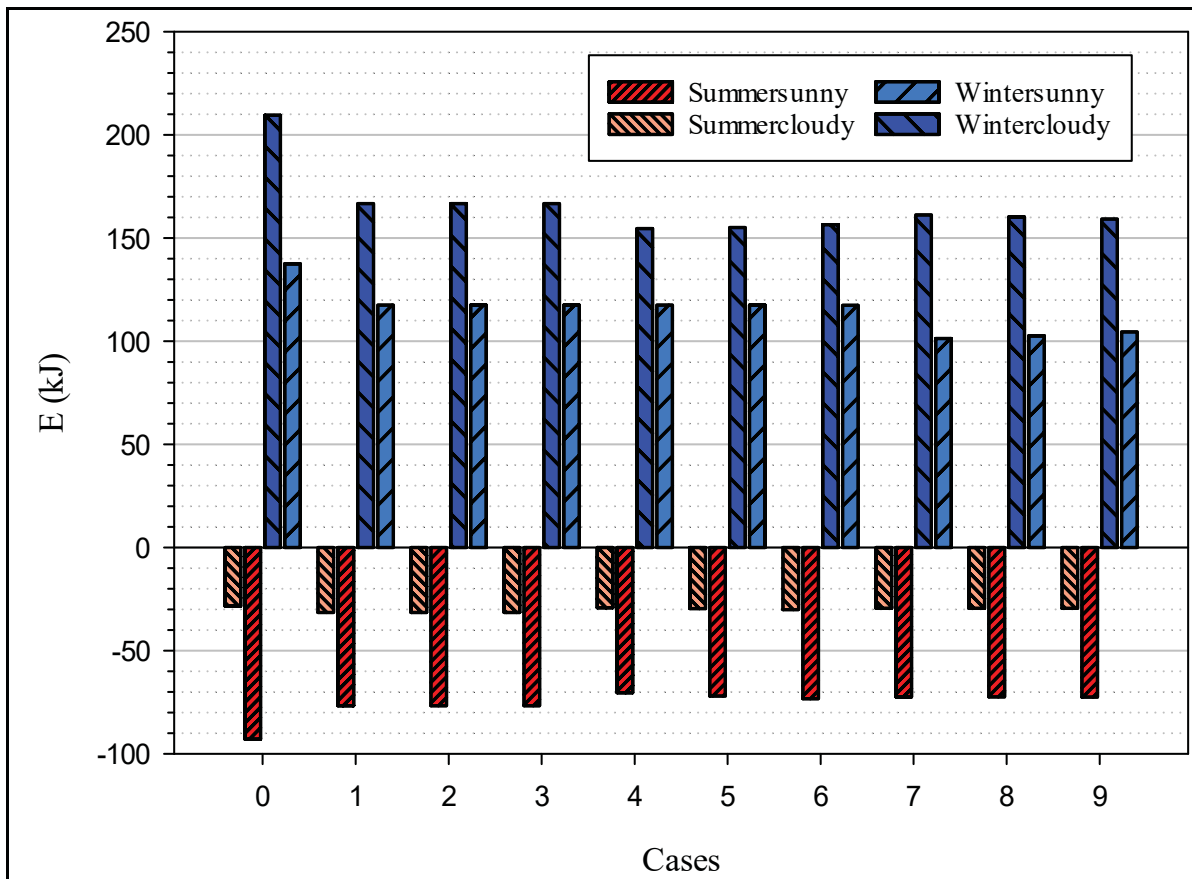


Figure 2.13 Heat energy vibration for the all scenarios in the DGW-SSPCM and DGW-REF systems

Table 2.5 Energy savings of all studied cases for various climatic conditions

| <b>Climatic condition</b> | <b>Case 1 (%)</b> | <b>Case 2 (%)</b> | <b>Case 3 (%)</b> | <b>Case 4 (%)</b> | <b>Case 5 (%)</b> | <b>Case 6 (%)</b> | <b>Case 7 (%)</b> | <b>Case 8 (%)</b> |
|---------------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Summer sunny              | 17.4              | 17.4              | 17.4              | 24.2              | 22.5              | 21.1              | 22.1              | 22.1              |
| Summer cloudy             | 10.9              | 10.9              | 10.9              | 3.1               | 1.4               | 6.3               | 4.1               | 4.1               |
| Winter sunny              | 14.6              | 14.6              | 14.6              | 14.6              | 14.6              | 14.6              | 26.3              | 25.4              |
| Winter cloudy             | 20.4              | 20.4              | 20.4              | 26.2              | 26.0              | 25.3              | 23.1              | 23.6              |

## 2.5 Conclusion

This study primarily focuses on assessing the energy performance of the glazing systems, subjected to natural weather conditions. The study includes modeling and analysis of a proposed double-glazing configuration that incorporates a 2 mm layer of solid-solid phase change materials (SSPCM) applied to the inner pane of glass within the air gap. The solid-solid phase change material is chosen due to their advantages over the commonly used liquid-solid phase change materials for glazing system applications. A model was developed using the finite volume method in the ANSYS FLUENT to perform numerical simulations. The model was validated against experimental data, where its predictions were in good agreement with the test results. With the model, different transient temperature values and ranges are investigated in the new proposed glazing system to assess the energy performance of the system during the coldest and hottest days of the year in cloudy and sunny days of Miami, FL weather conditions. A thickness of 2 mm was used for the solid-solid phase change material with transient temperatures ranging from 15 °C to 30 °C and transient temperature ranges between 1 °C and 5 °C. The obtained results showed energy performance enhancement of the glazing system with solid-solid phase change materials as opposed to traditional double-glazing windows. The results showed that the obtained highest energy savings of the system during heating and cooling degree hours are 24%, 26% and 23% for the case with the transient temperature magnitude and range of 25 °C and 1 °C in summer sunny, winter sunny, and winter cloudy days, while an energy loss of 3% is observed in this case for the summer cloudy days.

Overall, a more energy-efficient glazing system could be achieved by selecting the solid-solid phase change material with a small thickness to be applied to the inner glass pane of a DGW within the air gap with appropriate thermophysical properties leading to full phase transition cycles along with the lowest possible phase transition temperature range.

## CHAPTER 3

### ENHANCING BUILDING ENERGY EFFICIENCY: INNOVATIONS IN GLAZING SYSTEMS UTILIZING SOLID-SOLID PHASE CHANGE MATERIALS

Hossein Arasteh <sup>a</sup>, Wahid Maref <sup>a</sup>, Hamed H. Saber <sup>b</sup>

<sup>a</sup> Department of Construction Engineering, École de technologie supérieure,  
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C1K3

<sup>b</sup> Deanship of Research and Industrial Development, and Mechanical Engineering  
Department at Jubail Industrial College, Royal Commission of Jubail and Yanbu, Jubail  
Industrial City, 31961, Saudi Arabia

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#### Abstract

This study investigates the energy efficiency of a double-glazing window (DGW) integrating a solid-solid phase change material (SSPCM) with limited thickness, applied to the inner glass pane within the air gap. Numerical model, validated against experimental data, is developed using a finite volume method in ANSYS Fluent. In this model, the Discrete Ordinates (DO) model is applied to simulate radiation, while the enthalpy-porosity approach is used to capture the solidification and melting processes in the phase change material. With this model, the energy performance of the system is analyzed under various transient temperature values (10 to 30 °C) and ranges (1 to 5 °C) during the coldest and hottest days of the year, as well as during cloudy and sunny days in Montreal (Dfb), Vancouver (Cfb), and Miami (Aw). According to the obtained results in Montreal, the DGW-SSPCM system consistently saves energy under summer sunny conditions, with optimal performance when the SSPCM remains transparent. However, it incurs energy losses in cloudy days, where the energy lost is 2.3 times greater than the energy saved in sunny days. In Vancouver, the system shows consistent energy savings, particularly at  $T_c = 30$  °C, with average savings of 20.5 kJ (23%) under summer sunny

conditions. The system is most beneficial in Vancouver, where winter energy savings in cloudy days (50.6 kJ) are 7.1 times greater than the losses in sunny days (7.1 kJ). In Miami, the system results in energy losses by 60% and 5% (at  $T_c = 30\text{ }^{\circ}\text{C}$ ) under both summer sunny and cloudy conditions, respectively, indicating unsuitability for its climate. During winter sunny conditions, all three cities experience energy losses, with Vancouver showing the lowest of 7.1 kJ (3%) and Montreal the highest of 64.4 kJ (19%) at  $T_c = 30\text{ }^{\circ}\text{C}$ . In winter cloudy conditions, the system saves energy in all cities, with the highest savings in Miami of 54.5 kJ (26%) at  $T_c = 30\text{ }^{\circ}\text{C}$ . Overall, the DGW-SSPCM system has proven to be beneficial in Vancouver across various conditions in terms of energy and visual performance. These findings highlight the necessity of considering localized climate factors when designing and implementing energy-efficient glazing systems. Finally, the DGW-SSPCM system has provided complete visual clarity during office hours, making it more suitable for commercial buildings.

**Keywords:** Building Energy; Solid-Solid Phase Change Material; Glazing System; Zero Energy Buildings; Computational Fluid Dynamics.

### 3.1 Introduction

Building envelopes serve as the critical interface between indoor and outdoor environments, playing a significant role in mediating the conflicts between occupant comfort and the environmental impact of buildings. Adaptive facades, an advanced component of building envelopes, possess the ability to selectively transmit, filter, or block various phenomena such as heat, mass, and light. This capability enables them to regulate environmental conditions effectively, thereby enhancing indoor environmental quality. Additionally, adaptive facades offer a promising approach to reducing the energy consumption of buildings. By optimizing the interaction between the interior and exterior environments, adaptive facades contribute to improved indoor comfort and energy efficiency, ultimately supporting the development of more sustainable building practices. Among the opaque and transparent components of building envelopes, fenestration systems (e.g., windows, curtain walls, skylight devices) are identified as the primary source of heat loss in building constructions. These systems are

responsible for approximately 60% of the overall heat loss, significantly impacting the thermal efficiency of buildings (Wang et al., 2021).

There are three general methods to increase the thermal performance of glazing systems within buildings namely thermal resistance, solar control, and thermal inertia. The thermal resistance can be improved using different techniques such as the use of inert gases within the air gap of multi-glazing windows (Cho et al., 2023) as well as the use of materials with low thermal conductivity such as hydrogel (Chen et al., 2024) and aerogel (Khaled Mohammad and Ghosh, 2023). To implement the second technique, solar control, different methods are available in literature such as photovoltaic systems (Uddin et al., 2023), thermochromic (Wang et al., 2024) and thermotropic (Liu et al., 2023) materials, laminated coatings (Han et al., 2023), low-e coatings (Sorooshnia et al., 2025), switchable systems (Field and Ghosh, 2023), and so forth. The last approach in thermal performance enhancement of glazing systems, which is thermal inertia improvement and is the focus of current study, can be addressed by using thermal energy storage materials within the fenestration system like phase change materials (PCMs). The use of PCMs in glazing systems have been extensively reviewed in our recent research (Arasteh et al., 2023) showing a promising method in enhancing the thermal performance of glazing systems, however providing a satisfactory visual view has almost always been challenging. These materials absorb and release heat through phase change cycles, which can involve a solid-to-liquid transition, referred to as solid-liquid phase change material (SLPCM), or a solid-to-solid transition, known as solid-solid phase change material (SSPCM), as of the application within glazing systems. The current study implements the SSPCMs in glazing systems as they are advantageous compared to SLPCMs by offering low subcooling phenomenon, less material degradation, more consistent optical properties encapsulation-free implementation, no leakage, less phase-segregation, small volume variation, and high thermal stability (Fallahi et al., 2017). Unlike SLPCMs, SSPCMs can be directly adhered to a surface or pane of a multi-glazing window with a specific thickness, remaining solid throughout their phase transition. This property allows the air or inert gas, which possesses low thermal conductivity, to remain between the indoor and outdoor environments. This arrangement is beneficial because SLPCM fills the air gap (connecting indoor and outdoor environments), it decreases the thermal resistance of the glazing system due to its higher thermal conductivity

compared to air. Encapsulating SLPCM can mitigate this issue, allowing it to perform similarly to SSPCM by maintaining solid phase and preserving thermal resistance. SSPCMs undergo a phase transition between opaque (semi-crystalline) and transparent (amorphous) states, where only the soft segments melt, supported by the hard segment (polymeric backbone) with a significantly higher melting temperature. As a result, the SSPCM remains solid during phase transition by melting and freezing the soft segments, which are anchored by the hard segments. The phase transition process of SSPCMs has been comprehensively discussed and analyzed in (Arasteh et al., 2023; Gao et al., 2021; Wang et al., 2023).

Despite the extensive literature on SLPCM applications in glazing units, studies on SSPCMs in smart glazing are limited. Raj et al. (2020) conducted a review study discussing the applications of SSPCMs and recent advancements in their thermophysical properties. This study compiled a comprehensive list of organic, polymeric, organometallic, and commercial SSPCMs, along with their thermophysical properties, phase transition temperatures, melting temperatures, molecular characteristics, and thermal behavior. These reviews serve as valuable resources for researchers and practitioners interested in utilizing SSPCMs in various applications. Another review study (Fallahi et al., 2017) focused on the molecular properties and thermal characteristics of SSPCMs for thermal energy storage. They examined the relationship between molecular structure, phase transition mechanisms, and thermal properties of the four main categories of SSPCMs: polymeric, organic, organometallic, and inorganic. The authors provided guidance on selecting appropriate SSPCMs for various applications based on desired physical, thermal, and mechanical properties, offering a comprehensive list within each main category. Guldentops et al. (2018) explored a building enclosure system utilizing SSPCMs to passively regulate temperature in a south-facing building in central Massachusetts, accounting for both summer and winter climates. They developed a finite element model to analyze the system's energy performance, identifying optimized configurations for each season. However, the study noted the need for refining the extinction coefficients and transition temperatures of SSPCMs for effective year-round operation. Gao et al. (2021) integrated a thin SSPCM layer into the interior side of a double-glazing window (DGW) and performed a numerical analysis to evaluate annual energy savings. The authors used EnergyPlus for the numerical study but had to develop an equivalent model due to the



software's limitations in simulating latent energy storage materials. The results showed that a 3 mm SSPCM layer improved energy savings in warm, mixed, and cold climates, surpassing the performance of low-emissivity windows. Ma et al. (2022) assessed a glazing system combining silica aerogel and SSPCM in a severe cold region of China, focusing on both daylighting and energy performance. EnergyPlus was used for energy analysis, and Radiance software for daylighting analysis. Similar to Gao et al. (2021), due to software limitations, an equivalent SSPCM model was employed. The study identified transition temperature, latent heat, absorption coefficient, and refractive index as key parameters through sensitivity analysis. A 10 mm thickness of silica aerogel was recommended to maximize energy savings while meeting daylighting standards in China. Their findings suggested the viability of employing DGW-SSPCM in severe cold regions. Wang et al. (2023) developed an inverse model to derive expressions for the extinction coefficient and refractive index of SSPCMs as a function of temperature for the translucent phase, providing constant values for the opaque and transparent phases. These optical properties were incorporated into the current study. Recently, Zhang et al. (2024) conducted a two-dimensional numerical parametric study using the finite volume method to investigate the optical and thermal properties of a triple-glazed window containing SSPCM in the inner air gap and silica aerogel in the outer air gap. The study simulated 24 hours of severe cold weather in a Chinese city. Sensitivity analysis indicated that the thermal efficiency of the glazing system was significantly affected by the melting temperature and latent heat of the PCM, with the absorption coefficient and refractive index having minor effects. The optimal melting temperature of the PCM was found to be 18 °C, resulting in a 15% energy saving rate.

Based on the aforementioned literature review, it is evident that there are few studies investigating the energy performance of SSPCMs in glazing systems using 3D modeling. The existing numerical models are either using EnergyPlus that has some limitations in capturing the phase transition phenomenon within the SSPCM, hence using an equivalent model has been inevitable or 2D models that assess the SSPCM behavior fully filled the air gap space of a triple-glazed window. Therefore, to bridge this gap, the main objective of this study is to develop a 3D model and use it to assess the energy performance of a DGW incorporating SSPCMs. The idea of placing the SSPCM onto the interior pane between the air gap has come

up to keep the material's temperature as high as possible to yield an almost full transparent window throughout the whole year. Following model validation, a parametric study was conducted by varying the transient temperature and transient temperature range of a south-facing DGW-SSPCM over a 24-hour real-time period. The simulations were performed for sunny and cloudy days during the coldest and hottest days of the year 2022 in Montreal, Vancouver, and Miami.

## 3.2 Methodology

### 3.2.1 Geometrical details

In the current study the results of a double-glazing window integrated with a solid-solid phase change material (DGW-SSPCM) is compared to a reference double-glazing window (DGW-REF). The SSPCM has been adhered to the interior pane of the DGW within the air gap. Both DGW-REF and DGW-SSPCM consist of two panes, each measuring 20 cm in length, 20 cm in width, and 4 mm in thickness. The DGW-REF configuration features a 1.6 cm air gap, shown in Figure 3.1a. In contrast, the DGW-SSPCM configuration incorporates a 2 mm-thick SSPCM layer on the interior pane, reducing the air gap to 1.4 cm, shown in Figure 3.1b.

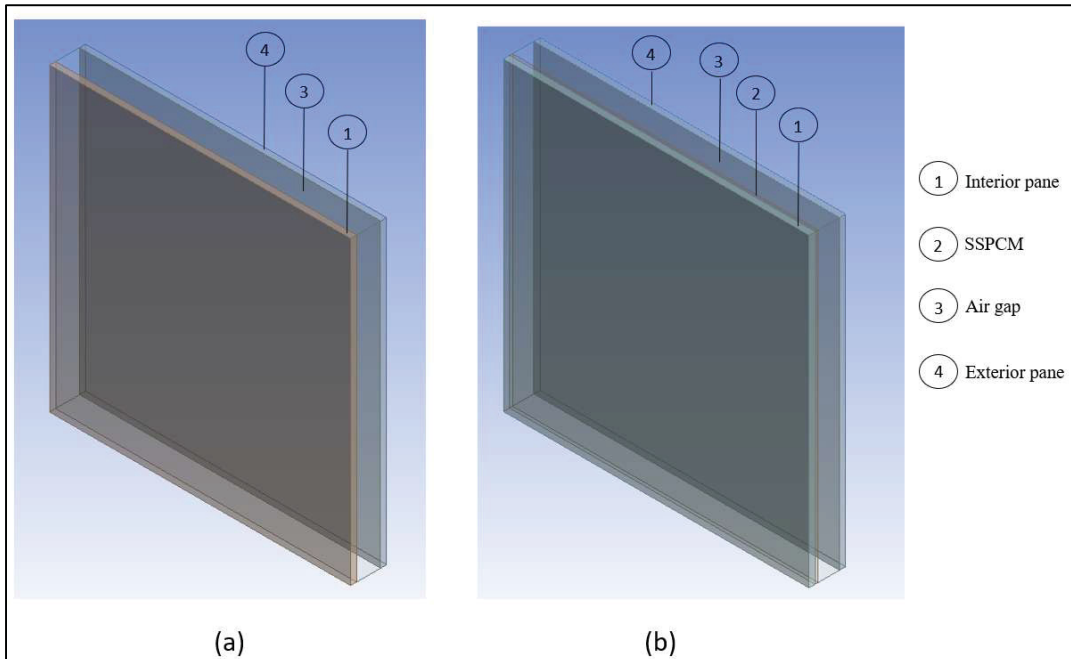


Figure 3.1 The 3D geometry of the (a) DGW-REF and (b) DGW-SSPCM

### 3.2.2 Material perspective

In the current study, the glazing system is composed of two 4 mm clear glass with an emissivity of 0.9 (ASHRAE, 2021). The thermophysical and optical properties were obtained from (Gowreesunker et al., 2013). The thermal energy storage material (SSPCM) was chosen from (PCM Products, 2024). The optical properties of the SSPCM including refractive index as well as absorption and scattering coefficients were derived from correlations developed by (Wang et al., 2023). The thermophysical properties of the materials employed in this study are detailed in Table 3.1. Additionally, Table 3.2 lists the various phase change temperatures and their respective ranges that were examined in this research.

Table 3.1 Materials thermophysical properties

| Material                                   | Density<br>(kg/m <sup>3</sup> ) | Specific<br>heat<br>(J/kgK) | Thermal<br>conductivity<br>(W/mK) | Absorption<br>coefficient<br>(1/m) | Scattering<br>coefficient<br>(1/m) | Refractive<br>index    | Latent<br>heat<br>(kJ/kg) |
|--------------------------------------------|---------------------------------|-----------------------------|-----------------------------------|------------------------------------|------------------------------------|------------------------|---------------------------|
| Air*                                       | 1.225                           | 1006.43                     | 0.0242                            | 0                                  | 0                                  | 1                      | -                         |
| Glass                                      | 2500                            | 840                         | 1.3                               | 19                                 | 0                                  | 1.5                    | -                         |
| SSPCM                                      | 1055                            | 1630                        | 0.36                              | 33.80 (tr)<br>25.73 (op)           | 0 (tr)<br>119.02 (op)              | 1.11 (tr)<br>5.33 (op) | 110                       |
| *Properties at temperature range 10~30 °C. |                                 |                             |                                   |                                    |                                    |                        |                           |

Table 3.2 List of scenarios for the phase change temperature values and ranges

| Summer | Cases | Glazing system                              | Winter | Cases | Glazing system                              |
|--------|-------|---------------------------------------------|--------|-------|---------------------------------------------|
|        | 0     | DGW-REF                                     |        | 0     | DGW-REF                                     |
|        | 1     | $T_c = 20\text{ °C}, dT_{pc} = 1\text{ °C}$ |        | 1     | $T_c = 15\text{ °C}, dT_{pc} = 1\text{ °C}$ |
|        | 2     | $T_c = 20\text{ °C}, dT_{pc} = 3\text{ °C}$ |        | 2     | $T_c = 15\text{ °C}, dT_{pc} = 3\text{ °C}$ |
|        | 3     | $T_c = 20\text{ °C}, dT_{pc} = 5\text{ °C}$ |        | 3     | $T_c = 15\text{ °C}, dT_{pc} = 5\text{ °C}$ |
|        | 4     | $T_c = 25\text{ °C}, dT_{pc} = 1\text{ °C}$ |        | 4     | $T_c = 20\text{ °C}, dT_{pc} = 1\text{ °C}$ |
|        | 5     | $T_c = 25\text{ °C}, dT_{pc} = 3\text{ °C}$ |        | 5     | $T_c = 20\text{ °C}, dT_{pc} = 3\text{ °C}$ |
|        | 6     | $T_c = 25\text{ °C}, dT_{pc} = 5\text{ °C}$ |        | 6     | $T_c = 20\text{ °C}, dT_{pc} = 5\text{ °C}$ |
|        | 7     | $T_c = 30\text{ °C}, dT_{pc} = 1\text{ °C}$ |        | 7     | $T_c = 25\text{ °C}, dT_{pc} = 1\text{ °C}$ |
|        | 8     | $T_c = 30\text{ °C}, dT_{pc} = 3\text{ °C}$ |        | 8     | $T_c = 25\text{ °C}, dT_{pc} = 3\text{ °C}$ |
|        | 9     | $T_c = 30\text{ °C}, dT_{pc} = 5\text{ °C}$ |        | 9     | $T_c = 25\text{ °C}, dT_{pc} = 5\text{ °C}$ |

The optical thickness ( $d$ ) of a substance, defined by Equation (3.1), is a common way to describe the extinction coefficient (*ANSYS FLUENT*, 2021). In this equation,  $s$  refers to the sample's actual thickness, which is specified as 2 mm for the DGW-SSPCM setups in this study.

$$d = (\sigma_a + \sigma_s)s \quad (3.1)$$

In Equation (3.1),  $\sigma_a$  and  $\sigma_s$  represents the absorption and scattering coefficients, respectively. This study assumes an isotropic scattering coefficient. By applying Beer-Lambert's law to non-gaseous materials, Equation (3.2) can be used to calculate the PCM transmittance (Guldentops et al., 2018):

$$\tau_{PCM} = 10^{-d} \quad (3.2)$$

where  $\tau_{PCM}$  represents the transmittance of the PCM. First, the absorption coefficient is calculated using Equation (3.3) (Gowreesunker et al., 2013). This value is then applied in Equation (3.1) to determine the scattering coefficient.

$$\sigma_a = \sigma_s \left[ \frac{\tau_{PCM,tr} - \tau_{PCM,op}}{1 - \tau_{PCM,op}} \beta + \frac{1 - \tau_{PCM,tr}}{1 - \tau_{PCM,op}} \right] \quad (3.3)$$

In Equations (3.1) to (3.3),  $\tau$  and  $\beta$  represent the transmittance and transparency fraction of the material, respectively. The subscripts PCM, tr, and op represent the phase change material, transparent and opaque, respectively. For the SSPCM, the refractive index and extinction coefficient are as follows: for the transparent phase, they are 1.11 and  $25.73 \text{ m}^{-1}$ , respectively, and for the opaque phase, they are 5.33 and  $152.82 \text{ m}^{-1}$ , respectively (Wang et al., 2023).

For the translucent phase, Equations (3.3) and (3.4) are used to calculate the average optical properties as a function of the transparency fraction, which replaces the term 'liquid fraction' since there is no liquid phase in SSPCM. The transparency fraction represents the portion of

the material in the transparent phase, with  $\beta$  being 0 for fully opaque SSPCM and 1 for fully transparent SSPCM. When the transparency fraction is 0, it indicates that the SSPCM temperature is at or below the lower limit of the transient temperature range, known as the opaqueus temperature (akin to liquidus temperature in SLPCM), meaning the material is in the opaque phase.

Conversely, a transparency fraction of 1 indicates that the SSPCM temperature is at or above the upper limit of the transient temperature range, known as the transparentus temperature (akin to solidus temperature in SLPCM), meaning the material is in the transparent phase. A transparency fraction between 0 and 1 signifies that the SSPCM is in the translucent phase, similar to the mushy zone in SLPCMs.

$$\sigma_{a,cell} = 33.8\beta + 25.73(1 - \beta) \quad (3.4)$$

$$\sigma_{s,cell} = 119.02(1 - \beta) \quad (3.5)$$

### 3.2.3 Governing equations

To model the SSPCM, the enthalpy-porosity approach in FLUENT was utilized, assigning a very high viscosity value to the SSPCM to ensure nearly zero velocity within it. In this study, natural convection effects within the air gap of the DGW were neglected for all configurations (i.e., DGW-SSPCM and DGW-REF) to focus on evaluating the feasibility and effectiveness of incorporating SSPCM into glazing systems. Using the climate in three cities with different climatic conditions (i.e. Montreal, Vancouver, and Miami) as a case study under natural conditions, this approach aims to determine whether energy savings can be realized in a glazing system with SSPCM compared to one without it. The governing equations for this study considering the Discrete Ordinates (DO) model for radiation and a solidification/melting model for SSPCM are as follows.

- Energy equation (*ANSYS FLUENT*, 2021):

$$\frac{\partial}{\partial t}(\rho H) = \nabla \cdot (k \nabla T) + S_h \quad (3.6)$$

In Equation (3.6), the enthalpy of the PCM,  $H$ , is calculated as the sum of the sensible enthalpy,  $h_s$ , and latent heat,  $\Delta H$  as:

$$H = h_s + \Delta H \quad (3.7)$$

where,

$$h_s = h_{s,ref} + \int_{T_{ref}}^T c_p dT \quad (3.8)$$

In Equation (3.7), the fractional latent heat of the PCM,  $\Delta H$ , can be expressed in terms of the PCM's latent heat of fusion,  $L$ . Note that  $\Delta H$  can vary between 0 (opaque phase),  $L$  (transparent phase), and values between 0 and  $L$  when  $T_{opaque} < T < T_{transparentus}$  (translucent phase).

$$\Delta H = \beta L \quad (3.9)$$

In this study, the transparency fraction is calculated as following:

$$\beta = \begin{cases} 0 & \text{if } T \leq T_{opaque} \\ 1 & \text{if } T \geq T_{transparentus} \\ \frac{T - T_{opaque}}{T_{transparentus} - T_{opaque}} & \text{if } T_{opaque} < T < T_{transparentus} \end{cases} \quad (3.10)$$

The term  $S_h$  in Equation (3.6) denotes the volumetric heat source/sink related to phase change, which is defined as:

$$S_h = -\frac{\partial(\rho\Delta H)}{\partial t} \quad (3.11)$$

- Radiation equation:

In this study, the Discrete Ordinates (DO) model is adopted to simulate radiation effects because it offers the most comprehensive treatment of radiation in ANSYS FLUENT. This model enables the simulation of radiation scattering and absorption across various optical thicknesses. By converting the radiation heat transfer equation into a transport equation for radiation intensity and solving it across a finite number of discrete solid angles (*ANSYS FLUENT*, 2021), the DO model enhances precision. However, the increased number of equations required by the DO model slows down the simulation process.

The radiative transfer equation for an absorbing, emitting, and scattering medium at position  $\vec{r}$  in the direction  $\vec{s}$  is (*ANSYS FLUENT*, 2021):

$$\frac{dI(\vec{r}, \vec{s})}{ds} + (\sigma_a + \sigma_s)I(\vec{r}, \vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \phi(\vec{s}, \vec{s}') d\Omega' \quad (3.12)$$

The DO model considers the radiative transfer equation in the direction  $\vec{s}$  as a field equation and is written as (*ANSYS FLUENT*, 2021):

$$\begin{aligned} & \nabla \cdot (I(\vec{r}, \vec{s})\vec{s}) + (\sigma_a + \sigma_s)I(\vec{r}, \vec{s}) \\ &= an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \phi(\vec{s}, \vec{s}') d\Omega' \end{aligned} \quad (3.13)$$

In Equations (3.12) and (3.13),  $I$ ,  $n$ ,  $\vec{r}$ ,  $\vec{s}$ ,  $\vec{s}'$ ,  $\phi$ ,  $\Omega'$ , and  $\sigma$  represent radiation intensity, refractive index, position vector, direction vector, scattering direction vector, phase function, solid angle, and the Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ ), respectively.

### 3.2.4 *Weather conditions*

The glazing system in this study represents a south-facing window located in Montreal, Vancouver, and Miami. For Montreal, the coordinates are 45.52°N latitude and 73.42°W longitude. The coldest and hottest days selected for this study in Montreal are January 22<sup>nd</sup> and July 21<sup>st</sup>, 2022. The time zone is GMT-5 during Eastern Standard Time (EST) and GMT-4 during Eastern Daylight Time (EDT). Montreal's climate code based on the Köppen-Geiger classification (Beck et al., 2018) is Dfb, representing a humid continental climate with warm summers and no dry season. For Vancouver, the coordinates are 49.3°N latitude and 123.12°W longitude.

The selected coldest and hottest days in Vancouver are December 22<sup>nd</sup> and July 29<sup>th</sup>, 2022. The time zone is GMT-8 during Pacific Standard Time (PST) and GMT-7 during Pacific Daylight Time (PDT). Vancouver's climate code based on the Köppen-Geiger classification (Beck et al., 2018) is Cfb, representing a temperate oceanic climate with warm summers and no dry season. For Miami, the coordinates are 25.76°N latitude and 80.19°W longitude. The coldest and hottest days chosen for this study in Miami are January 30<sup>th</sup> and August 18<sup>th</sup>, 2022. The time zone is GMT-5 during Eastern Standard Time (EST) and GMT-4 during Eastern Daylight Time (EDT). Miami's climate code based on the Köppen-Geiger classification (Beck et al., 2018) is Aw, representing a tropical savanna climate with a distinct dry season in winter. All climatic conditions are considered for both sunny and cloudy days on the hottest and coldest days of the year. The ambient weather conditions include hourly wind speed (*Historical Climate Data in Canada*, 2023; *Weather History in Miami*, 2022), hourly ambient temperature (*Historical Climate Data in Canada*, 2023; *Weather History in Miami*, 2022), hourly solar direct irradiation (*ANSYS FLUENT*, 2021), and hourly solar diffuse irradiation (*ANSYS FLUENT*, 2021), for the coldest and hottest days, as depicted in Figure 3.2.



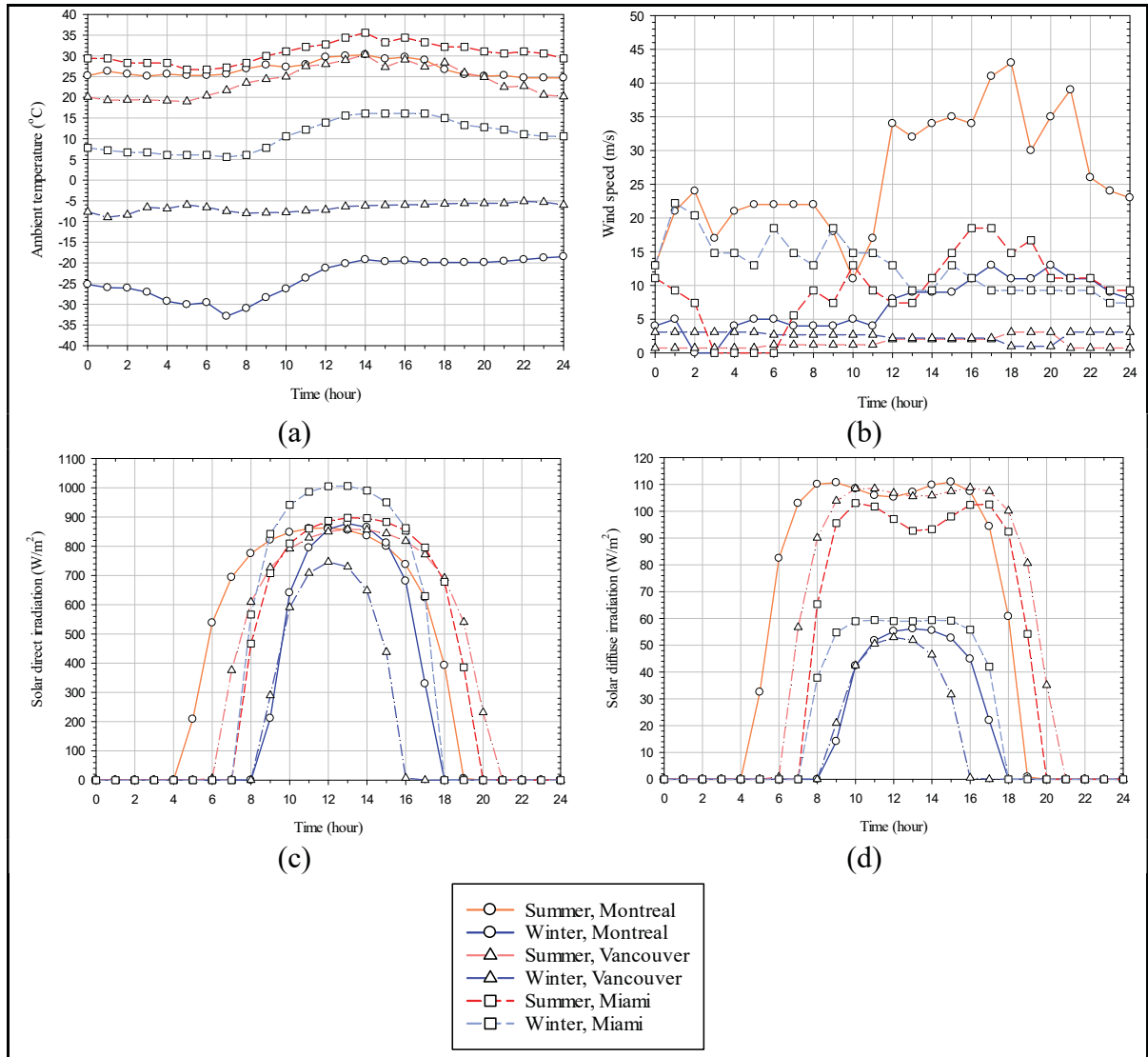


Figure 3.2 Climate data for Montreal, Vancouver, and Miami in summer and winter: (a) Ambient temperature (*Historical Climate Data in Canada, 2023; Weather History in Miami, 2022*), (b) Wind speed (*Historical Climate Data in Canada, 2023; Weather History in Miami, 2022*), (c) Solar direct irradiation (*ANSYS FLUENT, 2021*), and (d) Solar diffuse irradiation (*ANSYS FLUENT, 2021*)

### 3.2.5 Initial and boundary conditions

The initial temperatures for all components of both the DGW-REF and DGW-SSPCM configurations are set to 26°C for summer and 24°C for winter. The side surfaces (exterior top, bottom, front, and back) of the window are treated as thermally insulated or adiabatic (i.e., no

energy transport on these sides). The interface between two material layers is modeled using coupled thermal boundary conditions and semi-transparent radiation boundary conditions, ensuring continuity of temperature and heat flux across the real and shadow surfaces while allowing incoming radiation to pass through the surface. In this study, all material layers are assumed to be in perfect thermal contact. This means that the thermal contact resistances at the interfaces of material layers are set to zero. Mixed thermal boundary conditions, which include both convection and radiation, are applied to the window's indoor and outdoor surfaces.

Therefore, it is necessary to determine parameters such as the heat transfer coefficient, free stream temperature, external emissivity, and external radiation temperature for these surfaces. Furthermore, to account for solar irradiation within the numerical domain, semi-transparent boundary conditions are established. This necessitates defining parameters like direct solar irradiation, diffuse solar irradiation, and the beam direction vectors in the x, y, and z directions for both indoor and outdoor surfaces. The emissivity of typical clear glass is set at 0.9 (ASHRAE, 2021) for all boundaries. The sunshine factor is set to 1 to represent a sunny day and to 0 for a cloudy day, which results in zero direct solar irradiation.

For the window's indoor surface thermal and radiation boundary conditions, the heat transfer coefficient is set to  $8.7 \text{ W/m}^2\text{K}$  (ASHRAE, 2021). The free stream temperature and external radiation temperature are both set to  $26^\circ\text{C}$  in summer and  $24^\circ\text{C}$  in winter. No solar irradiation is applied to the indoor radiation boundary condition to obviously not model a direct or diffuse solar irradiation to the indoor surface. In summary, the boundary condition on the outdoor surface is heat flux with  $q_{h,\text{outd}}$ . Also, the boundary condition on the indoor surface is heat flux with  $q_{h,\text{ind}}$ . Both  $q_{h,\text{outd}}$  and  $q_{h,\text{ind}}$  account for heat transfer by convection, radiative heat exchange between these surfaces and the the environment (sky conditions, ground, adjacent constructions/buildings, wind speed, cloud index, etc.). The detailed procedure for determining both  $q_{h,\text{outd}}$  and  $q_{h,\text{ind}}$  are available in (Saber et al., 2019). In this procedure, the hourly cloud index is 1.0 for overcast conditions and 0 for clear conditions.

For the window's outdoor surface thermal and radiation boundary conditions, all parameters except emissivity are imported into ANSYS FLUENT using User Defined Functions (UDFs) written in C programming, compatible with the FLUENT library, to simulate a full 24-hour

day. These UDFs utilize piecewise linear functions to incorporate the hourly weather data. The hourly ambient temperature is used for the free stream temperature in the thermal boundary condition. Additionally, hourly values for direct and diffuse solar irradiances, as well as the x, y, and z beam direction vectors, are set in the radiation boundary conditions. The hourly heat transfer coefficient, which depends on wind speed, and the hourly external radiation temperature or sky temperature, which depends on ambient temperature, are calculated using Equations (3.14) and (3.15) (Goia et al., 2012).

$$h_a = 5.62 + 3.9 v_{wind} \quad (3.14)$$

$$T_{sky} = 0.0552 T_{air,o}^{1.5} \quad (3.15)$$

In Equation (3.14),  $h_a$  in W/m<sup>2</sup>K and  $v_{wind}$  in m/s. Also, both  $T_{sky}$  and  $T_{air,o}$  in Equation (3.15) are in K.

### 3.2.6 Study of initial condition effects

As previously mentioned, the initial conditions were assumed for this analysis. In this section, we examine the impact of these assumed initial conditions on the results. To investigate the effect of the assumed initial conditions on thermal performance, numerical simulations were conducted over a period of 7 consecutive days.

The thermal performance of the glazing system at a specific location is influenced by hourly weather data. By utilizing the hourly weather data for the simulation period (i.e., 7 days), the variations in thermal performance over time are contingent upon two primary factors: (a) the assumed values of the initial conditions and (b) the temporal fluctuations in the weather data. To isolate the influence of factor (b), the weather data from Day 1, where the assumed initial conditions were applied, was replicated for the subsequent days. Consequently, any observed changes in thermal performance over time can be attributed predominantly to the assumed initial conditions. The case under study is for DGW-SSPCM in Montreal with phase transition temperature ( $T_c$ ) of 25°C and phase transition temperature range ( $\Delta T_c$ ) of 1°C, in which the SSPCM experiences a full phase transition. Figure 3.3 presents the transparency fraction of the

DGW-SSPCM system over 7 simulated days. The repeated cycle shows how the transparency fraction stabilizes after the first day, demonstrating that the assumed initial condition effects are effectively eliminated.

Figure 3.4 illustrates the interior surface temperature of both the DGW-REF and DGW-SSPCM systems over the same 7-day period. A comparison of the curves shows that, after the first day, the temperature variations become stable (i.e., the assumed initial conditions have no effect). Table 3.3 provides the deviation percentage for both systems over the 7 simulated days, which is defined as:  $((\text{Thermal energy of current round} - \text{Thermal energy of previous round}) / \text{Thermal energy of previous round}) \times 100\%$ . The DGW-REF system exhibits a minor deviation of 0.29% on Day 2, which becomes negligible for the remaining days, indicating consistency after the second day. For the DGW-SSPCM system, although the deviation on Day 2 is 3.28%, this value is sufficiently low to be considered negligible for the simulations, in order to reach a precise solution with the minimum computational cost. The system achieves 0% deviation from Day 3 onward.

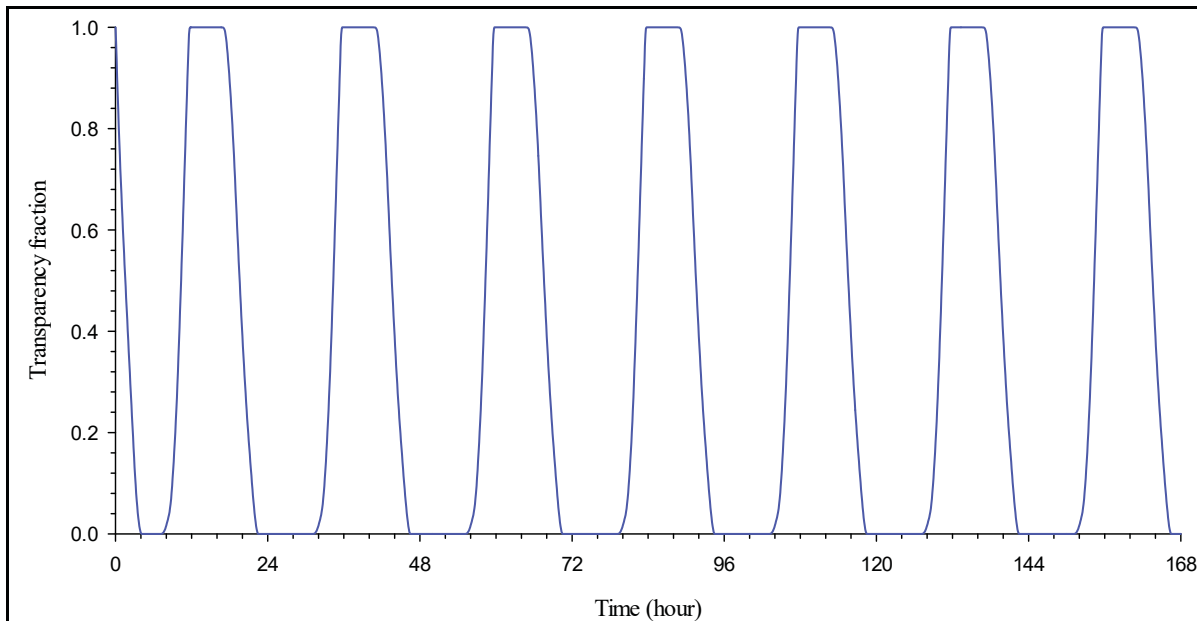


Figure 3.3 Transparency fraction of the DGW-SSPCM system in 7 days

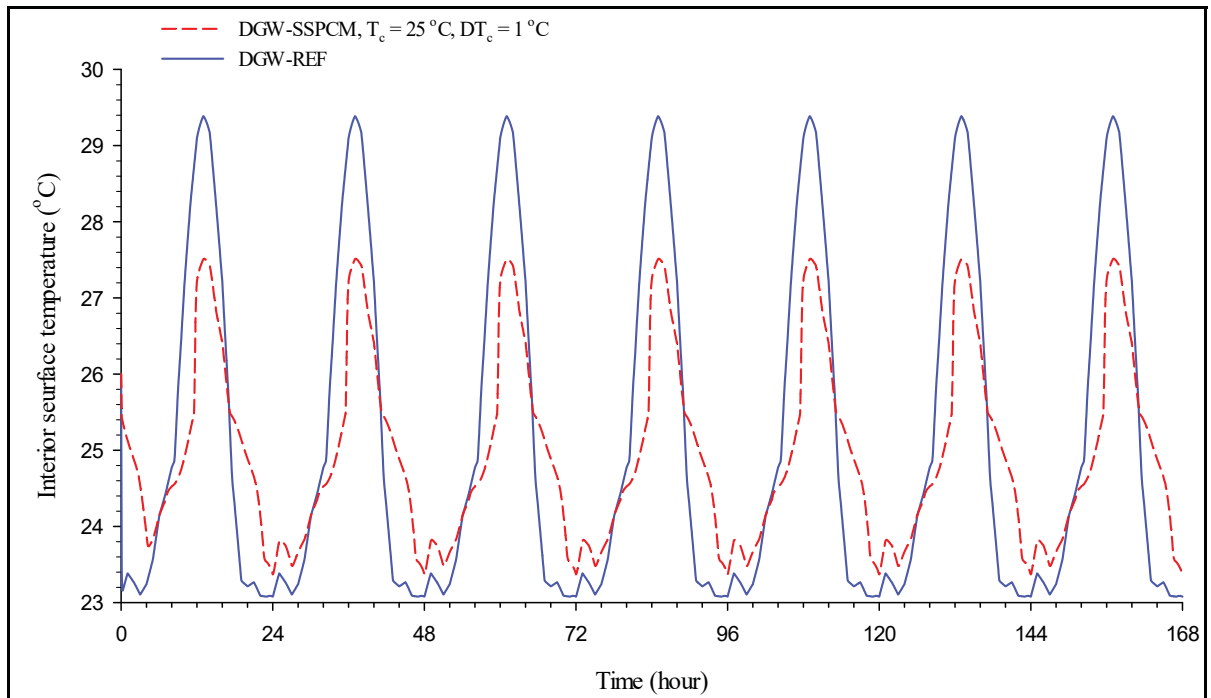


Figure 3.4 Interior surface temperature of the systems DGW-REF and DGW-SSPCM in 7 days

Table 3.3 Thermal energy values for single summer design day duplicated 7 times

| Thermal energy (kJ) | DGW-REF | Deviation (%) | DGW-SSPCM | Deviation (%) |
|---------------------|---------|---------------|-----------|---------------|
| Day 1 (Round 1)     | 99.6971 | -             | 89.1331   | -             |
| Day 2 (Round 2)     | 99.4057 | 0.29          | 86.2118   | 3.28          |
| Day 3 (Round 3)     | 99.4057 | 0             | 86.2118   | 0             |
| Day 4 (Round 4)     | 99.4057 | 0             | 86.2118   | 0             |
| Day 5 (Round 5)     | 99.4057 | 0             | 86.2118   | 0             |
| Day 6 (Round 6)     | 99.4057 | 0             | 86.2118   | 0             |
| Day 7 (Round 7)     | 99.4057 | 0             | 86.2118   | 0             |

### 3.3 Numerical procedure

#### 3.3.1 *Model description*

The commercial CFD code ANSYS FLUENT (version 2022 R1) is used, employing the SIMPLE algorithm for velocity-pressure coupling. Design Modeler and Ansys Meshing were utilized to generate the geometry and grid, respectively. For the discretization of pressure, momentum, and energy, a second-order upwind scheme is applied, while the DO model and transient formulation use a first order upwind and first-order implicit scheme, respectively. The convergence criteria were set to be less than  $10^{-6}$ ,  $10^{-6}$ ,  $10^{-6}$ ,  $10^{-6}$ ,  $10^{-9}$ , and  $10^{-9}$  for mass conservation, x-velocity, y-velocity, z-velocity, energy and DO-intensity, respectively.

#### 3.3.2 *Model validation*

In this research, the model traditionally used for SLPCMs has been adapted for SSPCMs through the solidification/melting model. The key difference is that SSPCMs do not exhibit natural convection because they do not have a liquid phase when melting. By disregarding the gravity effect and accounting for the high viscosity of the SLPCM's liquid phase, its behavior can be approximated to that of an SSPCM.

To validate the numerical model that includes the Discrete Ordinates (DO) model and the solidification/melting model in glazing systems, transient numerical results over a simulation period of 12,000 seconds were compared with experimental data from Gowreesunkera et al. (2013) concerning the transmittance of PCM-filled glazing units over time. In their study, the researchers developed an experimental setup to measure the changes in radiation effects within the mushy phase, which is not possible with a spectrophotometer alone. This setup provided a realistic depiction of the radiation behavior in a PCM-glazed system. The entire setup was placed in an environmental chamber with controlled air temperature. A 150 W metal halide lamp emitting diffuse neutral white light was used as the light source. The regular double glazing measured 20 cm by 20 cm with a total thickness of 24 mm, consisting of 4 mm glass, a 16 mm air cavity, and another 4 mm glass layer. In the PCM-filled glazing configuration, the air cavity was replaced with RT27. The irradiation level and initial PCM/air temperature were set to 950 W/m<sup>2</sup> and 13°C, respectively.

In this study, the experimental data by Gowreesunker et al. (2013) was used to validate the present model. This data is provided in Figure 3.5a by the black-dashed curve. Due to the uncertainties in the measurements, the upper and lower error limits are also provided in this figure by dashed-gray curves. In this figure, the overall transmittance was defined by the ratio of radiation flux between the front and back faces. As shown in Figure 3.5a, the transmittance values from the simulation, shown by the red curve, are in close agreement with the experimental data, with variations staying within the margin of error. Additionally, the observed transmittance trends exhibit similarity between the simulation results and the experimental data. However, in this figure, it is visible that in some areas the simulation results and experimental data do not match well. It can be attributed to the enthalpy-porosity model, which assumes a linear relationship between temperature and the liquid fraction within the phase change temperature range. This model treats the mushy zone as a porous medium, with the porosity linearly dependent on the local temperature. This assumption simplifies the modeling of melting and solidification, creating discrepancies between numerical results and experimental data, especially when a non-linear jump is observed in the experimental results. As the numerical results are in agreement with the experimental data being within  $\pm 10\%$  as shown in Figure 3.5b, the numerical model is validated and can be reliably used in this study.

### 3.3.3 *Grid sensitivity*

To determine the optimal grid size for a mesh-independent solution, various grid sizes, from fine to coarse, were generated over the numerical domain of a DGW-SSPCM. The mean total heat flux over a 24-hour period, as described in Equation (3.16), on the interior surface of the inner glass pane was used as the criterion for assessing grid independence. The results are presented in Table 3.4. According to this table, a grid size with 82,369 elements was found to be approximately optimal, as its relative error is less than 1%. Therefore, this grid size was used in the study. For the grid size with 82,369 elements used in this study, the grid generated in the computational domain is displayed in Figure 3.6, including both an overview of the entire domain and a zoomed-in view.

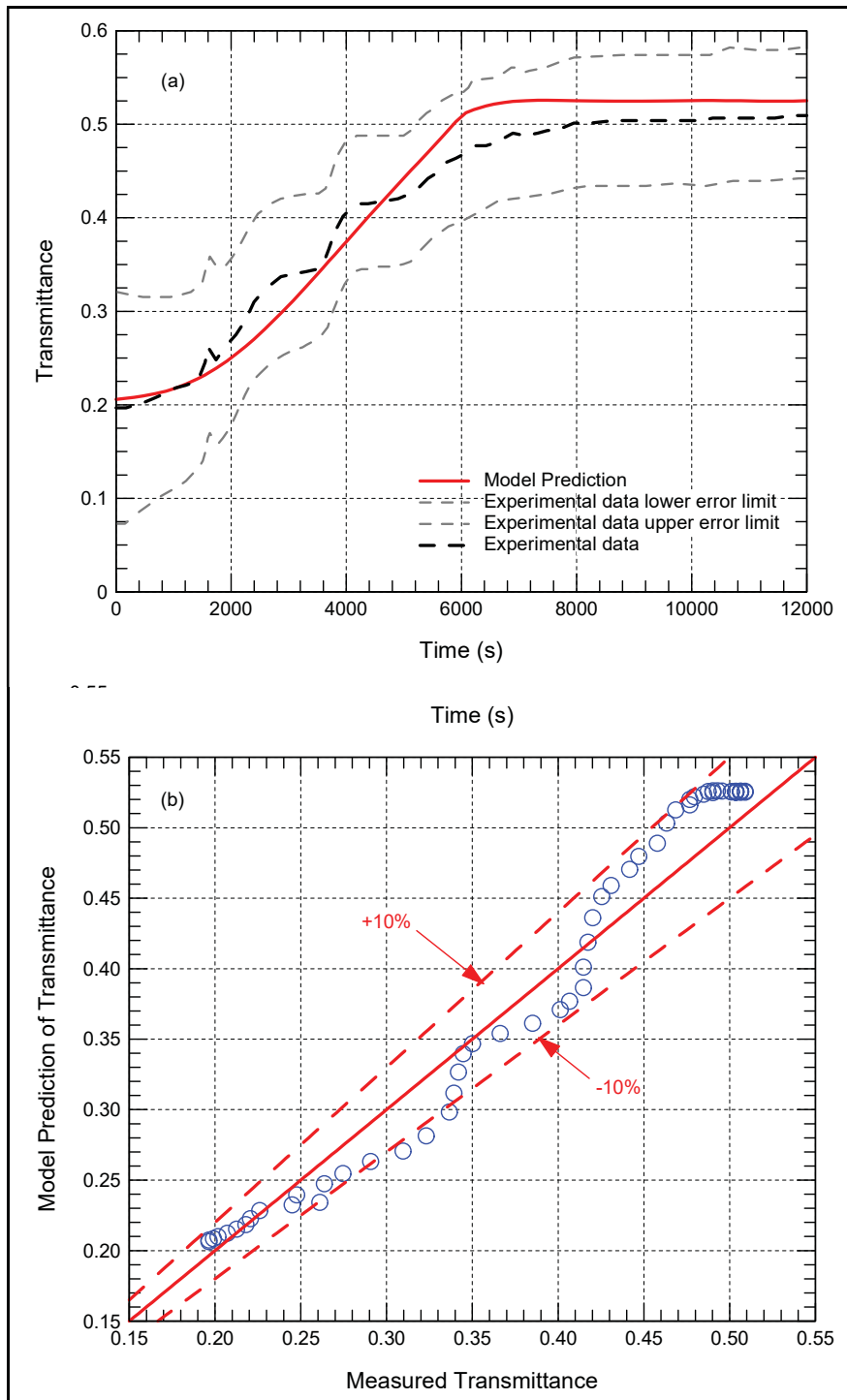


Figure 3.5 Current numerical model validation study against the experimental data of (Gowreesunker et al., 2013)



$$\overline{q''} = \frac{1}{t} \int_0^t q'' dt \quad (3.16)$$

Table 3.4 Grid sensitivity analysis

| Case | Number of elements | $\overline{q''}$ (W/m <sup>2</sup> ) | Error (%) |
|------|--------------------|--------------------------------------|-----------|
| 1    | 288923             | 15.47104                             | -         |
| 2    | 158661             | 15.5293                              | 0.376595  |
| 3    | 82369              | 15.58556                             | 0.740245  |
| 4    | 27440              | 15.71381                             | 1.569181  |
| 5    | 11025              | 15.8746                              | 2.608495  |
| 6    | 4050               | 16.1296                              | 4.25671   |

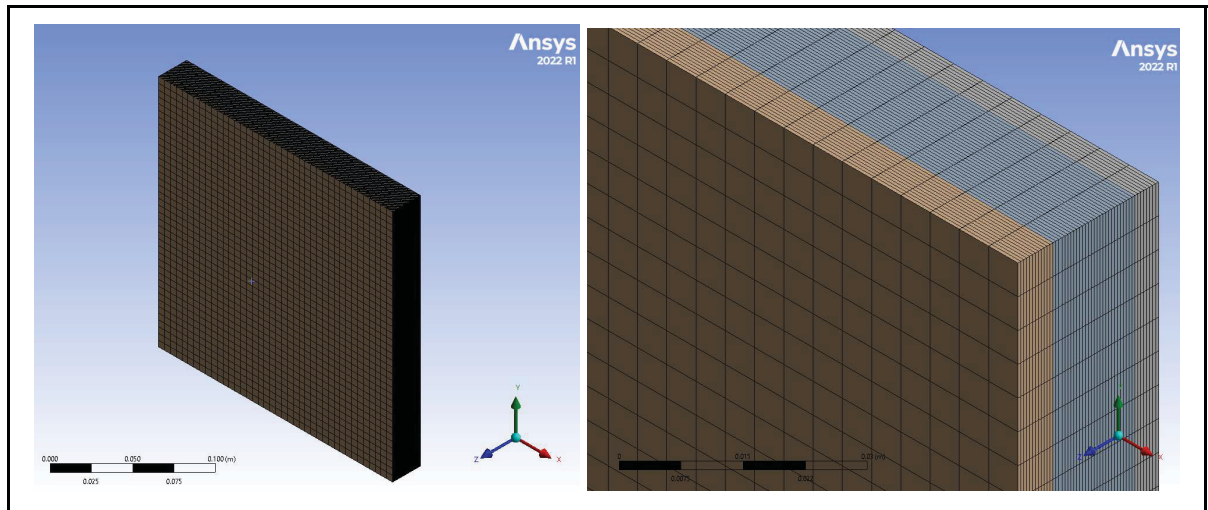


Figure 3.6 The generated grid in this study: (a) the entire domain and (b) a zoomed-in view

### 3.3.4 Time step sensitivity

The aim of the time step sensitivity analysis is to identify the largest time step size that maintains accuracy. Following the same method as in the previous section, the average total heat flux over a 24-hour period on the interior surface of the inner glass pane was used to determine the optimal time step size, aiming to minimize CPU time. Table 3.5 presents the results for various time step sizes. It indicates that a time step size of 5 minutes results in a relative error of less than 1% and is appropriate for use in the simulations.

Table 3.5 Time-step sensitivity analysis

| Case | Time step size | $\overline{q''}$ (W/m <sup>2</sup> ) | Error (%) |
|------|----------------|--------------------------------------|-----------|
| 1    | 10 sec         | 15.73079                             | -         |
| 2    | 30 sec         | 15.72085                             | 0.06315   |
| 3    | 1 min          | 15.70591                             | 0.15812   |
| 4    | 2.5 min        | 15.66088                             | 0.44443   |
| 5    | 5 min          | 15.58556                             | 0.92319   |
| 6    | 10 min         | 15.43214                             | 1.89849   |
| 7    | 20 min         | 15.11929                             | 3.88729   |
| 8    | 30 min         | 14.82675                             | 5.74694   |

### 3.4 Results and discussion

Numerical simulations are performed for the scenarios outlined in Table 3.2. These simulations span a 24-hour real-time period, covering both sunny and cloudy days during the coldest and hottest days of 2022 in Montreal, Vancouver, and Miami. The parametric study is conducted to analyze the effects of various parameters, including phase transition temperature ( $T_c$ ) and phase transition temperature range ( $\Delta T_c$ ), as well as four climatic conditions (summer sunny, summer cloudy, winter sunny, and winter cloudy), on transparency fraction, interior surface temperature, total heat flux on the interior surface, and the glazing system's energy savings.

#### 3.4.1 Transparency fraction

This section analyzes the variations in the transparency fraction of the SSPCM, defined in Equation (3.10), for the scenarios outlined in Table 3.2 during summer and winter, focusing on the hottest and coldest sunny and cloudy days.

Figure 3.7 illustrates the variations of the transparency fraction of the SSPCM in summer sunny days in the three studied cities for all cases. According to this figure, the transparency fraction displays distinct diurnal patterns across all locations, influenced by phase transition temperature ( $T_c$ ) and phase transition temperature range ( $\Delta T_c$ ). The transparency fraction increases from 0 to 1 as the temperature rises, indicating the SSPCM is storing heat using its

high latent heat thermal energy storage. Conversely, it decreases from 1 to 0 as the temperature falls, releasing stored heat to the surroundings. In Montreal, Figure 3.7a, the transparency fraction increases sharply in the morning, peaking around noon, and decreases towards the evening. Notably, at  $T_c = 20^\circ\text{C}$ , the transparency fraction remains at 1 throughout the day, providing continuous visual clarity. Conversely, at  $T_c = 30^\circ\text{C}$ , the transparency fraction stays at 0, indicating the SSPCM remains opaque. At  $T_c = 25^\circ\text{C}$  the SSPCM has undergone a full phase transition in which smaller  $\Delta T_c$  values result in sharper transitions, while larger  $\Delta T_c$  values delay this transition. However, it is important to note that when the SSPCM does not experience a full phase transition, the glazing system cannot benefit from its high latent thermal storage capability. Vancouver, Figure 3.7b, exhibits a different pattern. At  $T_c = 20^\circ\text{C}$ , although the SSPCM remains transparent throughout the day, it reaches the translucent phase at night for  $\Delta T_c = 3^\circ\text{C}$  and  $\Delta T_c = 5^\circ\text{C}$ . Similarly, at  $T_c = 30^\circ\text{C}$ , the SSPCM also undergoes partial phase transitions, becoming translucent during the warmest part of the day and returning to an opaque state in the evening. This partial phase transition behavior limits the full utilization of the SSPCM's latent heat storage capability. In the meanwhile, the full phase transition is achieved at  $T_c = 25^\circ\text{C}$ , being transparent during the office hours. The transparency fraction in Miami, Figure 3.7c, is similar to Montreal. The SSPCM stays transparent and opaque throughout the day at  $T_c = 20^\circ\text{C}$  and  $T_c = 30^\circ\text{C}$ , respectively, and goes a full transition at  $T_c = 25^\circ\text{C}$  by staying transparent during the office hours. However, the SSPCM experiences more prolonged periods of partial transparency, likely due to higher ambient temperatures. Larger  $\Delta T_c$  values (e.g.,  $5^\circ\text{C}$ ) result in more gradual changes in transparency, while smaller  $\Delta T_c$  values (e.g.,  $1^\circ\text{C}$ ) cause sharper transitions. This is evident across all locations, with  $\Delta T_c = 1^\circ\text{C}$  curves showing the steepest transitions. Overall, Montreal and Vancouver exhibit similar trends with slight variations in transition timings and transparency duration, attributed to climatic differences. Three cities benefit from SSPCM's transparency aligning with office hours, enhancing the utility of SSPCM in commercial buildings. Miami's higher average temperatures lead to more sustained periods of partial transparency, reflecting the SSPCM's behavior under consistently warmer conditions. This partial transparency is less critical for visual clarity during office hours but may still provide adequate daylighting for residential buildings.

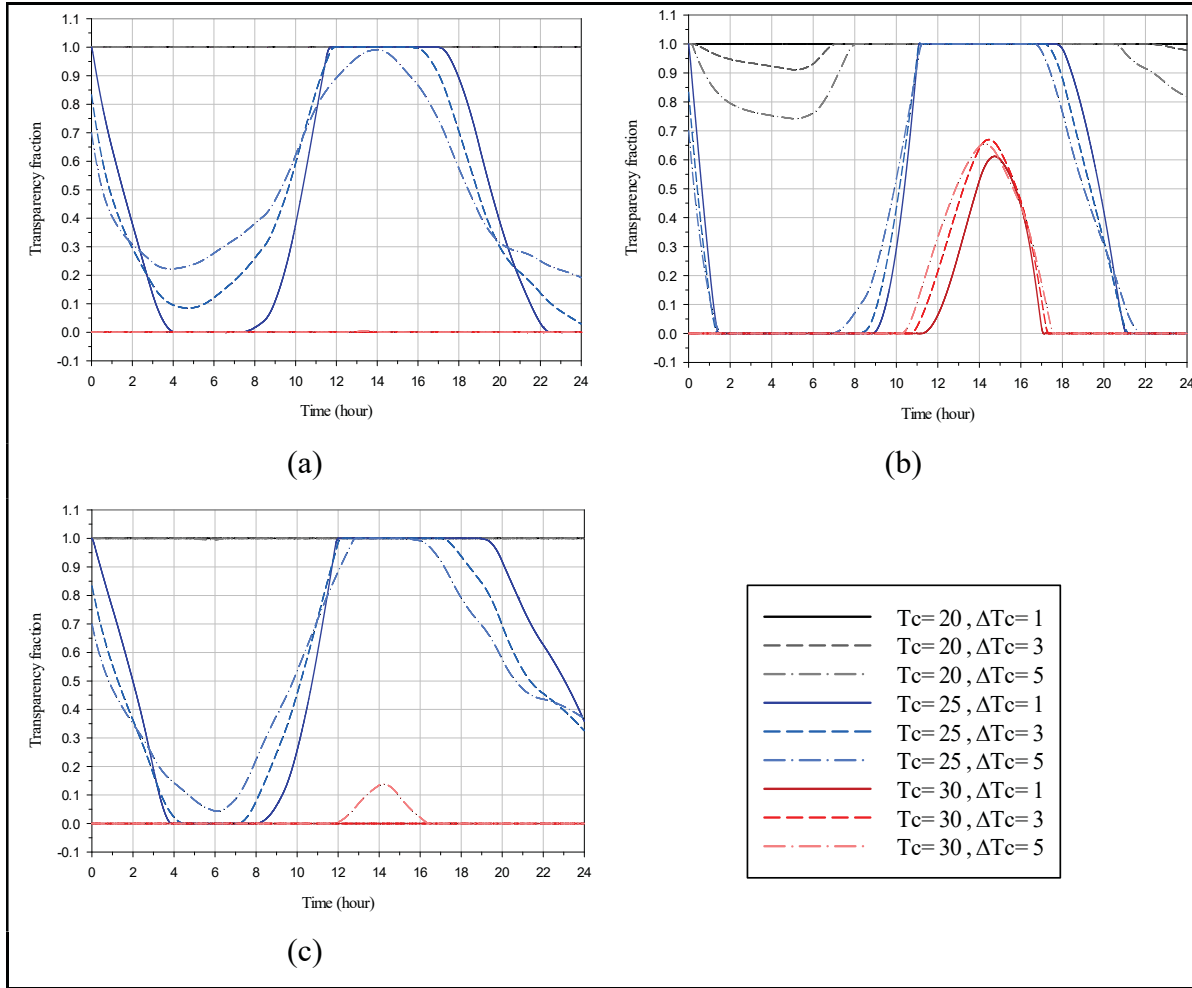


Figure 3.7 SSPCM's transparency fraction variations in summer sunny conditions for (a) Montreal, (b) Vancouver, (c) and Miami

Figure 3.8 explores the behavior of the SSPCM's transparency fraction in summer cloudy conditions for Montreal, Vancouver, and Miami. In Montreal and Vancouver, Figures 3.8a and 3.8b, the full phase transition of the SSPCM does not occur for all scenarios due to the lack of direct solar irradiation, while it occurs in Miami according to higher ambient temperatures. In three cities, only at  $T_c = 25^\circ\text{C}$  partial phase transition of the SSPCM occurs, indicating the impact of cloud cover on the SSPCM's performance. The SSPCM's performance in cloudy conditions is characterized by less distinct and lower peaks in transparency fraction compared to sunny conditions, as seen in Figure 3.7. The reduced solar heating on cloudy days limits the SSPCM's ability to fully transition, thereby impacting its heat storage and release capabilities. Higher  $\Delta T_c$  values result in more extensive phase transitions of the SSPCM, but these

transitions occur more abruptly compared to those with lower  $\Delta T_c$  values. The intermediate  $T_c$  value of  $25^\circ\text{C}$  provides a better balance, ensuring some level of transparency during office hours, enhancing both visual comfort and energy efficiency.

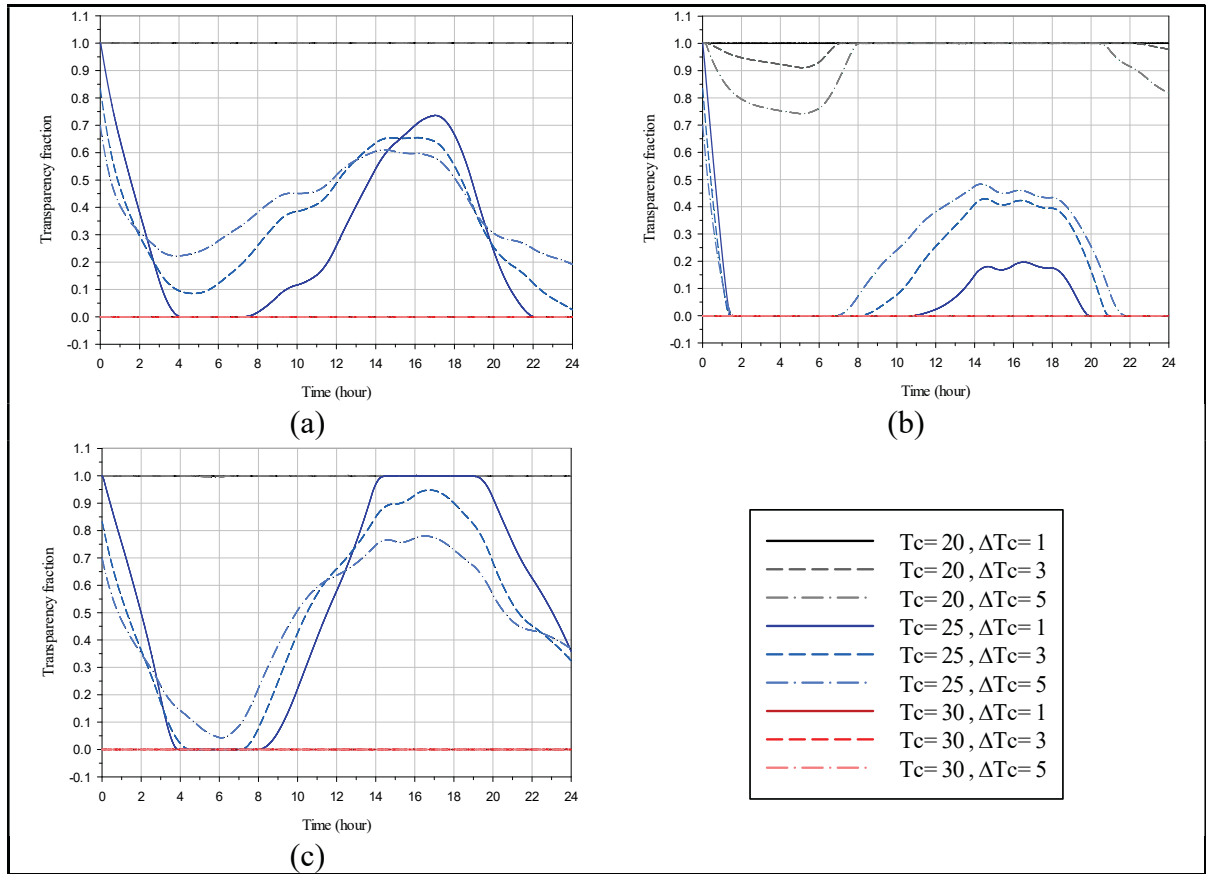


Figure 3.8 SSPCM's transparency fraction variations in summer cloudy conditions for (a) Montreal, (b) Vancouver, (c) and Miami

Figure 3.9 illustrates the variations of the transparency fraction of the SSPCM in winter sunny conditions for the three studied cities. In Montreal, Figure 3.9a, the transparency fraction shows significant changes throughout the day. At  $T_c = 10^\circ\text{C}$ , the transparency fraction drops during the night partially (more reduction in higher  $\Delta T_c$ ) and SSPCM falls into translucent phase and by the appearance of the sun it returns back to the opaque phase. At  $T_c = 20^\circ\text{C}$ , a partial phase transition from transparent to translucent is visible and SSPCM doesn't go under a full phase transition. For  $T_c = 20^\circ\text{C}$ , the full phase transition is visible and  $\Delta T_c$  has little impact on the transparency fraction. The SSPCM stays transparent during the office hours and opaque in the rest of the day, making it suitable for commercial buildings.

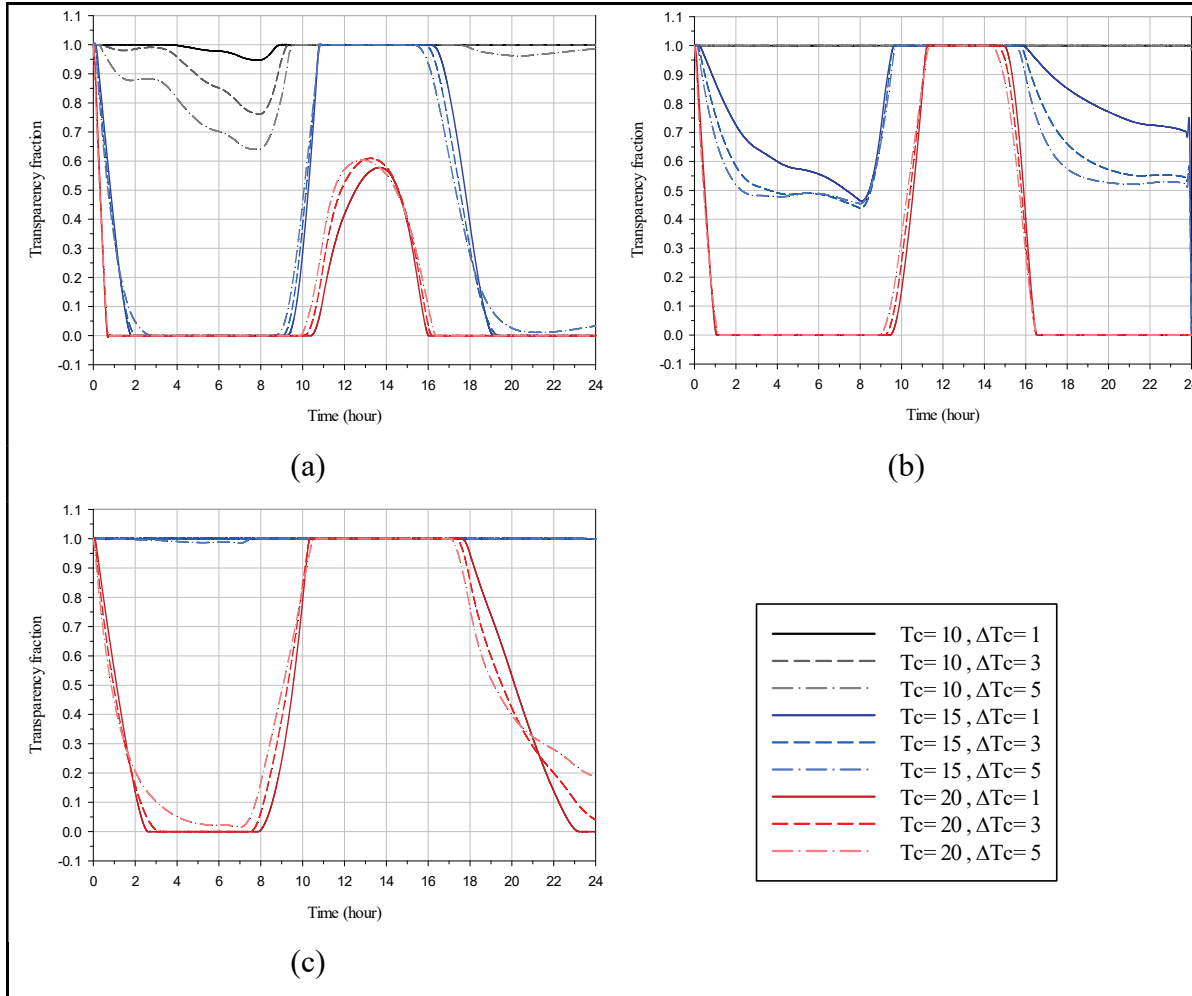


Figure 3.9 SSPCM's transparency fraction variations in winter sunny conditions for (a) Montreal, (b) Vancouver, (c) and Miami

In Vancouver, Figure 3.9b, the transparency fraction also varies throughout the day but with distinct patterns for different  $T_c$  values. At  $T_c = 10^\circ\text{C}$ , the transparency fraction remains close to 1 for most of the day, indicating consistent transparency. Due to warmer winters in Vancouver compared to Montreal, the SSPCM stays translucent and transparent for  $T_c = 20^\circ\text{C}$  and  $T_c = 15^\circ\text{C}$ , during the night and stays transparent during the day. This indicates that Vancouver's climate may allow for a more stable transparency fraction with intermediate  $T_c$  values, balancing visual clarity and thermal storage. Due to even warmer winters in Miami, Figure 3.9c, the transparency fraction demonstrates highest values throughout the day for  $T_c = 10^\circ\text{C}$  and  $T_c = 15^\circ\text{C}$ , maintaining constant transparency.

For  $T_c = 20^\circ\text{C}$ , the full phase transitioning of the SSPCM provides the high latent thermal storage to the glazing system by staying opaque at night and transparent during the night, making it effective for maintaining visual clarity while utilizing the SSPCM's thermal storage capabilities. Overall, in winter sunny conditions, the SSPCM shows effective heat storage and release patterns across all three cities, with notable transparency peaks during midday. Proposing a system that offers a balanced approach, ensuring transparency during key daylight hours while leveraging the SSPCM's thermal storage potential differs from city to city as  $T_c = 15^\circ\text{C}$  yields such a system in Montreal, but it is  $T_c = 20^\circ\text{C}$  in Vancouver and Miami. This behavior highlights the importance of selecting appropriate  $T_c$  values based on specific climatic conditions to optimize the performance of SSPCMs in double glazing systems.

Figure 3.10 depicts the changes in the transparency fraction of the SSPCM under winter cloudy conditions for the three examined cities. the SSPCM's performance in winter cloudy conditions is characterized by lower and less distinct peaks in transparency fraction compared to sunny conditions, as seen in Figures 3.7 and 3.9. The reduced solar heating due to the absence of direct solar irradiation on cloudy days limits the full phase change transition of SSPCM, thereby impacting its heat storage and release capabilities.

In Montreal, Figure 3.10a, The SSPCM experiences small phase transitions, particularly at  $T_c = 10^\circ\text{C}$  and higher  $\Delta T_c$  values. In Vancouver, Figure 3.10b, at  $T_c = 15^\circ\text{C}$ , the SSPCM stays in the translucent phase all day long, with lower  $\Delta T_c$  values showing higher transparency fraction fluctuations. In Miami, Figure 3.10c, the transparency fraction demonstrates a pattern of partial transparency with peaks occurring later in the day. At  $T_c = 20^\circ\text{C}$ , the transparency fraction shows partial phase transitions, which are stronger with higher  $\Delta T_c$  values, but remains mostly opaque throughout the day. The comparison between sunny and cloudy conditions underscores the need to consider weather variability in the application of SSPCMs for energy efficiency and visual comfort.

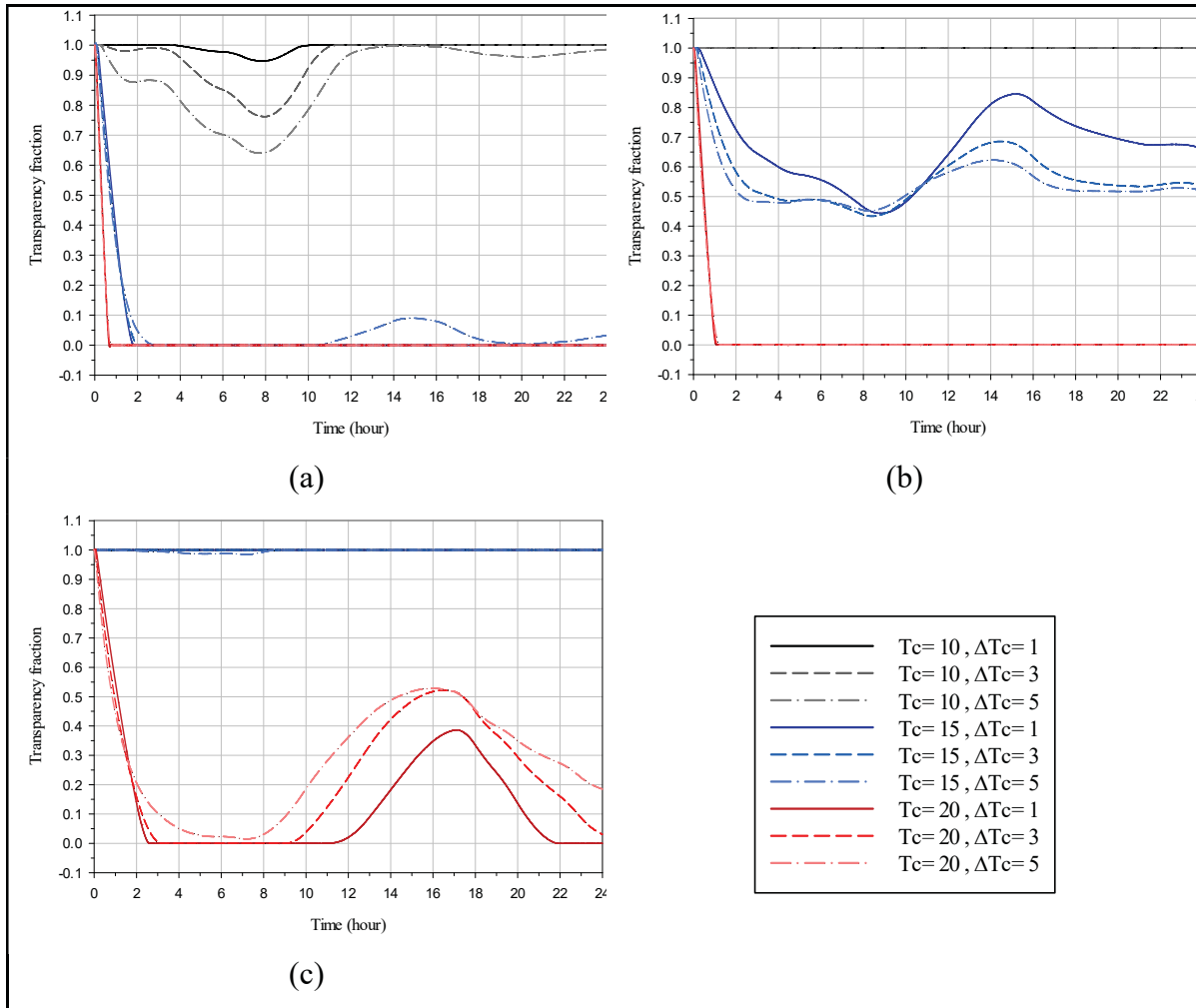


Figure 3.10 SSPCM's transparency fraction variations in winter cloudy conditions for (a) Montreal, (b) Vancouver, (c) and Miami

### 3.4.2 Interior surface temperature

This section discusses the simulation results pertaining to the variations in the interior surface temperature of the glazing system during the hottest summer and coldest winter days under both sunny and cloudy sky conditions.

Figure 3.11 illustrates the variations of the interior surface temperature of the double-glazed window equipped with SSPCM in summer sunny conditions for the three studied cities. The interior surface temperature is crucial for maintaining thermal comfort, with lower temperatures preferred in summer. In Montreal, Figure 3.11a, the use of SSPCM at  $T_c = 25^\circ\text{C}$



and  $\Delta T_c = 5^\circ\text{C}$  has reduced the interior surface temperature by nearly  $2^\circ\text{C}$  at the peak cooling load demand. This reduction is achieved by utilizing the SSPCM's capability to store direct solar irradiation, preventing it from entering the building.

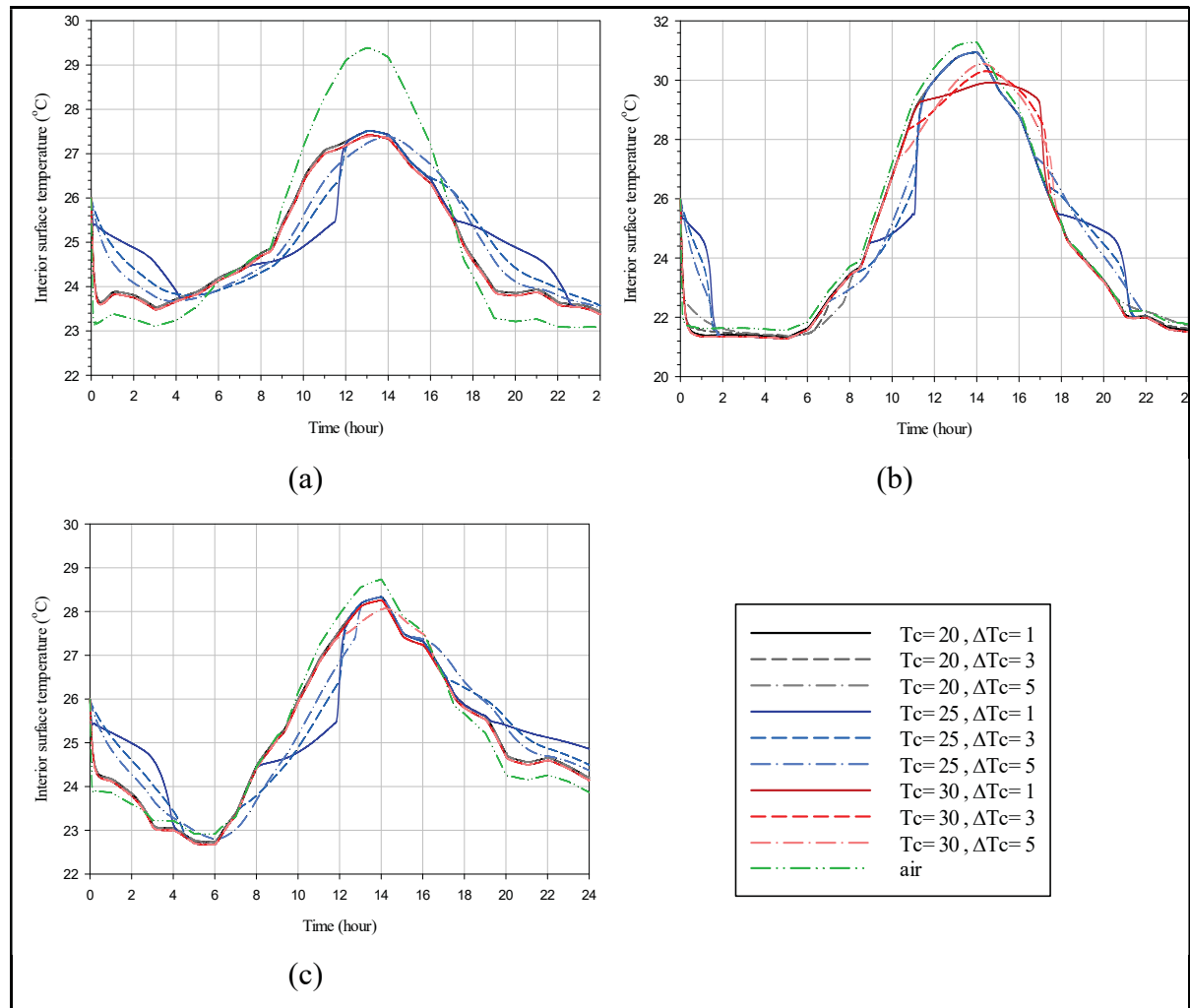


Figure 3.11 SSPCM's interior surface temperature variations in summer sunny conditions for (a) Montreal, (b) Vancouver, (c) and Miami

According to Figure 3.11a, only at  $T_c = 25^\circ\text{C}$  does the SSPCM undergo phase transition, which results in a different temperature trend in Figure 3.11a compared to the other two  $T_c$  values. At  $T_c = 25^\circ\text{C}$ , lower temperatures are achieved, thus providing better thermal comfort. During the day, the SSPCM absorbs solar heat, utilizing its high latent heat thermal storage capability, which is evident as the interior surface temperature is lower (leading to energy savings during peak load hours). At night, the stored heat is released, resulting in higher interior surface

temperatures. Additionally, lower  $\Delta T_c$  values cause lower interior surface temperatures with sharper gradients. In Vancouver, the use of SSPCM has also reduced the interior surface temperature by around  $0.8^\circ\text{C}$  at  $T_c = 30^\circ\text{C}$  and  $\Delta T_c = 1^\circ\text{C}$  at the peak cooling load demand, which is less than the reduction observed in Montreal. This is due to the faster phase transition of the SSPCM caused by higher ambient temperatures. The interior surface temperature reduction in Miami is almost similar to Vancouver, due to the rapid phase transition of the SSPCM due to higher ambient temperatures. Consequently, the current setup of DGW-SSPCM is more beneficial for thermal comfort under Montreal's summer sunny climatic conditions. In addition, the importance of selecting appropriate  $T_c$  and  $\Delta T_c$  values based on specific climatic conditions to optimize the performance of SSPCMs in double glazing systems for improved thermal comfort in summer is evident.

Figure 3.12 displays the variations of the interior surface temperature of the studied scenarios in summer cloudy conditions for the three studied cities. In Montreal, Figure 3.12a, the SSPCM with  $T_c = 25^\circ\text{C}$  and  $\Delta T_c = 1^\circ\text{C}$  shows nearly a  $1^\circ\text{C}$  reduction in the interior surface temperature during the peak load hour. The SSPCM stores heat during the day, providing thermal comfort during peak hours, and releases it at the start of the evening, thereby smoothing temperature fluctuations. Similarly, in Vancouver, Figure 3.12b, the SSPCM with  $T_c = 25^\circ\text{C}$  and  $\Delta T_c = 1^\circ\text{C}$  also reduces the interior surface temperature, though the reduction is less pronounced than in Montreal. The SSPCM effectively stores heat during the day and releases it in the evening, helping to smooth out temperature variations and improve thermal comfort. In Miami, Figure 3.12c, the SSPCM with  $T_c = 25^\circ\text{C}$  and  $\Delta T_c = 1^\circ\text{C}$  significantly reduces the interior surface temperature and smooths out fluctuations. The impact is more pronounced due to the warmer climate, with the SSPCM storing more heat during the day and releasing it in the evening, maintaining lower interior surface temperatures and enhancing thermal comfort during peak load hours. Similar to summer sunny climatic conditions, in summer cloudy conditions, the DGW-SSPCM has been more advantageous in Montreal for improving thermal comfort compared to the other two cities. The ability of the SSPCM to effectively store and release heat, thereby moderating the interior surface temperature, underscores its potential for enhancing thermal comfort and reducing cooling loads in buildings.

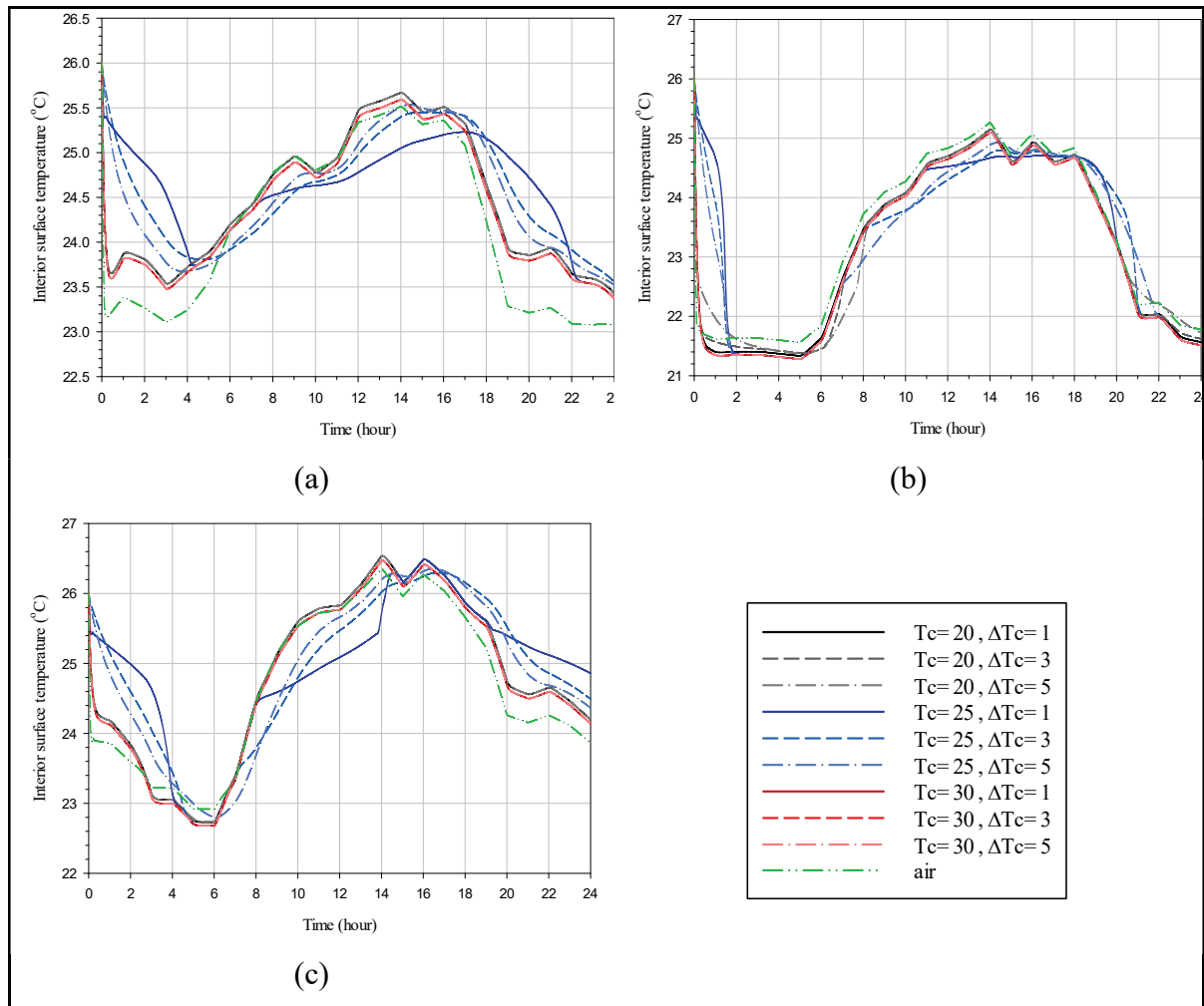


Figure 3.12 SSPCM's interior surface temperature variations in summer cloudy conditions for (a) Montreal, (b) Vancouver, (c) and Miami

Figure 3.13 displays the variations of the interior surface temperature of the DGW-SSPCM in winter sunny conditions for the three studied cities. The interior surface temperature is crucial for maintaining thermal comfort, with higher temperatures preferred in winter. In Montreal Figure 3.13a, the SSPCM blocks a significant amount of solar heat during the day, creating a noticeable difference between the interior surface temperatures of DGW-SSPCM and DGW-REF. At  $T_c = 15^\circ\text{C}$ , the stored heat is released to the interior at the start of the evening, enhancing the interior surface temperature and improving thermal comfort during these hours when heating demand is higher, as the SSPCM undergoes a full phase transition at this temperature. In Vancouver Figure 3.13b, a similar pattern occurs for the interior surface temperature, but with a smaller temperature reduction for DGW-SSPCM compared to DGW-

REF during the day and a noticeable temperature increase at the start of the evening at  $T_c = 20^\circ\text{C}$ . In Miami, Figure 3.13c, the released heat is more significant, causing the interior surface temperature to increase from the start of the evening until midnight due to the warmer winters in Miami.

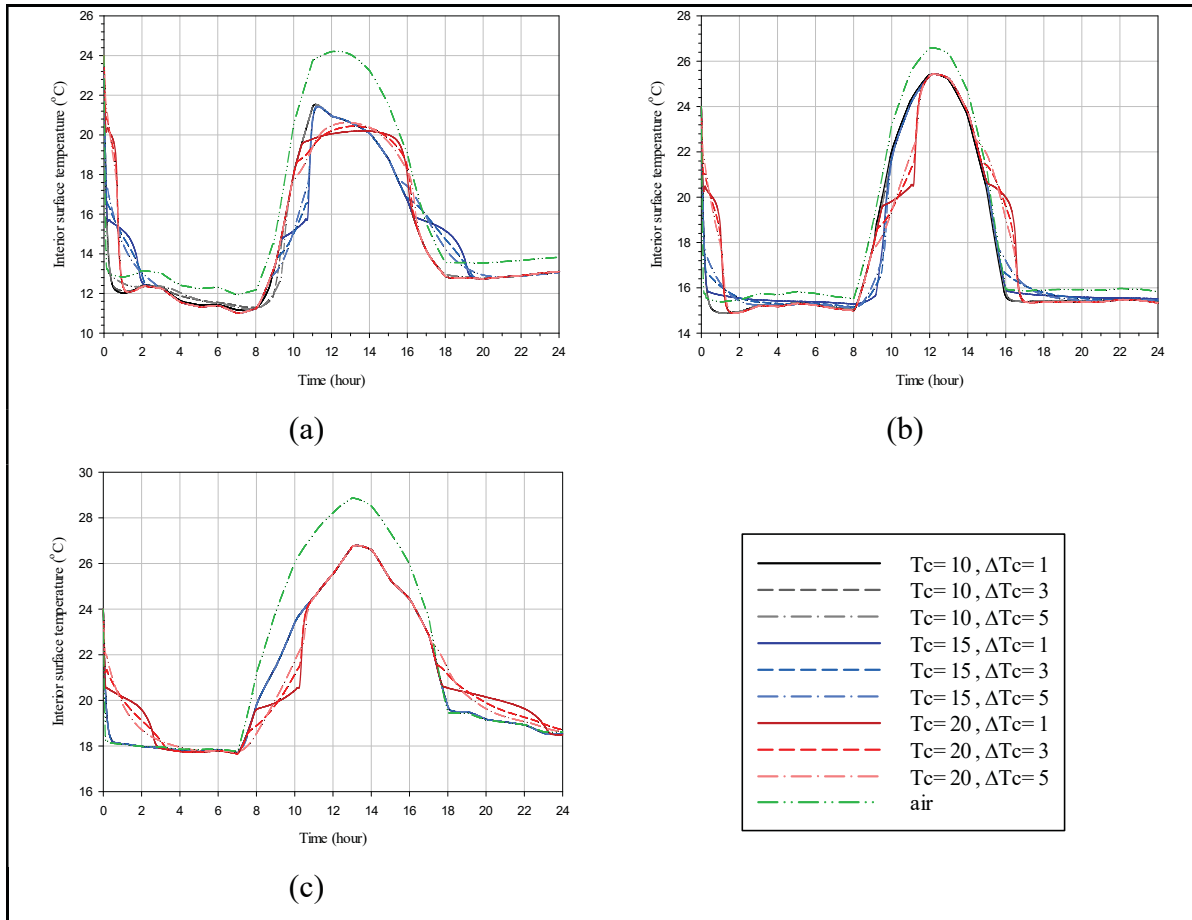


Figure 3.13 SSPCM's interior surface temperature variations in winter sunny conditions for (a) Montreal, (b) Vancouver, (c) and Miami

Figure 3.14 shows the interior surface temperature distribution for the studied cases in winter cloudy conditions for the three cities. In Montreal and Vancouver, Figures 3.14a and 3.14b, due to the lack of direct solar irradiation, the presence of SSPCM appears to worsen the interior surface temperature. This is because of the system's lower thermal resistance and the absence of thermal inertia utilization, which prevents effective heat retention and release. Without sufficient solar energy, the SSPCM cannot undergo a full phase change cycle, thereby diminishing its ability to regulate the interior temperature effectively. However, in Miami

Figure 3.14c, the situation is different. There has been enough ambient heat to cause the SSPCM to store heat during the day through a full phase change cycle. As the ambient temperature drops, the SSPCM releases the stored heat to the surroundings at the start of the evening and continues until midnight. This results in a higher interior surface temperature, contributing to improved thermal comfort during the cooler evening and night hours. The warmer winters in Miami provide a more conducive environment for the SSPCM to function optimally, highlighting the importance of ambient conditions for the effective performance of SSPCM in enhancing thermal comfort.

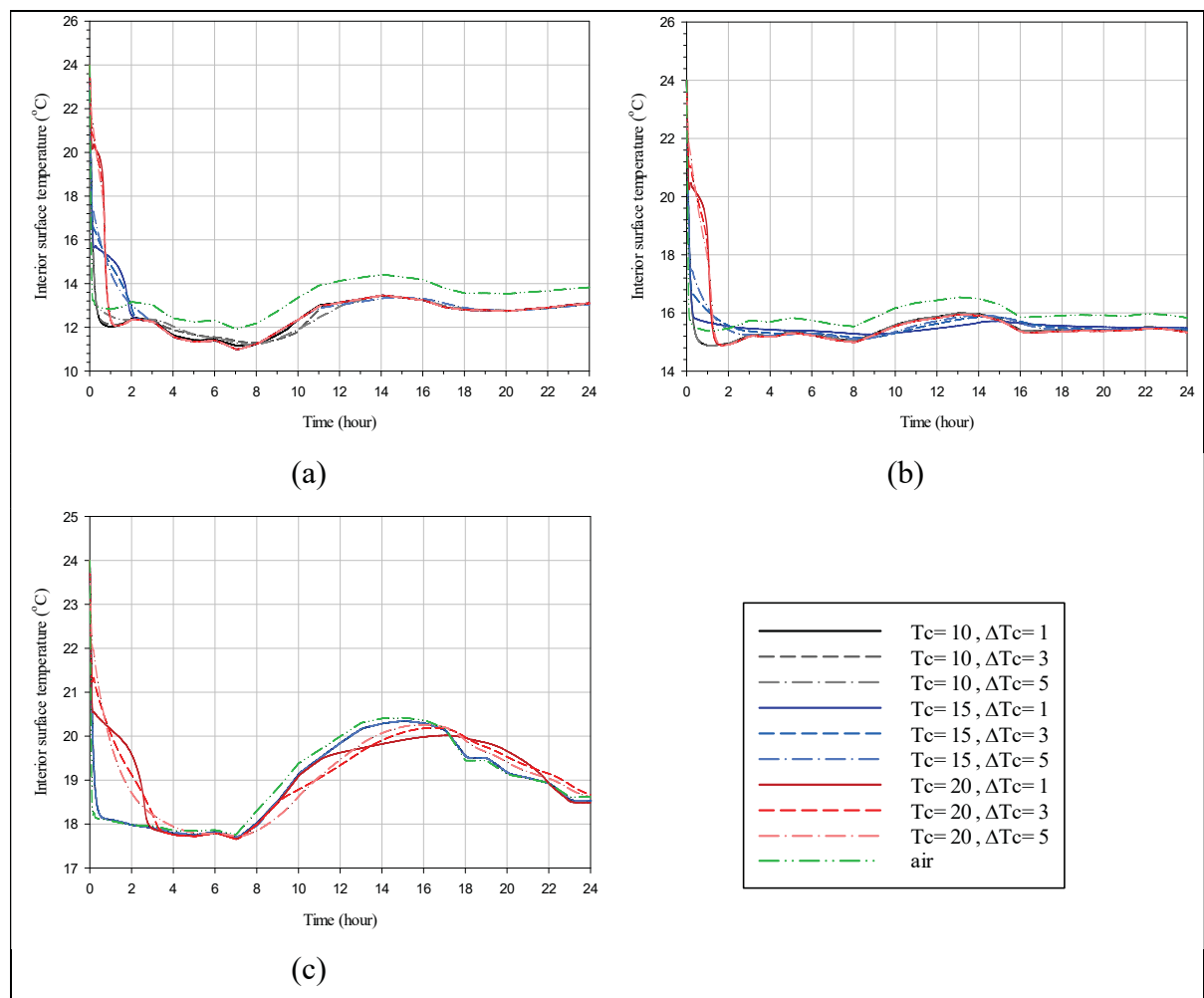


Figure 3.14 SSPCM's interior surface temperature variations in winter cloudy conditions for (a) Montreal, (b) Vancouver, (c) and Miami

### 3.4.3 *Energy performance*

To quantify the energy savings or losses of the DGW-SSPCM system compared to the DGW-REF case, we use Equation (3.18), which builds on Equation (3.17) where thermal energy is defined. In Equation (3.17),  $\overline{q''}$  represents the mean total heat flux on the interior surface of the inner pane of the DGW, as defined in Equation (3.16). This parameter can be either positive or negative, depending on the direction of the heat flux: positive for heat flux from inside to outside and negative for the opposite direction. Energy savings are achieved when the absolute negative value is lower (indicating less total heat flux entering the building) and when the positive value is lower (indicating less total heat flux escaping from the building).

$$E = \overline{q''} \times t \times A \quad (3.17)$$

$$\Delta E = E_{final} - E_{ref} \quad (3.18)$$

This section analyzes the thermal energy performance of the proposed glazing system under various sky conditions in three cities: Montreal, Vancouver, and Miami. Table 3.6 summarizes all the thermal energy values in all the cases outlined in Table 3.2.

Figure 3.15 displays the thermal energy in all studied scenarios, under summer sunny conditions in Montreal, Vancouver, and Miami. In addition, the thermal energy for all studied scenarios is listed in Table 3.6 for the three analyzed cities under sunny summer climatic conditions.

In Montreal, the DGW-SSPCM system achieved energy savings in all cases compared to the DGW-REF system, primarily due to the significant solar energy blockage by the SSPCM, which utilizes its latent thermal storage capacity. As mentioned earlier, negative values represent the total thermal energy entering the building, hence the smaller the absolute value, the greater the energy savings.

Table 3.6 Materials thermophysical properties

| Climatic condition | City      | Case 0 | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 | Case 7 | Case 8 | Case 9 |
|--------------------|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Summer sunny       | Montreal  | -99.7  | -89.3  | -89.3  | -89.3  | -93.7  | -92.5  | -90.2  | -82.3  | -82.3  | -82.3  |
|                    | Vancouver | -90.1  | -72.7  | -73.0  | -74.4  | -80.4  | -79.2  | -78.3  | -69.0  | -69.4  | -69.6  |
|                    | Miami     | -93.2  | -      | -      | -      | -      | -      | -      | -98.1  | -98.1  | -98.3  |
| Summer cloudy      | Montreal  | -11.2  | -56.2  | -56.2  | -56.2  | -59.6  | -58.5  | -56.6  | -50.9  | -50.9  | -50.9  |
|                    | Vancouver | 43.3   | 26.6   | 26.3   | 25.0   | 20.1   | 20.9   | 21.7   | 27.6   | 27.6   | 27.6   |
|                    | Miami     | -46.1  | -79.6  | -79.6  | -79.6  | -82.3  | -81.0  | -79.3  | -73.6  | -73.6  | -73.6  |
| Winter sunny       | Montreal  | 342.1  | 429.6  | 428.8  | 427.3  | 408.6  | 408.4  | 408.7  | 406.5  | 406.6  | 406.6  |
|                    | Vancouver | 228.8  | 252.7  | 252.7  | 252.7  | 247.5  | 244.9  | 244.3  | 235.9  | 235.9  | 235.9  |
|                    | Miami     | -22.9  | 48.9   | 48.9   | 48.9   | 48.9   | 48.9   | 48.8   | 38.5   | 38.8   | 39.9   |
| Winter cloudy      | Montreal  | 559.0  | 548.1  | 547.1  | 545.3  | 519.9  | 519.9  | 520.5  | 519.7  | 519.7  | 519.8  |
|                    | Vancouver | 408.2  | 378.2  | 378.2  | 378.2  | 370.9  | 368.2  | 367.7  | 357.6  | 357.6  | 357.6  |
|                    | Miami     | 209.6  | 166.8  | 166.8  | 166.8  | 166.8  | 166.8  | 166.7  | 154.7  | 155.2  | 156.6  |

The energy savings for cases 1 to 9 compared to DGW-REF system are 10.4, 10.4, 10.4, 6.0, 7.2, 9.5, 17.4, 17.4, and 17.4 kJ, respectively. The highest energy savings are observed in the cases 7, 8, and 9 ( $T_c = 30^\circ\text{C}$ ), due to the SSPCM remaining opaque throughout the entire day. However, considering the poor visual view of the glazing system in these cases, they are not suitable for fenestration systems. Considering both energy savings and visual clarity, cases 1 to 3 ( $T_c = 20^\circ\text{C}$ ) are optimal, as the SSPCM remains in the transparent phase throughout the entire day, providing both energy efficiency and a clear visual view. In cases 4, 5, and 6, the SSPCM undergoes a full phase transition. The lower energy savings of these cases compared to cases 1, 2, and 3, which remained transparent throughout the entire day, can be attributed to the latent thermal heat being released into the indoor environment at night by the SSPCM, due to the latent heat storage during the day. In Vancouver, a similar trend in the behavior of the SSPCM-DGW is observed across scenarios 1 to 9. All cases show energy savings for the DGW-SSPCM system compared to the DGW-REF system, with cases 7, 8, and 9 demonstrating the highest energy savings. The energy savings for cases 1 to 9 compared to DGW-REF system are 17.4, 17.2, 15.8, 9.7, 10.9, 11.9, 21.2, 20.7 and 20.5 kJ, respectively.

Comparing the energy savings in the two cities, the energy performance of the DGW-SSPCM system is more beneficial in Vancouver. In Miami, the trend is completely different from the other two cities, as all scenarios result in an energy loss for the DGW-SSPCM system compared to the DGW-REF system. This is due to the higher ambient temperatures under summer sunny conditions in Miami compared to Montreal and Vancouver. The energy loss for cases 1 to 9 compared to DGW-REF system are 12.2, 12.2, 12.2, 15.1, 14.0, 12.6, 5.0, 5.0, and 5.1 kJ, respectively. The lowest energy losses are observed in cases 7, 8, and 9, where the SSPCM remains transparent throughout the entire day.

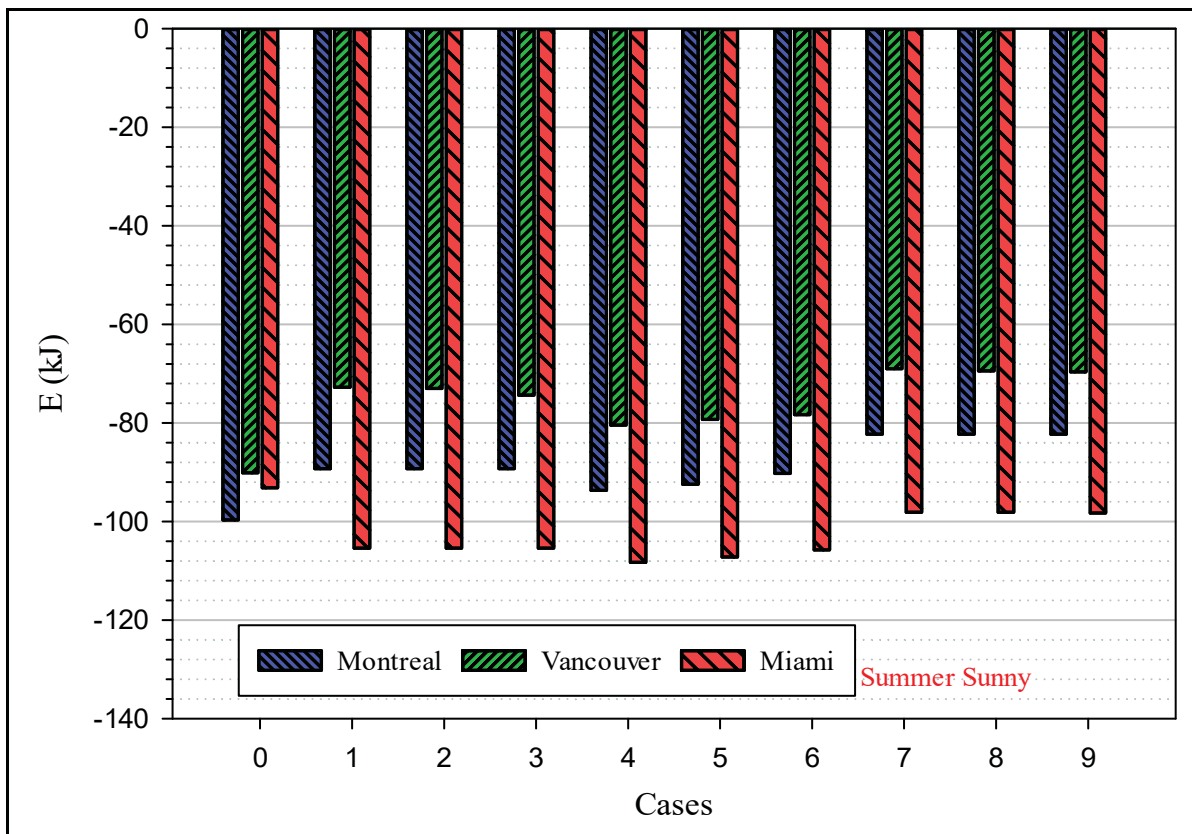


Figure 3.15 The thermal energy in all studied scenarios under summer sunny conditions in Montreal, Vancouver, and Miami

Figure 3.16 illustrates the thermal energy in all studied cases, under summer cloudy conditions in the three studied cities. In Miami and Montreal, the DGW-SSPCM system show energy losses in all cases, due to hot ambient temperatures in summer cloudy conditions and the absent of direct solar irradiation. In Montreal, the energy loss for cases 1 to 9 compared to DGW-REF



system are 45.1, 45.1, 45.1, 48.4, 47.4, 45.4, 39.7, 39.7, 39.7, and 39.7 kJ, respectively. In Miami, the energy loss for cases 1 to 9 compared to DGW-REF system are 33.6, 33.6, 33.6, 36.3, 35.0, 33.3, 27.5, 27.5, and 27.5 kJ, respectively. For both cities, the lowest energy losses are attributed to the cases 7, 8, and 9 ( $T_c = 30^\circ\text{C}$ ), where the SSPCM remains transparent throughout the entire day. The system's behavior in Vancouver differs due to lower ambient temperatures during summer cloudy conditions compared to the other two cities. In Vancouver, the thermal energy values are positive, with lower values indicating energy savings by preventing the escape of air-conditioned air from the building. In Vancouver, the energy savings for cases 1 to 9 compared to DGW-REF system are 16.7, 16.9, 18.3, 23.2, 22.4, 21.6, 15.7, 15.7, and 15.7 kJ, respectively. The highest energy savings attributed to the cases 4, 5, and 6 in which the SSPCM undergoes a partial phase transition during the day. In addition, although among the three cases, case 4 with the lowest  $\Delta T_c$  results in higher energy savings, the difference is not significant. It can be inferred that the impact of the SSPCM's  $T_c$  on the energy savings of the glazing system is more significant than the effect of its  $\Delta T_c$ .

According to Figures 3.15 and 3.16, in Vancouver, energy savings are obtained using the DGW-SSPCM system on both sunny and cloudy days. Hence, using this glazing system would enhance thermal energy performance in Vancouver during summer, while maintaining visual clarity. In Montreal, energy savings are achieved on sunny days, while energy losses occur on cloudy days. Comparing the amounts of energy saved and lost for the case with the highest energy saving, it is evident that the energy lost on a cloudy day is more (almost 2.3 times) than the energy saved on a sunny day. In Miami, using the proposed DGW-SSPCM system results in energy losses during summer on both cloudy and sunny days. Therefore, having a 2 mm SSPCM attached to the inner pane of a DGW in Miami would not be beneficial in terms of energy savings.

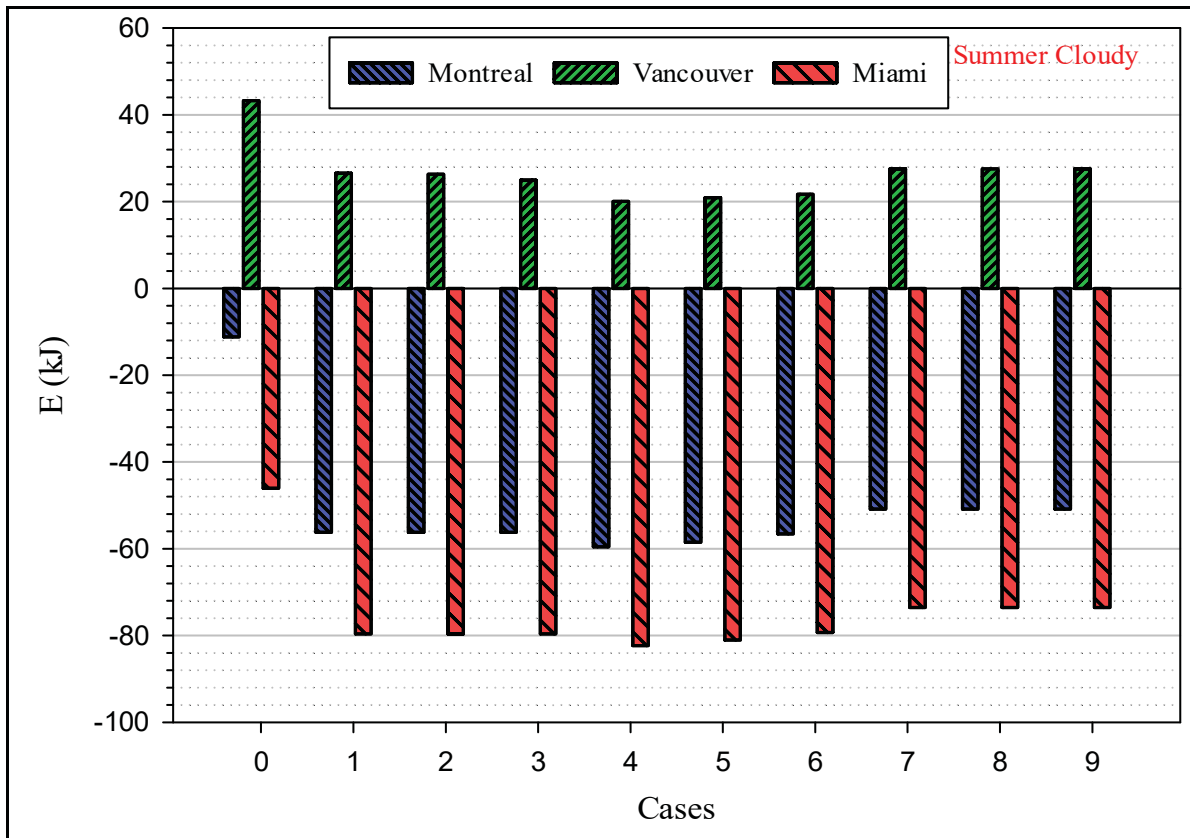


Figure 3.16 The thermal energy in all studied scenarios under summer sunny conditions in Montreal, Vancouver, and Miami

Figure 3.17 shows the thermal energy for all the cases studied under winter sunny conditions in the three cities analyzed. This figure indicates an energy loss in all cases under these conditions. The energy loss for cases 1 to 9 compared to the DGW-REF system are 87.4, 86.6, 85.2, 66.5, 66.3, 66.5, 64.4, 64.4, and 64.5 kJ for Montreal; 23.9, 23.9, 23.9, 18.7, 16.1, 15.5, 7.2, 7.1, and 7.1 kJ for Vancouver; and 71.8, 71.8, 71.8, 71.8, 71.8, 71.8, 61.4, 61.7, and 62.9 kJ for Miami. The energy losses across all cities under winter sunny conditions suggest that the blockage of direct solar irradiation during the day by the SSPCM has been greater than the heat released into the indoor environment at night, resulting in a net energy loss. The lowest energy loss is observed in cases 7, 8, and 9 ( $T_c = 20^\circ\text{C}$ ), where the SSPCM undergoes a phase transition, releasing the heat stored during the day into the indoor environment at night, and also stays transparent for a longer period during the day. Furthermore, it is observable that although the effect of  $\Delta T_c$  on the glazing energy performance is not significant, higher values

result in less energy loss due to the SSPCM's longer charging and discharging times. It is also evident that energy losses in Vancouver are less than in the other two cities. The winter ambient temperature in Vancouver remains between those of the other two cities. This highlights the fact that designing an appropriate glazing system incorporating thermal energy storage materials needs to be considered case by case, due to the substantial number of dependent parameters affecting the energy performance and visual aspects of the fenestration system.

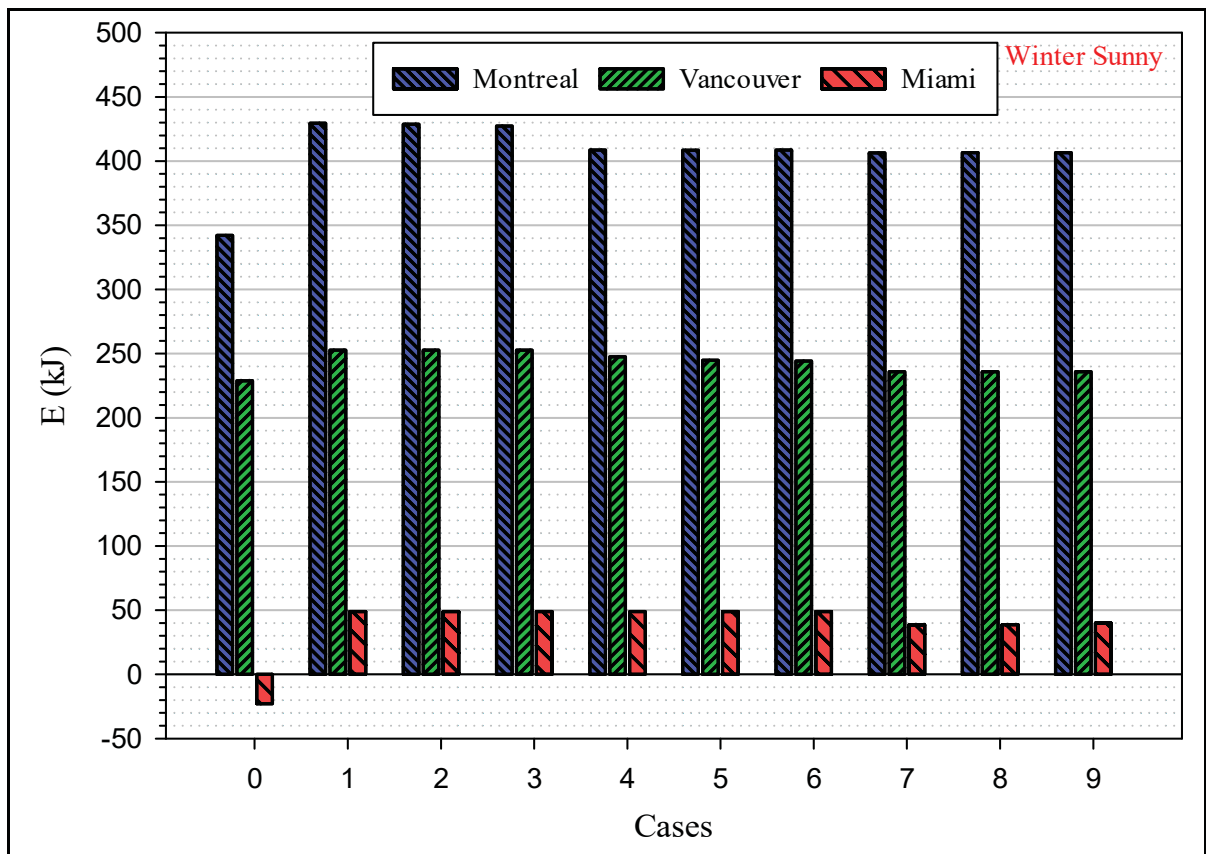


Figure 3.17 The thermal energy in all studied scenarios under summer sunny conditions in Montreal, Vancouver, and Miami

Under winter cloudy conditions, the behavior of the fenestration system differs, resulting in energy savings in all three cities, as shown in Figure 3.18. In the absence of direct solar irradiation, the SSPCM not only releases the stored heat during the day into the indoor environment at night but also it acts as an insulator, retaining the warmed air within the building. The energy savings for cases 1 to 9 compared to the DGW-REF system are as

follows: 10.9, 11.9, 13.7, 39.0, 39.1, 38.5, 39.3, 39.3, and 39.2 kJ for Montreal; 30.0, 30.0, 30.0, 37.2, 39.9, 40.4, 50.6, 50.6, and 50.5 kJ for Vancouver; and 42.8, 42.8, 42.8, 42.8, 42.8, 42.8, 54.9, 54.4, and 53.0 kJ for Miami. It is visible that the cases 7, 8, and 9 ( $T_c = 20^\circ\text{C}$ ) yields the highest energy savings due to the phase transition of the SSPCM through the day. The highest energy savings are attributed to Miami, followed by Vancouver, and then Montreal. days. Comparing the amounts of energy saved and lost for the case with the highest energy saving, it is evident that in Montreal and Miami, the energy lost on a sunny day is almost 1.7 and 1.2 times, respectively, greater than the energy saved on a cloudy day. In contrast, in Vancouver, the energy saved on a cloudy day is almost 7.1 times greater than the energy lost on a sunny day. Consequently, the use of the proposed DGW-SSPCM in winter is undoubtedly beneficial in Vancouver in terms of energy savings.

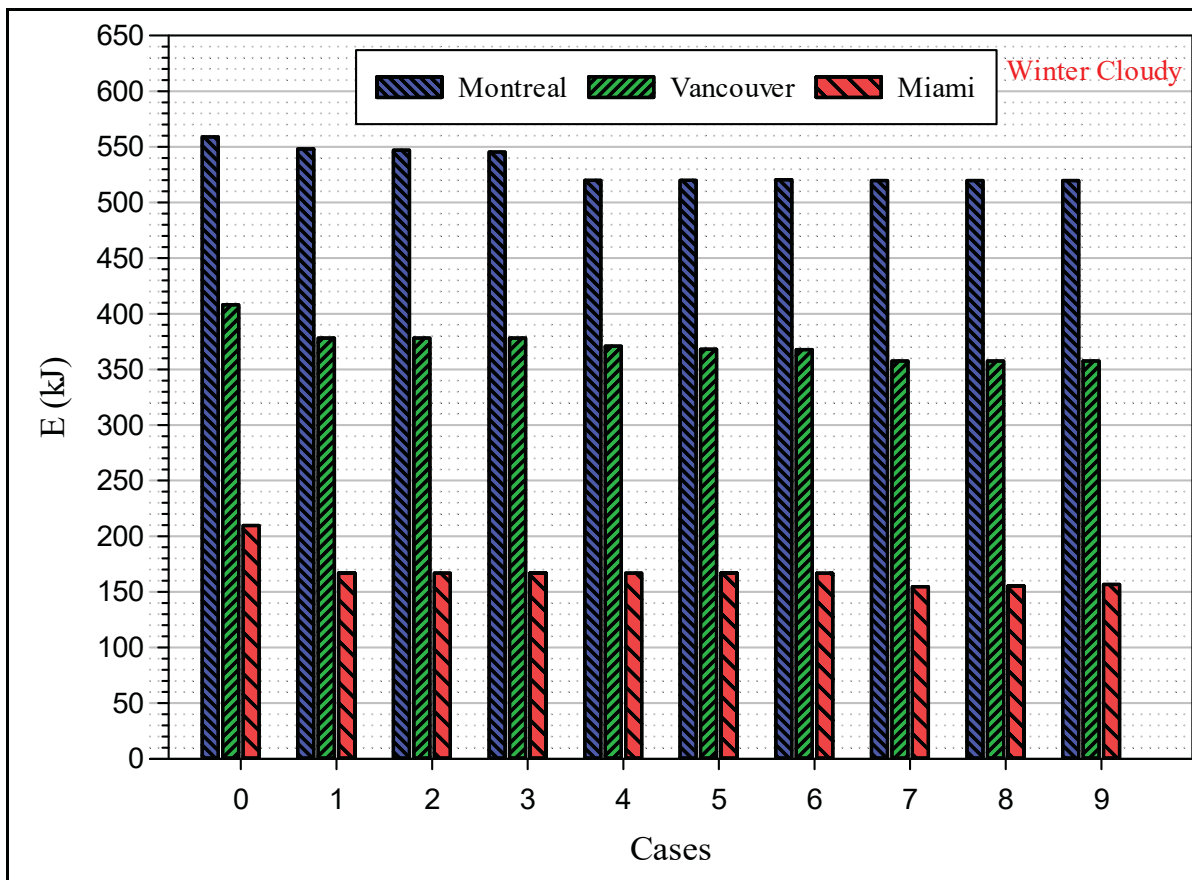


Figure 3.18 The thermal energy in all studied scenarios under summer sunny conditions in Montreal, Vancouver, and Miami

### 3.5 Conclusion

This study focuses on evaluating the energy efficiency of a double-glazing system that integrates a solid-solid phase change material (SSPCM) with limited thickness, applied to the inner glass pane within the air gap. The SSPCM is preferred due to its superior properties compared to traditional liquid-solid phase change materials in glazing applications. Numerical simulations were conducted using a model developed with the finite volume method in ANSYS FLUENT. The accuracy of this model was confirmed by comparing its predictions with experimental data, which showed a high level of agreement. The model was then used to explore various transient temperature values and ranges within the proposed glazing system to determine its energy performance under both the coldest and hottest days of the year, as well as during cloudy and sunny days in Montreal (Dfb), Vancouver (Cfb), and Miami (Aw). A 2 mm thickness of SSPCM was utilized, with transient temperature values between 15 °C and 30 °C and transient temperature ranges between 1 °C and 5 °C. The findings reveal significant differences in energy savings across the three cities, emphasizing the importance of localized climate conditions in assessing the efficacy of energy-saving technologies. The obtained results are as follows:

- In Montreal under summer sunny conditions, the DGW-SSPCM system demonstrates consistent energy savings compared to the DGW-REF system. The most notable savings are achieved in cases where the SSPCM remains opaque throughout the day with  $T_c = 20$  °C, although these configurations compromise visual clarity. Optimal results are observed in cases where the SSPCM remains transparent, balancing energy efficiency and visual clarity. However, under summer cloudy conditions, the system results in energy losses, with the energy lost on cloudy days being approximately 2.3 times greater than the energy saved on sunny days. The effect of transient temperature ranges of 1, 2, and 3 °C on thermal energy is subtle across all scenarios but becomes more pronounced when the SSPCM undergoes a phase transition at  $T_c = 25$  °C.
- Vancouver shows a similar trend with energy savings in all scenarios under summer sunny conditions. Under these climatic conditions, the highest thermal energy savings for the DGW-SSPCM system are observed at  $T_c = 30$  °C, averaging 20.5 kJ (23%) for

the three transient temperature ranges of 1, 2, and 3 °C in relation to the DGW-REF system. The energy performance is particularly enhanced under both sunny and cloudy days, making the DGW-SSPCM system highly beneficial for summer use while maintaining visual clarity. Under winter conditions, Vancouver benefits the most from the DGW-SSPCM system, with the energy saved on cloudy days (50.6 kJ) being almost 7.1 times greater than the energy lost on sunny days (7.1 kJ), highlighting the system's suitability for this city's moderate climate.

- In Miami, the DGW-SSPCM system results in energy losses by 60% and 5% (at  $T_c = 30$  °C) under both summer sunny and cloudy conditions, respectively, due to the high ambient temperatures. The energy losses observed indicate that the DGW-SSPCM system is not suitable for Miami's climate during the summer.
- During winter sunny conditions, all three cities experience energy losses with the DGW-SSPCM system, as the blockage of direct solar irradiation by the SSPCM surpasses the heat released into the indoor environment at night. The lowest energy losses are observed in cases where the SSPCM undergoes a phase transition and remains transparent for a longer period during the day. Notably, Vancouver exhibits the lowest energy loss among the three cities of 7.1 kJ (3%), which can be attributed to its moderate winter temperatures, while Montreal shows the highest energy loss of 64.4 kJ (19%) at  $T_c = 30$  °C.
- Under winter cloudy conditions, the DGW-SSPCM system yields energy savings in all three cities by acting as an insulator and releasing stored heat at night. The highest energy savings are observed in Miami (54.5 kJ, 26%), followed by Vancouver (50.6 kJ, 12%), and Montreal (39.3 kJ, 7%). In Montreal and Miami, the energy lost on a sunny day is significantly higher than the energy saved on a cloudy day, while in Vancouver, the energy saved on a cloudy day far exceeds the energy lost on a sunny day.
- In all cases, the transient temperature of the SSPCM has a more pronounced impact on the energy savings of the glazing system than the transient temperature range.

Lastly, the DGW-SSPCM system proves to be beneficial in Vancouver across various conditions in terms of energy performance. For Montreal and Miami, the system's effectiveness

is limited due to the respective weather conditions that lead to higher energy losses. These results underscore the necessity of considering localized climate factors when designing and implementing energy-efficient glazing systems. Considering the significant importance of providing a proper visual view, the DGW-SSPCM system offers complete visual clarity during office hours when undergoing a full phase transition, making it more suitable for commercial buildings.

For future research directions, several tasks could be considered. First, conducting experimental studies to validate the use of SSPCMs in glazing systems is crucial, particularly due to the current lack of experimental data in this domain. Additionally, simulating the system over consecutive days would provide a more comprehensive understanding of its long-term energy performance. Expanding the simulations to encompass various days throughout the year, coupled with the use of machine learning and optimization methods, could further refine the predictive modeling of the system's energy performance and optical properties across different climates and time periods. Furthermore, integrating ANSYS Fluent with EnergyPlus could enhance the accuracy of the simulations while reducing computational costs, enabling a more efficient evaluation of the system over extended periods. Last but not the least, conducting experimental studies to obtain more precise thermophysical and optical properties of SSPCMs would lead to more accurate modeling and optimization of these materials in building envelope applications, ultimately contributing to the development of more energy-efficient glazing systems.





## CHAPTER 4

### ENHANCING ENERGY PERFORMANCE OF GLAZING SYSTEMS USING SOLID-SOLID PHASE CHANGE MATERIALS

Hossein Arasteh <sup>a</sup>, Wahid Maref <sup>a</sup>, Hamed H. Saber <sup>b</sup>

<sup>a</sup> Department of Construction Engineering, École de technologie supérieure,  
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C1K3

<sup>b</sup> Deanship of Research and Industrial Development, and Mechanical Engineering  
Department at Jubail Industrial College, Royal Commission of Jubail and Yanbu, Jubail  
Industrial City, 31961, Saudi Arabia

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#### Abstract

In recent years, the implementation of decarbonization measures in response to global warming has brought significant attention to the building sector, recognizing it as a major contributor to CO<sub>2</sub> emissions. This study explores the unique combination of solid-solid phase change material (SSPCM) in double-glazed window (DGW) subjected to different climates, offering a novel approach to enhancing energy efficiency of glazing system, thus Building envelope. To assess the system's energy performance, numerical simulations were performed across a range of temperature conditions. These have included extreme temperatures of the hottest and coldest days of the year, as well as different weather patterns such as sunny and cloudy days in the cities of Montreal, Vancouver, and Miami. The obtained results demonstrated that during summer sunny conditions, energy savings were achieved in both Montreal (17.5%) and Vancouver (23.5%), while Miami experienced energy losses (5.3%). On summer cloudy days, energy savings were observed exclusively in Vancouver (53.6%), whereas energy losses occurred in both Montreal (356%) and Miami (36.3%). Under winter sunny conditions, all cities showed energy losses due to the SSPCM blocking beneficial direct solar radiation during the daytime (Montreal: 18.8%, Vancouver: 3.1%, and Miami: 270%). Conversely, during

winter cloudy conditions, energy savings were noted in all cities, as the SSPCM helped retain warm indoor air (Montreal: 7.0%, Vancouver: 12.4%, and Miami: 26.2%). The results revealed that complete visual transparency can be achieved during office hours, enhancing the suitability of the proposed glazing system for commercial applications. These findings can help in designing energy-efficient glazing systems subjected to various climatic conditions.

**Keywords:** Computational Fluid Dynamics; Carbon-free Buildings; Phase Change Materials; Fenestration Systems; Building Envelope.

#### 4.1 Introduction

Over the past years, across both industrialized and developing countries, energy policies in the construction industry have become stringent, with a focus on minimizing energy usage and cutting down carbon dioxide emissions (Zhang et al., 2020). With the rapid pace of urbanization, energy consumption in the construction industry has seen a significant increase over the past decade. While this ongoing expansion is crucial for a country's economic growth and technological progress, it inevitably transforms into a social and environmental challenge, resulting in long-term societal issues (Chen et al., 2019). Despite the limited availability of fossil fuels, global power consumption is projected to rise sharply in the near future. To address the current energy demands, a substantial boost in installed capacity will be essential, and achieving this will require several decades (Loulou and Labriet, 2008). Given these circumstances, governments are increasingly compelled to embrace renewable energy sources and innovative green technologies. This shift is crucial for achieving sustainable growth in all developing sectors (Dodd et al., 2018).

Given that the majority of people spend around 90% of their working time inside and rely extensively on mechanical heating and air conditioning, buildings have emerged as the leading consumers of energy worldwide (Zhao and Magoulès, 2012). Building envelopes serve as the critical interface between indoor and outdoor environments, playing a significant role in mediating the conflicts between occupant comfort and the environmental impact of buildings. Adaptive facades, an advanced component of building envelopes, possess the ability to selectively transmit, filter, or block various phenomena such as heat, mass, and light. This

capability enables them to regulate environmental conditions effectively, thereby enhancing indoor environmental quality (Liang and Xiang, 2024). Additionally, adaptive facades offer a promising approach to reducing the energy consumption of buildings. By optimizing the interaction between the interior and exterior environments, adaptive facades contribute to improved indoor comfort and energy efficiency, ultimately supporting the development of more sustainable building practices. Among the opaque and transparent components of building envelopes, the latter is among the building components with the lowest energy efficiency, primarily due to their poor thermal inertia and limited ability to withstand temperature changes. These systems are responsible for approximately 60% of the overall heat loss, significantly impacting the thermal efficiency of buildings (Badeche, 2022). Moreover, windows allow the majority of solar radiation to pass through, and their use has become increasingly popular among builders and construction firms in recent decades. The widespread adoption of translucent facades in different types of buildings has frequently led to a trade-off between energy efficiency and interior comfort. Problems such as summer overheating, winter energy loss, thermal discomfort, and tenant complaints about glare are common in heavily glazed structures using traditional envelope methods. As a result, there is now considerable research and development aimed at enhancing glazing systems (Truong et al., 2020).

Enhancing the thermal performance of glazing systems in buildings can be achieved through three main strategies namely: (a) improving thermal resistance (Lian et al., 2024; Sun et al., 2024; Xu et al., 2025), (b) implementing solar control (Nur-E-Alam et al., 2024; Wu et al., 2024; Yadav and Hachem-Vermette, 2024), and (c) increasing thermal inertia (Berville et al., 2024; Dellagi et al., 2024; Wagiri et al., 2024; Wang et al., 2023). The thermal transmittance, which is the reciprocal of thermal resistance of an air-filled space such as enclosed airspaces in building components (glazing systems in this study), highly depends on several parameters. Due to the heat transfer by natural convection inside the enclosed-airspaces, these parameters include the enclosed-airspace: (a) inclination angle, (b) average temperature, (c) temperature difference, (d) dimensions, and (e) heat-flow directions. For inclined enclosed-airspace, the latter includes heat-flow up to represent the case in which heat leaves the building (cold days), and heat-flow down to represent the case of heat enters the building (hot days). For vertical enclosed-airspace, however, the heat-flow direction is horizontal in which the heat enters

building (hot days) or leaves the building (cold days). Several studies were conducted to investigate the effects of these parameters on the thermal resistances of enclosed-airspaces (e.g., see (Saber et al., 2024)). As an example, for inclined building component having air-filled space at the same values of the parameters (a) through (d), the heat-flow up through the enclosed-airspace results in a higher thermal transmittance in relation to that for heat-flow down. The present study focuses on vertical multi-glazing windows in which the heat flow is horizontal.

In addition, the thermal performance and transmittance of glazing systems can differ based on their orientation and configuration (Tükel et al., 2019). The focus of this study, however, is on improving thermal inertia. This can be accomplished by incorporating thermal energy storage materials, such as phase change materials (PCMs), into the fenestration system. Our recent research has thoroughly reviewed the application of phase change materials (PCMs) in glazing systems, demonstrating their potential to enhance thermal performance, though achieving clear visual quality remains a challenge (Arasteh et al., 2023). PCMs manage heat by absorbing and releasing it through phase change cycles, which can either involve a transition from solid to liquid (solid-liquid phase change materials, SLPCMs) or from one solid state to another (solid-solid phase change materials, SSPCMs).

This study focuses on the use of SSPCMs in glazing systems due to their numerous advantages over SLPCMs. SSPCMs exhibit minimal subcooling, reduced material degradation, consistent optical properties, no need for encapsulation, no leakage, less phase segregation, small volume changes, and high thermal stability (Fallahi et al., 2017). Unlike SLPCMs, SSPCMs can be directly applied to a surface or pane of a multi-glazed window, maintaining their solid state throughout the phase transition. This allows the air or inert gas, which has low thermal conductivity, to remain between the indoor and outdoor environments. In contrast, SLPCMs, when filling the air gap, reduce the thermal resistance of the glazing system due to their higher thermal conductivity compared to air. Encapsulation of SLPCMs can mitigate this issue, enabling them to perform similarly to SSPCMs by maintaining a solid phase and preserving thermal resistance. SSPCMs transition between opaque (semi-crystalline) and transparent (amorphous) states, where only the soft segments melt, supported by the hard segments with a

significantly higher melting temperature. This ensures that SSPCMs remain solid during phase transitions, with the soft segments melting and freezing while anchored by the hard segments. The phase transition process of SSPCMs has been thoroughly discussed and analyzed in previous studies (Gao et al., 2021).

While there is a wealth of literature on SLPCM applications in glazing units, research on SSPCMs in smart glazing is relatively scarce. Raj et al. (2020) reviewed the applications and recent advancements in the thermophysical properties of SSPCMs, compiling a detailed list of organic, polymeric, organometallic, and commercial SSPCMs, along with their thermophysical properties, phase transition temperatures, melting points, molecular characteristics, and thermal behavior. These reviews are invaluable for researchers and practitioners interested in SSPCM applications. Another review (Fallahi et al., 2017) delved into the molecular properties and thermal characteristics of SSPCMs for thermal energy storage, examining the relationship between molecular structure, phase transition mechanisms, and thermal properties across four main categories: polymeric, organic, organometallic, and inorganic. The authors provided guidance on selecting appropriate SSPCMs for various applications based on desired physical, thermal, and mechanical properties. Gao et al. (2021) integrated a thin SSPCM layer into the interior side of a double-glazing window (DGW) and conducted a numerical analysis to evaluate annual energy savings. Due to limitations in EnergyPlus software for simulating latent energy storage materials, the authors developed an equivalent model. The results indicated that a 3 mm SSPCM layer improved energy savings in warm, mixed, and cold climates, outperforming low-emissivity windows. Wang et al. (2023) developed an inverse model to derive expressions for the extinction coefficient and refractive index of SSPCMs as a function of temperature for the translucent phase, providing constant values for the opaque and transparent phases. These optical properties were incorporated into the current study. Zhang et al. (2024) conducted a two-dimensional numerical parametric study using the finite volume method to investigate the optical and thermal properties of a triple-glazed window containing SSPCM in the inner air gap and silica aerogel in the outer air gap. The study simulated 24 hours of severe cold weather in a Chinese city. Sensitivity analysis indicated that the thermal efficiency of the glazing system was significantly influenced by the melting temperature and latent heat of the PCM, with the absorption coefficient and refractive

index having minor effects. The optimal melting temperature of the PCM was found to be 18°C, resulting in a 15.4% energy saving rate. Guldentops et al. (2018) investigated a building enclosure system using SSPCMs to passively regulate temperature in a south-facing building in central Massachusetts, considering both summer and winter climates. They developed a finite element model to analyze the system's energy performance and identified optimized configurations for each season. However, the study highlighted the need to refine the extinction coefficients and transition temperatures of SSPCMs for effective year-round operation. Ma et al. (2022) assessed a glazing system combining silica aerogel and SSPCM in a severe cold region of China, focusing on both daylighting and energy performance. They used EnergyPlus for energy analysis and Radiance software for daylighting analysis. An equivalent SSPCM model was employed due to software limitations. The study identified transition temperature, latent heat, absorption coefficient, and refractive index as key parameters through sensitivity analysis. A 10 mm thickness of silica aerogel was recommended to maximize energy savings while meeting daylighting standards in China, suggesting the viability of DGW-SSPCM in severe cold regions.

The literature review reveals a lack of studies on the energy performance of SSPCMs in glazing systems using 3D modeling. Existing numerical models often rely on EnergyPlus, which struggles to accurately simulate SSPCM phase transitions, leading to the use of equivalent models. Alternatively, 2D models have been used to evaluate SSPCM behavior when fully occupying the air gap of triple-glazed windows. To address this gap, this study aims to develop a 3D model to assess the energy performance of a double-glazed window (DGW) incorporating SSPCMs. The concept involves placing the SSPCM on the interior pane within the air gap to maintain a high material temperature, ensuring near-complete transparency throughout the year. After validating the model, a parametric study was conducted by varying the transient temperature and temperature range of a south-facing DGW-SSPCM over a 24-hour period. Simulations were carried out for both sunny and cloudy conditions on the coldest and hottest days of 2022 in Montreal, Vancouver, and Miami.

## 4.2 Research design

### 4.2.1 Geometric specifications

This study compares the performance of a double-glazing window with an integrated solid-solid phase change material (DGW-SSPCM) to that of a reference double-glazing window (DGW-REF). The SSPCM is applied to the interior pane within the air gap. Both configurations consist of two panes, each measuring 20 cm by 20 cm with a thickness of 4 mm. The DGW-REF has a 1.6 cm air gap, while the DGW-SSPCM features a 2 mm-thick SSPCM layer on the interior pane, reducing the air gap to 1.4 cm.

### 4.2.2 Thermophysical and optical properties

In this study, the glazing system consists of two clear glass panes, each 4 mm thick, with an emissivity of 0.9 (ASHRAE, 2021). The thermophysical and optical properties of the glass were obtained from (Gowreesunker et al., 2013). The thermal energy storage material (SSPCM) was chosen from (*PCM Products*, 2024), and its thermophysical properties were derived from this reference. The optical properties of the SSPCM including refractive index as well as absorption and scattering coefficients were derived from correlations developed by (Wang et al., 2023). Table 4.1 provides a detailed overview of the thermophysical properties of the materials used in this study. In this study various phase transition temperatures ( $T_c$ ) and phase transition temperature ranges ( $\Delta T_c$ ) are examined. The studied parameters are  $T_c = 20^\circ\text{C}$ ,  $25^\circ\text{C}$ ,  $30^\circ\text{C}$  and  $\Delta T_c = 1^\circ\text{C}$ ,  $3^\circ\text{C}$ ,  $5^\circ\text{C}$  in summer and  $T_c = 10^\circ\text{C}$ ,  $15^\circ\text{C}$ ,  $20^\circ\text{C}$  and  $\Delta T_c = 1^\circ\text{C}$ ,  $3^\circ\text{C}$ ,  $5^\circ\text{C}$  in winter for the SSPCM comparing to the DGW-SSPCM case.

It is important to point out that both  $T_c$  and  $\Delta T_c$  are key characteristics of SSPCMs. In this study, different  $T_c$  and  $\Delta T_c$  values are used to explore how the system behaves under various conditions—whether the SSPCM remains in a transparent phase, remains in an opaque phase, or goes through a full phase change cycle during the day. This approach allows for a comprehensive evaluation of the performance of the system under multiple scenarios. Although different  $T_c$  values are used for summer and winter simulations, this does not necessarily imply that multiple SSPCMs would be required for practical applications. A well-

chosen SSPCM with an appropriate  $\Delta T_c$  can potentially accommodate both seasonal variations by managing its phase transition within a suitable temperature range. However, careful selection of an SSPCM with an optimized phase transition temperature for specific climates is essential.

The extinction coefficient is defined as the sum of absorption and scattering coefficients (Jin et al., 2022):

$$\sigma_\varepsilon = \sigma_a + \sigma_s \quad (4.1)$$

The extinction coefficient of a substance, often described by its optical thickness ( $d$ ) as per Equation (4.2), is a standard measure. In this context,  $s$  denotes the actual thickness of the sample, which is 2 mm for the DGW-SSPCM configurations used in this research (*ANSYS FLUENT*, 2021).

Table 4.1 Thermophysical properties of the materials utilized in this study

| Property                                  | Air*    | Glass | SSPCM               |
|-------------------------------------------|---------|-------|---------------------|
| Density (kg/m <sup>3</sup> )              | 1.225   | 2500  | 1055                |
| Specific heat (J/kgK)                     | 1006.43 | 840   | 1630                |
| Thermal conductivity (W/mK)               | 0.0242  | 1.3   | 0.36                |
| Absorption coefficient (1/m)              | 0       | 19    | 25.73 (Transparent) |
|                                           |         |       | 33.80 (Opaque)      |
| Scattering coefficient (1/m)              | 0       | 0     | 0 (Transparent)     |
|                                           |         |       | 119.02 (Opaque)     |
| Refractive index                          | 1       | 1.5   | 1.11 (Transparent)  |
|                                           |         |       | 5.33 (Opaque)       |
| Latent heat (kJ/kg)                       | -       | -     | 110                 |
| *Properties at temperature range 10~30 °C |         |       |                     |

$$d = (\sigma_a + \sigma_s)s \quad (4.2)$$



In this study, an isotropic scattering coefficient is assumed. By utilizing Beer-Lambert's law for non-gaseous materials, Equation (4.3) allows for the calculation of PCM transmittance (Guldentops et al., 2018):

$$\tau_{PCM} = 10^{-d} \quad (4.3)$$

Initially, the absorption coefficient is determined using Equation (4.4) (Gowreesunker et al., 2013). This coefficient is subsequently used in Equation (4.1) to calculate the scattering coefficient.

$$\sigma_a = \sigma_s \left[ \frac{\tau_{PCM,tr} - \tau_{PCM,op}}{1 - \tau_{PCM,op}} \beta + \frac{1 - \tau_{PCM,tr}}{1 - \tau_{PCM,op}} \right] \quad (4.4)$$

For the SSPCM, the refractive index and extinction coefficient are as follows: in the transparent phase, they are 1.11 and  $25.73 \text{ m}^{-1}$ , respectively, and in the opaque phase, they are 5.33 and  $152.82 \text{ m}^{-1}$ , respectively (Wang et al., 2023). For the translucent phase, Equations (4.5) and (4.6) are used to calculate the average optical properties based on the transparency fraction, which replaces the term 'liquid fraction' since SSPCM has no liquid phase. The transparency fraction indicates the proportion of the material in the transparent phase, with  $\beta$  being 0 for fully opaque SSPCM and 1 for fully transparent SSPCM. A transparency fraction of 0 means the SSPCM temperature is at or below the lower limit of the transient temperature range, known as the opaqueus temperature (like the liquidus temperature in SLPCM), indicating the material is in the opaque phase. Conversely, a transparency fraction of 1 means the SSPCM temperature is at or above the upper limit of the transient temperature range, known as the transparentus temperature (like the solidus temperature in SLPCM), indicating the material is in the transparent phase. A transparency fraction between 0 and 1 signifies that the SSPCM is in the translucent phase, akin to the mushy zone in SLPCMs.

$$\sigma_{a,cell} = 33.8\beta + 25.73(1 - \beta) \quad (4.5)$$

$$\sigma_{s,cell} = 119.02(1 - \beta) \quad (4.6)$$

where,  $\sigma_{a,cell}$  and  $\sigma_{s,cell}$  represent the absorption and scattering coefficients within a cell of the numerical domain, respectively.

#### 4.2.3 Governing equations

To model the SSPCM, the enthalpy-porosity approach in ANSYS FLUENT was used, with a very high viscosity assigned to ensure the material remained nearly stationary. This study focused on evaluating the feasibility and effectiveness of incorporating SSPCM into glazing systems by neglecting natural convection effects within the air gap of the DGW for all configurations (i.e., DGW-SSPCM and DGW-REF). Using the climates of three cities with different conditions (i.e., Montreal, Vancouver, and Miami) as case studies under natural conditions, the approach aimed to determine if energy savings could be realized in a glazing system with SSPCM compared to one without it. The governing equations for this study included the Discrete Ordinates (DO) model for radiation and a solidification/melting model for SSPCM (ANSYS FLUENT, 2021).

The energy equation is as follows:

$$\frac{\partial}{\partial t}(\rho H) = \nabla \cdot (k \nabla T) + S_h \quad (4.7)$$

According to Equation (4.7), the enthalpy of the PCM,  $H$ , is determined by adding the sensible enthalpy,  $h_s$ , and the latent heat,  $\Delta H$ , as follows:

$$H = h_s + \Delta H \quad (4.8)$$

where,

$$h_s = h_{s,ref} + \int_{T_{ref}}^T c_p dT \quad (4.9)$$

In Equation (4.8), the fractional latent heat of the PCM,  $\Delta H$ , can be expressed in terms of the PCM's latent heat of fusion,  $L$ . Note that  $\Delta H$  can vary between 0 and  $L$  when  $T_{opaqueus} < T < T_{transparentus}$  (translucent phase).

$$\Delta H = \beta L \quad (4.10)$$

The transparency fraction can be defined as:

$$\beta = \begin{cases} 0 & \text{if } T \leq T_{opaqueus} \\ 1 & \text{if } T \geq T_{transparentus} \\ \frac{T - T_{opaqueus}}{T_{transparentus} - T_{opaqueus}} & \text{if } T_{opaqueus} < T < T_{transparentus} \end{cases} \quad (4.11)$$

The term  $S_h$  in Equation (4.7) denotes the volumetric heat source/sink related to phase change, which is defined as:

$$S_h = -\frac{\partial(\rho\Delta H)}{\partial t} \quad (4.12)$$

The radiation equation is defined as follows:

In this study, radiation effects are simulated using the Discrete Ordinates (DO) model, which is the most comprehensive method available in ANSYS FLUENT. This model allows simulation of radiation scattering and absorption across various optical thicknesses. It converts the radiation heat transfer equation into a transport equation for radiation intensity, solving it over a finite number of discrete solid angles (*ANSYS FLUENT*, 2021). While this enhances precision, it also increases the number of equations, thereby slowing down the simulation process.

The radiative transfer equation for a medium that absorbs, emits, and scatters at position  $\vec{r}$  in the direction  $\vec{s}$  is given by:

$$\frac{dI(\vec{r}, \vec{s})}{ds} + (\sigma_a + \sigma_s)I(\vec{r}, \vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \phi(\vec{s}, \vec{s}') d\Omega' \quad (4.13)$$

The DO model considers the radiative transfer equation in the direction  $\vec{s}$  as a field equation and is written as:

$$\begin{aligned} & \nabla \cdot (I(\vec{r}, \vec{s})\vec{s}) + (\sigma_a + \sigma_s)I(\vec{r}, \vec{s}) \\ &= an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \phi(\vec{s}, \vec{s}') d\Omega' \end{aligned} \quad (4.14)$$

In Equations (4.13) and (4.14),  $\sigma$  is the Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ ).

#### 4.2.4 Climatic conditions

This study examines a south-facing window glazing system in three cities: Montreal, Vancouver, and Miami. Montreal, located at  $45.52^\circ\text{N}$  latitude and  $73.42^\circ\text{W}$  longitude, experiences its coldest and hottest days on January 22<sup>nd</sup> and July 21<sup>st</sup>, 2022. The time zone is GMT-5 during Eastern Standard Time (EST) and GMT-4 during Eastern Daylight Time (EDT). Vancouver, situated at  $49.3^\circ\text{N}$  latitude and  $123.12^\circ\text{W}$  longitude, has its coldest and hottest days on December 22<sup>nd</sup> and July 29<sup>th</sup>, 2022. The time zone is GMT-8 during Pacific Standard Time (PST) and GMT-7 during Pacific Daylight Time (PDT). Miami, at  $25.76^\circ\text{N}$  latitude and  $80.19^\circ\text{W}$  longitude, experiences its coldest and hottest days on January 30<sup>th</sup> and August 18<sup>th</sup>, 2022. The time zone is GMT-5 during Eastern Standard Time (EST) and GMT-4 during Eastern Daylight Time (EDT). The study considers all climatic conditions for both sunny and cloudy days on the hottest and coldest days of the year. Ambient weather conditions include hourly wind speed (*Historical Climate Data in Canada*, 2023; *Weather History in Miami*, 2022), hourly ambient temperature (*Historical Climate Data in Canada*, 2023; *Weather History in Miami*, 2022), hourly solar direct irradiation, and hourly solar diffuse irradiation (*ANSYS FLUENT*, 2021), as illustrated in Figure 4.1.

Montreal, Vancouver, and Miami having Heating Degree Days (HDD) of 4400-4800, 2000-2400 and 0-100 respectively, were selected for the study to represent a diverse range of climate conditions in order to allow for a comprehensive evaluation of the SSPCM's performance in different climatic conditions.

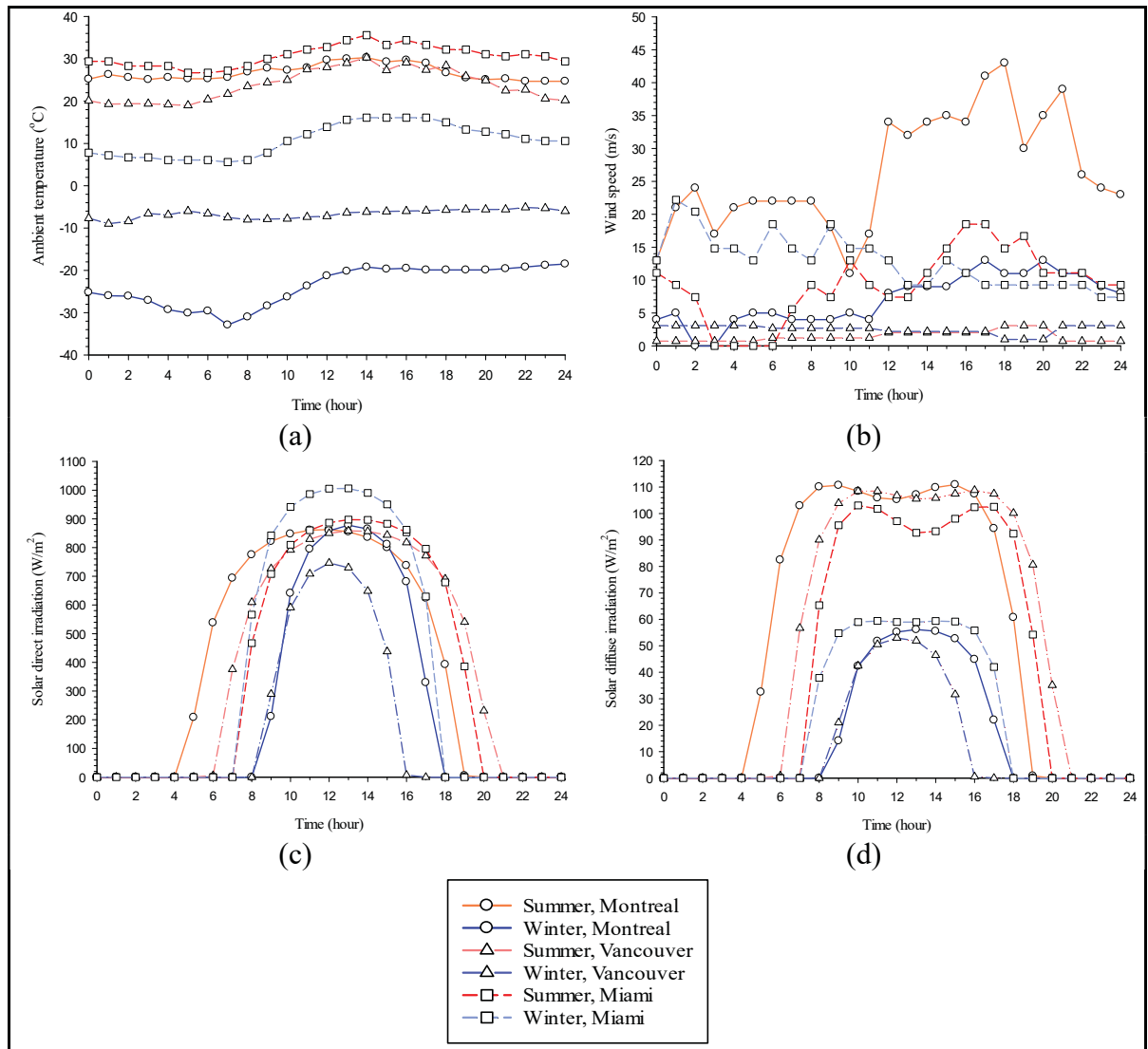


Figure 4.1 Climate data for Montreal, Vancouver, and Miami in summer and winter: (a) Ambient temperature (*Historical Climate Data in Canada, 2023; Weather History in Miami, 2022*), (b) Wind speed (*Historical Climate Data in Canada, 2023; Weather History in Miami, 2022*), (c) Solar direct irradiation (*ANSYS FLUENT, 2021*), and (d) Solar diffuse irradiation (*ANSYS FLUENT, 2021*)

Montreal, which is classified under the Köppen-Geiger climate classification as Dfb (Beck et al., 2018), experiences a humid continental climate with cold winters and warm summers. This climate presents a significant challenge for energy-efficient systems, with extreme temperature variations that test the SSPCM's ability to adapt to both heating and cooling needs. Vancouver, with a Köppen-Geiger classification of Cfb (Beck et al., 2018), has an oceanic climate

characterized by mild, wet winters and cool, dry summers. This relatively moderate climate allows for an evaluation of the SSPCM's performance in a region with less temperature fluctuation compared to Montreal and Miami, providing insights into its effectiveness in milder conditions. Miami's tropical savanna climate, classified as Aw in the Köppen-Geiger system (Beck et al., 2018), features hot, humid summers and warm winters. The city's climate is crucial for assessing the SSPCM's performance in a consistently warm environment, where cooling demands are significant and the material's effectiveness in hot conditions is tested.

#### **4.2.5 Initial and boundary conditions**

The initial temperatures for all components in both the DGW-REF and DGW-SSPCM configurations are set to 26°C for summer and 24°C for winter. The window's side surfaces (exterior top, bottom, front, and back) are treated as thermally insulated or adiabatic. Mixed thermal boundary conditions, which include both convection and radiation, are applied to the window's indoor and outdoor surfaces. Therefore, it is necessary to determine parameters such as the heat transfer coefficient, free stream temperature, external emissivity, and external radiation temperature for these surfaces. Furthermore, to account for solar irradiation within the numerical domain, semi-transparent boundary conditions are established. This necessitates defining parameters like direct solar irradiation, diffuse solar irradiation, and the beam direction vectors in the x, y, and z directions for both indoor and outdoor surfaces. The emissivity of typical clear glass is set at 0.9 for all boundaries. The sunshine factor is set to 1 to represent a sunny day and to 0 for a cloudy day, which results in zero direct solar irradiation.

The indoor conditions can be determined as a result of conducting numerical simulation for the whole building. However, the present study focuses on assessing the thermal performance of only one building component (double-glazing window) of the building envelope. As such, the indoor conditions are needed as boundary conditions for solving the governing equations. In this study, the heat transfer coefficient for the window's indoor surface thermal and radiation boundary conditions is set to 8.7 W/m<sup>2</sup>K (ASHRAE, 2021; Jin et al., 2022). Both the free stream temperature and the external radiation temperature are set to 26°C in summer and 24°C in winter. To avoid modeling direct or diffuse solar irradiation on the indoor surface, no solar

irradiation is applied to the indoor radiation boundary condition. As the used indoor conditions above are not the same as those for the case of conducting whole building simulations, the contributions of the windows to the total heating and cooling loads with these indoor conditions may differ from those with the case of conducting whole building simulations. However, the used indoor conditions would insignificantly affect the comparison between the reference double-glazed window without SSPCM and that with SSPCM in terms of the percentages of energy savings/penalties.

To simulate a full 24-hour day, the window's outdoor surface thermal and radiation boundary conditions are set using User Defined Functions (UDFs) written in C programming, compatible with the ANSYS FLUENT library. All parameters except emissivity are imported into ANSYS FLUENT. These UDFs use piecewise linear functions to incorporate hourly weather data. The free stream temperature in the thermal boundary condition is set using the hourly ambient temperature. Additionally, the radiation boundary conditions include hourly values for direct and diffuse solar irradiances and the x, y, and z beam direction vectors. The hourly heat transfer coefficient, which depends on wind speed, and the hourly external radiation temperature or sky temperature, which depends on ambient temperature, are calculated using Equations (4.15) and (4.16) (Goia et al., 2012).

$$h_a = 5.62 + 3.9 v_{wind} \quad (4.15)$$

$$T_{sky} = 0.0552 T_{air,o}^{1.5} \quad (4.16)$$

### 4.3 Numerical method

#### 4.3.1 Model structure and details

The commercial CFD code ANSYS FLUENT (version 2022 R1) is employed, utilizing the SIMPLE algorithm for velocity-pressure coupling. Design Modeler and Ansys Meshing are used to create the geometry and grid, respectively. For pressure, momentum, and energy discretization, a second-order upwind scheme is applied. The DO model and transient formulation use a first-order upwind and first-order implicit scheme, respectively.

Convergence criteria are set to be less than  $10^{-6}$  for mass conservation, x-velocity, y-velocity, and z-velocity, and less than  $10^{-9}$  for energy and DO-intensity.

#### **4.3.2 Numerical validation**

This research adapts the model traditionally used for SLPCMs to SSPCMs by employing the solidification/melting model. The primary difference lies in the absence of natural convection in SSPCMs, as they do not have a liquid phase during melting. By ignoring the gravity effect and considering the high viscosity of the SLPCM's liquid phase, its behavior can be approximated to that of an SSPCM.

To validate the numerical model, which incorporates the Discrete Ordinates (DO) model and the solidification/melting model in glazing systems, researchers compared transient numerical results over a 12,000-second simulation period with experimental data from Gowreesunkera et al. (2013) on the transmittance of PCM-filled glazing units over time. They developed an experimental setup, illustrated in Figure 4.2a, to measure radiation effects within the mushy phase, which cannot be achieved with a spectrophotometer alone. This setup provided a realistic depiction of radiation behavior in a PCM-glazed system. The entire setup was placed in an environmental chamber with controlled air temperature. A 150 W metal halide lamp emitting diffuse neutral white light was used as the light source. The regular double glazing measured 20 cm by 20 cm with a total thickness of 24 mm, consisting of 4 mm glass, a 16 mm air cavity, and another 4 mm glass layer. In the PCM-filled glazing configuration, the air cavity was replaced with an organic PCM named RT27, produced by RUBITHERM® GmbH. The irradiation level and initial PCM/air temperature were set to  $950 \text{ W/m}^2$  and  $13^\circ\text{C}$ , respectively. As shown in Figure 4.2b the transmittance values from the simulation align closely with the experimental data, with variations remaining within the margin of error. The overall transmittance was calculated by comparing the radiation flux between the front and back surfaces. The trends observed in the simulation results are similar to those seen in the experimental data. As the numerical results are in agreement with the experimental data being within  $\pm 10\%$  as shown in this figure, the numerical model is validated and can be reliably used in this study.



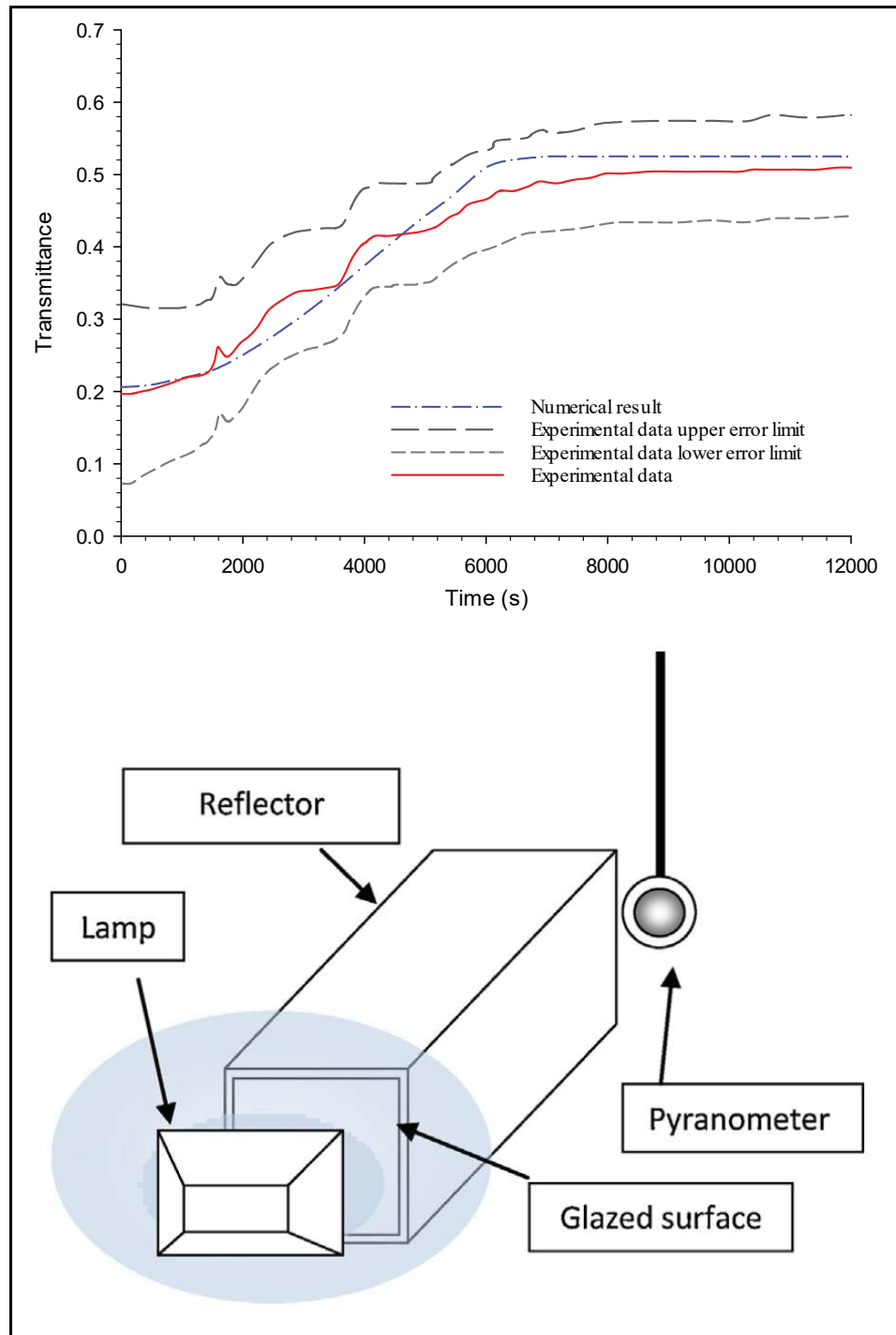


Figure 4.2 (a) A schematic of experimental setup and (b) Current numerical model results compared to the experimental data (Gowreesunker et al., 2013)

### 4.3.3 Grid sensitivity analysis

To achieve a mesh-independent solution, various grid sizes, ranging from fine to coarse, were generated over the numerical domain of a DGW-SSPCM. The criterion for assessing grid independence was the mean total heat flux over a 24-hour period on the interior surface of the inner glass pane, as described in Equation (4.17). The results, shown in Table 4.2, indicate that a grid size with 82,369 elements was approximately optimal, with a relative error of less than 1%. Consequently, this grid size was used in the study.

$$\overline{q''} = \frac{1}{t} \int_0^t q'' dt \quad (4.17)$$

where,  $t$  in Equation (4.17) is the time (sec).

Table 4.2 Grid sensitivity analysis

| Case | Number of elements | $\overline{q''}$ (W/m <sup>2</sup> ) | Error (%) |
|------|--------------------|--------------------------------------|-----------|
| 1    | 288923             | 15.47104                             | -         |
| 2    | 158661             | 15.5293                              | 0.376595  |
| 3    | 82369              | 15.58556                             | 0.740245  |
| 4    | 27440              | 15.71381                             | 1.569181  |
| 5    | 11025              | 15.8746                              | 2.608495  |
| 6    | 4050               | 16.1296                              | 4.25671   |

### 4.3.4 Time step study

The time step sensitivity analysis aims to identify the largest time step that still ensures accurate results. As in the previous section, the method involved calculating the average total heat flux over a 24-hour period on the interior side of the inner glass pane to determine the optimal time step, with the goal of minimizing CPU time. The results for various time steps are shown in Table 4.3, revealing that a 5-minute time step produces a relative error of under 1%, making it an appropriate choice for the simulations.

Table 4.3 Time-step sensitivity analysis

| Case | Time step size | $\overline{q''}$ (W/m <sup>2</sup> ) | Error (%) |
|------|----------------|--------------------------------------|-----------|
| 1    | 10 sec         | 15.73079                             | -         |
| 2    | 30 sec         | 15.72085                             | 0.06315   |
| 3    | 1 min          | 15.70591                             | 0.15812   |
| 4    | 2.5 min        | 15.66088                             | 0.44443   |
| 5    | 5 min          | 15.58556                             | 0.92319   |
| 6    | 10 min         | 15.43214                             | 1.89849   |
| 7    | 20 min         | 15.11929                             | 3.88729   |
| 8    | 30 min         | 14.82675                             | 5.74694   |

#### 4.3.5 Energy savings analysis

To comprehensively evaluate the energy savings or losses associated with the DGW-SSPCM system in comparison to the DGW-REF scenario, Equation (4.19) is employed. This equation extends the thermal energy analysis initiated in Equation (4.18). The focus is placed on the average heat flux across the interior surface of the inner pane of the double-glazed window (DGW), denoted as  $\overline{q''}$ , as specified in Equation (4.17). This heat flux can exhibit either a positive or negative value depending on its direction: a positive value indicates that heat is moving from the interior of the building to the outside environment, whereas a negative value reflects heat movement from the exterior into the interior of the building.

$$E = \overline{q''} \times t \times A \quad (4.18)$$

$$\Delta E = E_{final} - E_{ref} \quad (4.19)$$

Energy savings are realized when the magnitude of the negative heat flux decreases, which suggests a reduction in the amount of heat entering the building. This reduction in heat ingress is crucial for minimizing unwanted heat gain and improving overall energy efficiency. Conversely, energy savings are also achieved when the positive heat flux is reduced, indicating a lower rate of heat loss from the building to the outside. This signifies that less energy is being

wasted in maintaining indoor temperatures. By analyzing these changes in heat flux, one can assess the effectiveness of the DGW-SSPCM system in enhancing energy efficiency compared to the DGW-REF scenario, with the ultimate goal of achieving better thermal performance and reduced energy consumption.

#### 4.4 Results and discussion

This section presents a parametric study conducted through numerical simulations over a 24-hour period. The analysis focuses on three distinct climatic conditions—Montreal, Vancouver, and Miami—to evaluate the energy performance and thermal behavior of the proposed glazing system. It examines the impact of various parameters, such as phase transition temperature ( $T_c$ ) and its range ( $\Delta T_c$ ), as well as four different weather conditions (summer sunny, summer cloudy, winter sunny, and winter cloudy). The study investigates and analyzes how these factors influence the transparency fraction, interior surface temperature, and overall energy savings of the glazing system.

##### 4.4.1 *Evaluation of optical transmission and transparency characteristics*

Figure 4.3 illustrates the changes in the transparency fraction of the SSPCM during summer sunny days across the three cities for all cases. As depicted, the transparency fraction exhibits distinct daily patterns at each location, influenced by the phase transition temperature ( $T_c$ ) and the phase transition temperature range ( $\Delta T_c$ ). As temperatures rise, the SSPCM's transparency fraction increases from 0 to 1, reflecting heat storage through its latent thermal energy capacity. Conversely, as temperatures fall, the transparency fraction decreases from 1 to 0, releasing the stored heat. In Miami, the SSPCM maintains full transparency at  $T_c = 20^\circ\text{C}$  and remains fully opaque at  $T_c = 30^\circ\text{C}$  throughout the day. At  $T_c = 25^\circ\text{C}$ , the SSPCM undergoes a full phase transition, staying transparent during office hours. However, due to higher ambient temperatures, Miami experiences longer periods of partial transparency. Larger  $\Delta T_c$  values, such as  $5^\circ\text{C}$  (Figure 4.3c), result in more gradual transitions, while smaller values, like  $1^\circ\text{C}$  (Figure 4.3a), cause sharper changes in transparency.

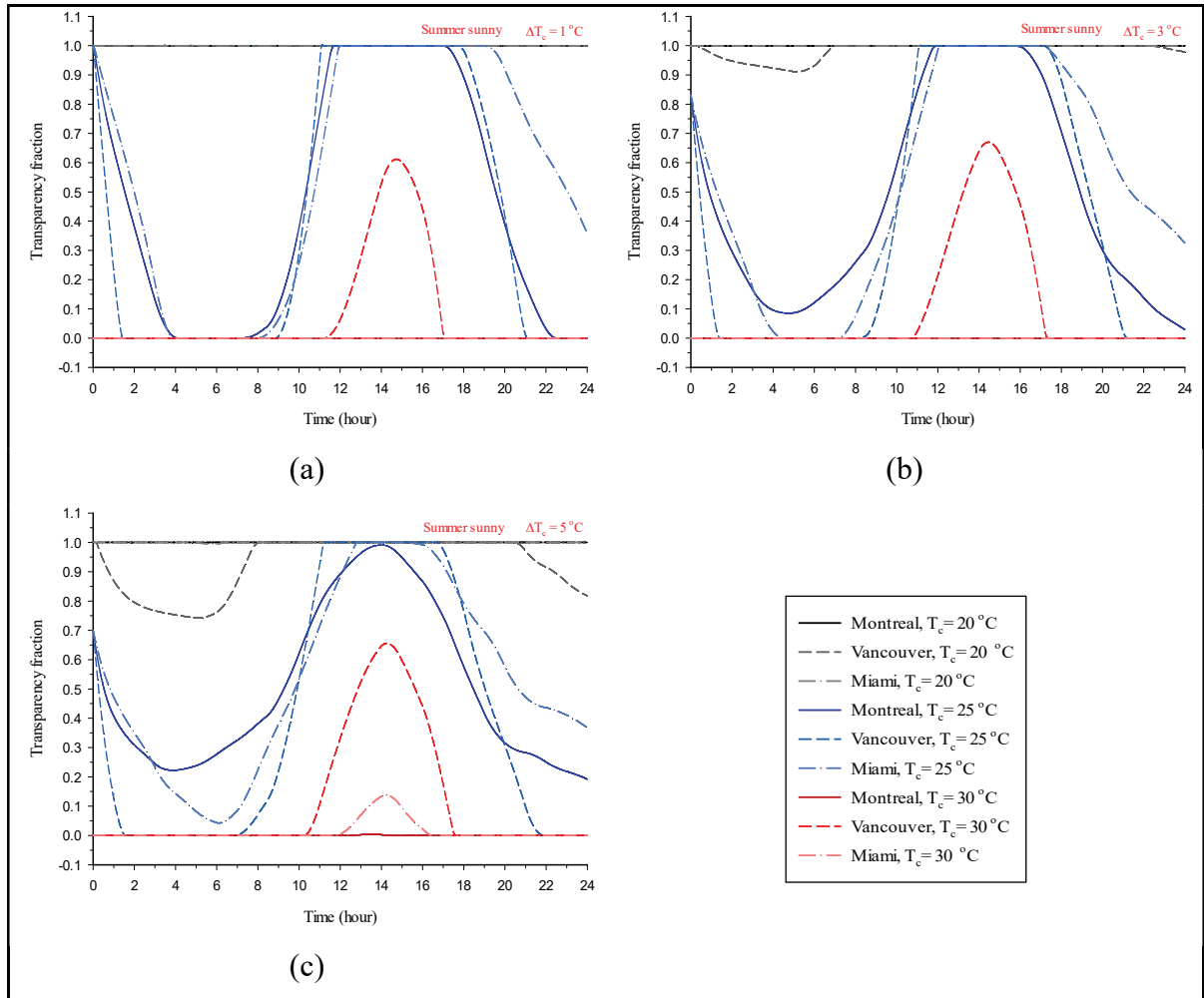


Figure 4.3 SSPCM's transparency fraction behavior under summer sunny conditions for (a)  $\Delta T_c = 1^\circ\text{C}$ , (b)  $\Delta T_c = 3^\circ\text{C}$ , (c) and  $\Delta T_c = 5^\circ\text{C}$ , across Montreal, Vancouver, and Miami

In Vancouver, the SSPCM remains transparent throughout the day at  $T_c = 20^\circ\text{C}$ , but becomes translucent at night with  $\Delta T_c$  values of  $3^\circ\text{C}$  (Figure 4.3b) and  $5^\circ\text{C}$  (Figure 4.3c). At  $T_c = 30^\circ\text{C}$ , partial transitions occur during the hottest part of the day, with the SSPCM returning to opacity by evening. This partial phase transition behavior limits the full utilization of the SSPCM's latent heat storage capabilities. At  $T_c = 25^\circ\text{C}$ , a full transition is achieved, with the SSPCM maintaining transparency during office hours.

In Montreal, the transparency fraction rises quickly in the morning, peaks around noon, and declines toward the evening. For  $T_c = 20^\circ\text{C}$ , the transparency remains at 1 throughout the day, ensuring visual clarity. At  $T_c = 30^\circ\text{C}$ , the SSPCM remains opaque with a transparency fraction

of 0. At  $T_c = 25^\circ\text{C}$ , a complete phase transition occurs, where smaller  $\Delta T_c$  values (Figure 4.3a) lead to sharper transitions, and larger values (Figure 4.3c) delay the transition. It should be noted that without a full phase transition, the glazing system cannot fully leverage the SSPCM's latent heat storage capabilities.

In summary, while Montreal and Vancouver exhibit similar trends, the timing and duration of transitions vary slightly due to climatic differences. The SSPCM's transparency during office hours across all three cities enhances its applicability for commercial uses. In Miami, the consistently warmer conditions lead to extended periods of partial transparency, which may be less critical for visual clarity in offices but still provide adequate daylight for residential buildings.

The SSPCM's transparency fraction behavior over 24 hours under summer cloudy conditions is depicted in Figure 4.4. It is visible that only at  $T_c = 25^\circ\text{C}$  partial phase transition of the SSPCM occurs in all cities, indicating the impact of cloud cover on the SSPCM's performance. The SSPCM's performance in cloudy conditions is characterized by less distinct and lower peaks in transparency fraction compared to sunny conditions, as seen in Figure 4.3. In Montreal and Vancouver, the full phase transition of the SSPCM does not occur for all scenarios due to the lack of direct solar irradiation, while it occurs in Miami according to higher ambient temperatures. The reduced solar heating on cloudy days limits the SSPCM's ability to fully transition, thereby impacting its heat storage and release capabilities. Higher  $\Delta T_c$  values (Figure 4.4c) result in more extensive phase transitions of the SSPCM, but these transitions occur more abruptly compared to those with lower  $\Delta T_c$  values (Figure 4.4a). The intermediate  $T_c$  value of  $25^\circ\text{C}$  provides a better balance, ensuring some level of transparency during office hours, enhancing both visual comfort and energy efficiency.

In summer cloudy conditions, in Figure 4.4, the variation in the transparency fraction of the SSPCM differs across the three cities due to differences in ambient temperatures and solar irradiation. In Montreal and Vancouver, the SSPCM shows minimal or no full phase transition under cloudy conditions because the lack of direct solar irradiation limits its ability to fully transition between transparent and opaque states.

This results in a relatively stable but lower transparency fraction, as reduced solar heating diminishes the SSPCM's heat storage and release capabilities. In contrast, the SSPCM in Miami experiences more noticeable variations in transparency despite the cloudy conditions that resulted in facilitating partial phase transitions even with limited direct solar irradiation. Consequently, Miami's SSPCM exhibits more significant changes in transparency compared to Montreal and Vancouver. The observed differences highlight how ambient temperature and solar irradiation levels influence the SSPCM's performance, with Miami's warmer climate allowing for greater transparency variation under cloudy conditions than the cooler climates of Montreal and Vancouver.

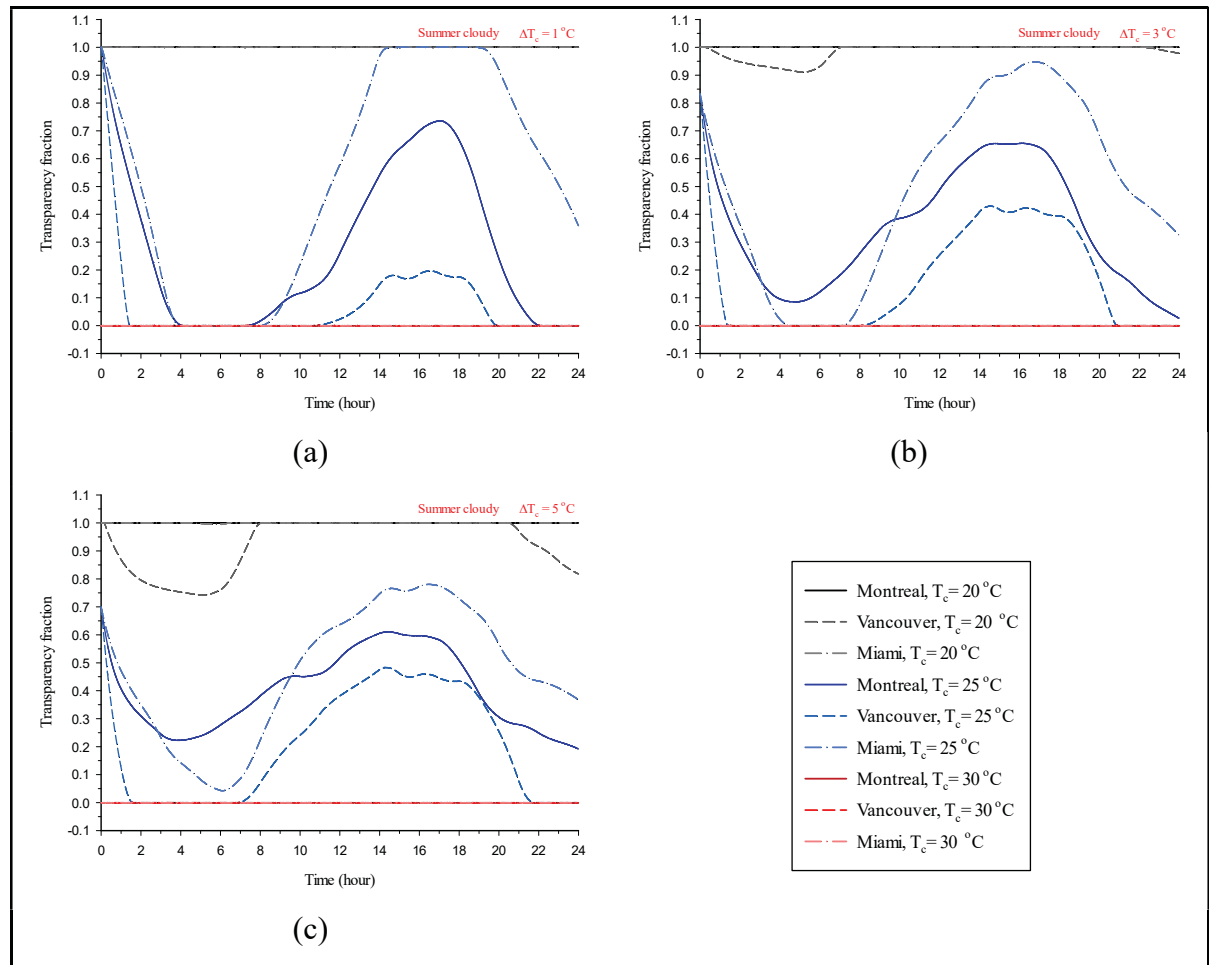


Figure 4.4 SSPCM's transparency fraction behavior under summer cloudy conditions for (a)  $\Delta T_c = 1^\circ\text{C}$ , (b)  $\Delta T_c = 3^\circ\text{C}$ , (c) and  $\Delta T_c = 5^\circ\text{C}$ , across Montreal, Vancouver, and Miami

In addition to the differences in transparency fraction observed in various cities, it is also noteworthy that the varying levels of ambient temperature and cloud cover impact the efficiency of the SSPCM in capturing and releasing thermal energy. In cities with higher ambient temperatures like Miami, the SSPCM exhibits a more responsive partial phase transition under cloudy conditions compared to Montreal and Vancouver, which have cooler climates. This indicates that even with limited solar irradiation, the SSPCM can still adapt to temperature fluctuations, albeit less effectively. The performance under cloudy conditions also suggests that in regions with more frequent overcast days, the design of SSPCMs could benefit from incorporating materials with optimized phase transition characteristics or hybrid systems to better handle varying climatic conditions.

Figure 4.5 illustrates the changes in the transparency fraction of the SSPCM during winter sunny conditions across the three cities studied. In Miami, where winter temperatures are relatively warm, the transparency fraction remains high throughout the day for  $T_c = 10^\circ\text{C}$  and  $T_c = 15^\circ\text{C}$ , indicating consistent transparency. At  $T_c = 20^\circ\text{C}$ , the SSPCM fully transitions, staying opaque at night and transparent during the day, enhancing both visual clarity and thermal storage.

In Vancouver, the transparency fraction varies with different  $T_c$  values. For  $T_c = 10^\circ\text{C}$ , transparency remains nearly constant throughout the day. Given Vancouver's milder winter temperatures, the SSPCM remains translucent or transparent at night for  $T_c = 20^\circ\text{C}$  and  $T_c = 15^\circ\text{C}$ , and maintains transparency during the day. This suggests that Vancouver's climate supports a more stable transparency fraction with intermediate  $T_c$  values, balancing visual clarity and thermal storage effectively.

In Montreal, the transparency fraction fluctuates significantly throughout the day. With  $T_c$  set at  $10^\circ\text{C}$ , the fraction decreases at night, with greater reductions observed at higher  $\Delta T_c$  values (Figure 4.5c), causing the SSPCM to become translucent. As the sun rises, it returns to an opaque state. For  $T_c = 20^\circ\text{C}$ , the SSPCM partially transitions from transparent to translucent without fully transitioning. At  $T_c = 25^\circ\text{C}$ , a full phase transition occurs, with  $\Delta T_c$  having a



minimal effect on transparency. This configuration allows the SSPCM to remain transparent during office hours and opaque otherwise, making it suitable for commercial buildings.

Overall, in winter sunny conditions, the SSPCM effectively manages heat storage and release across all three cities, with noticeable peaks in transparency around midday. The optimal  $T_c$  value for ensuring transparency during key daylight hours while maximizing thermal storage differs by city:  $T_c = 15^\circ\text{C}$  in Montreal, and  $T_c = 20^\circ\text{C}$  in Vancouver and Miami. This highlights the importance of selecting appropriate  $T_c$  values based on local climate to optimize SSPCM performance in double glazing systems.

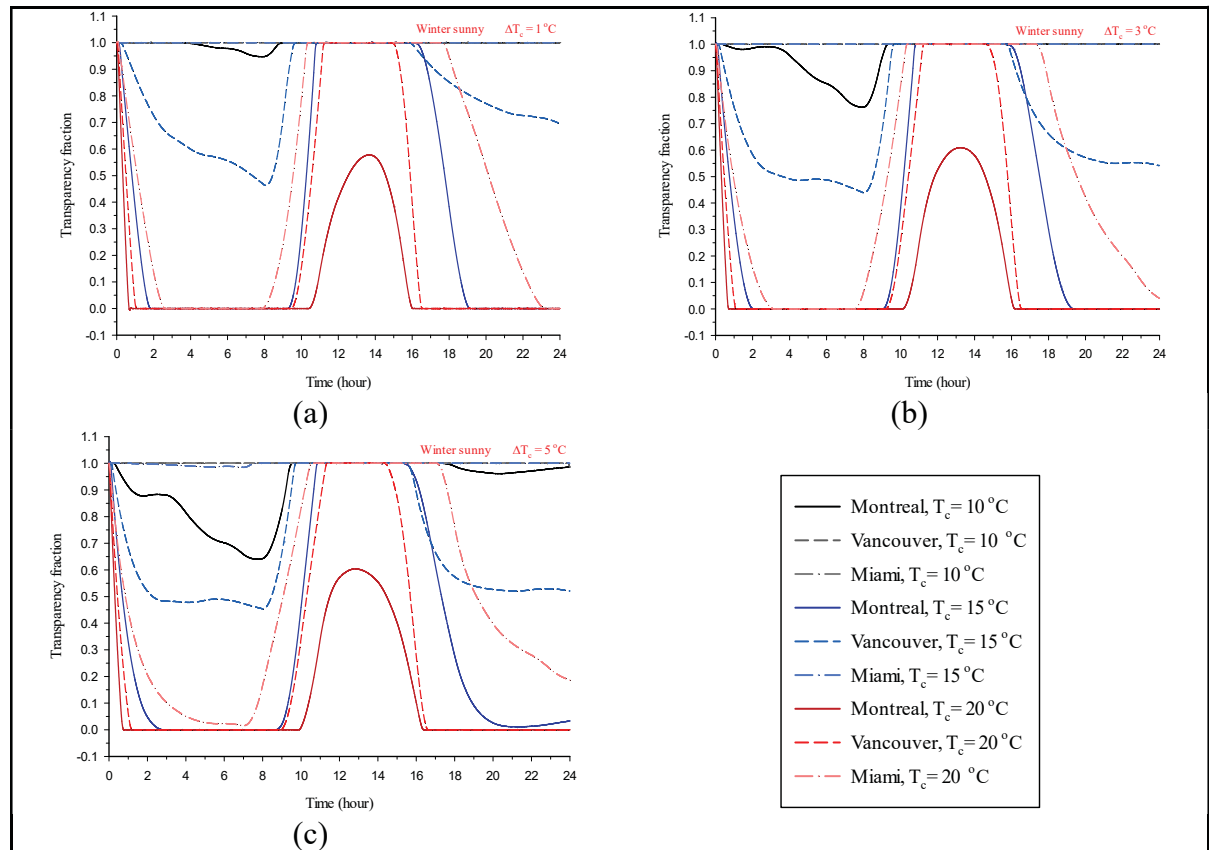


Figure 4.5 SSPCM's transparency fraction behavior under winter sunny conditions for (a)  $\Delta T_c = 1^\circ\text{C}$ , (b)  $\Delta T_c = 3^\circ\text{C}$ , (c) and  $\Delta T_c = 5^\circ\text{C}$ , across Montreal, Vancouver, and Miami

Figure 4.6 illustrates the changes in the SSPCM's transparency fraction during winter cloudy conditions across the three cities studied. In contrast to sunny conditions, where transparency

peaks are more distinct, the SSPCM displays smaller and less defined transparency peaks on cloudy days, as observed in Figures 4.3 and 4.5.

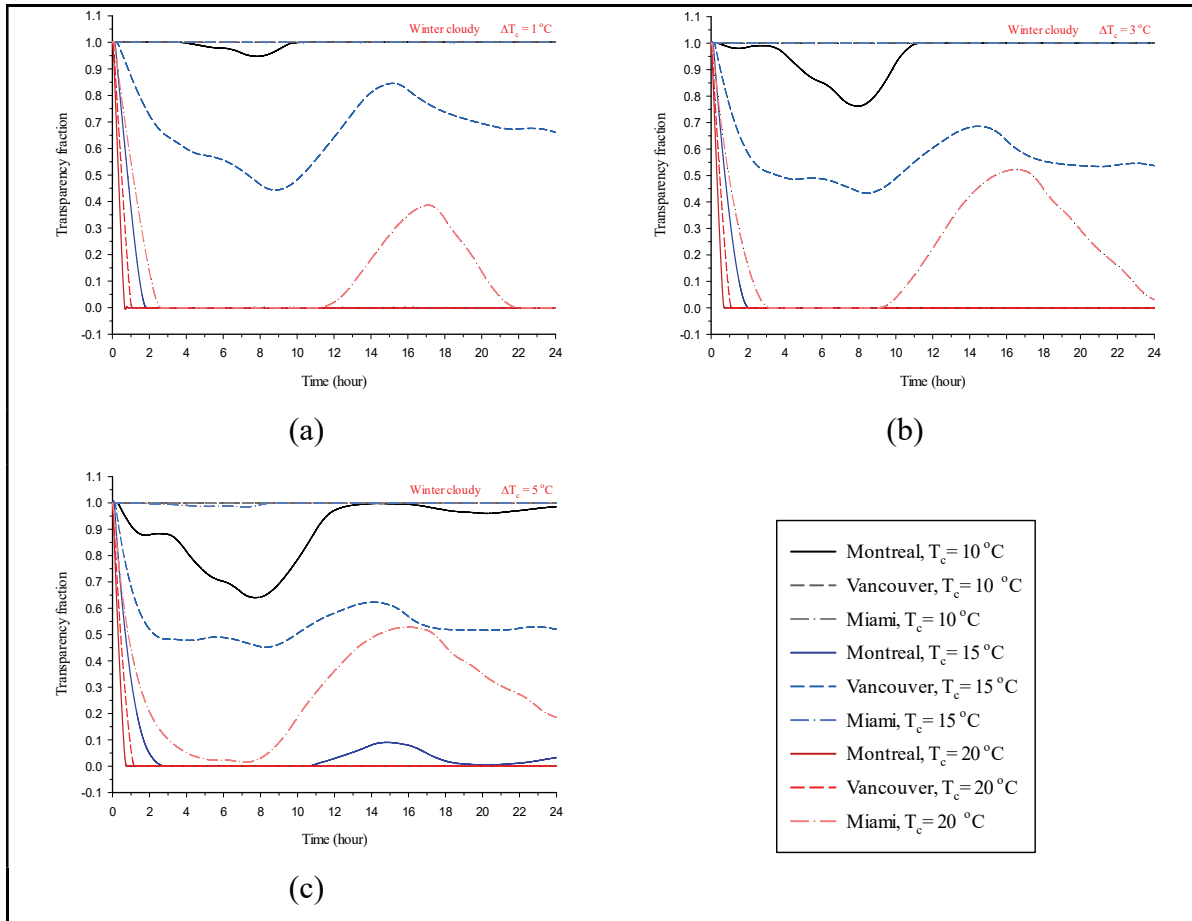


Figure 4.6 SSPCM's transparency fraction behavior under winter cloudy conditions for (a)  $\Delta T_c = 1^\circ\text{C}$ , (b)  $\Delta T_c = 3^\circ\text{C}$ , (c) and  $\Delta T_c = 5^\circ\text{C}$ , across Montreal, Vancouver, and Miami

The absence of direct solar radiation during cloudy weather restricts the SSPCM's ability to achieve a full phase transition, thus diminishing its effectiveness in heat storage and release. In Miami, the transparency pattern of the SSPCM shows partial transitions, with peaks in transparency occurring later in the day. At  $T_c = 20^\circ\text{C}$ , partial phase transitions are evident and become more pronounced with higher  $\Delta T_c$  values (Figure 4.6c), although the SSPCM remains predominantly opaque throughout the day.

In Vancouver, the SSPCM remains mainly translucent throughout the day at  $T_c = 15^\circ\text{C}$ . Lower  $\Delta T_c$  values (Figure 4.6a) lead to greater fluctuations in transparency, reflecting the moderate

impact of cloudy conditions on the SSPCM's performance. In Montreal, the SSPCM demonstrates only minor phase transitions, especially at  $T_c = 10^\circ\text{C}$  and with higher  $\Delta T_c$  values. The limited solar radiation results in minimal phase changes, affecting the SSPCM's ability to store and release heat effectively. This comparison between sunny and cloudy conditions highlights the importance of considering weather variability when utilizing SSPCMs to achieve optimal energy efficiency and visual comfort.

#### 4.4.2 *Analysis of thermal behavior and temperature profiles on interior surfaces*

Figure 4.7 illustrates the variations in the interior surface temperature of a double-glazed window equipped with SSPCM under summer sunny conditions across the three studied cities. In Miami, the SSPCM achieves a reduction of approximately  $0.8^\circ\text{C}$  in the interior surface temperature at  $T_c = 30^\circ\text{C}$  and  $\Delta T_c = 1^\circ\text{C}$  (Figure 4.7a) during peak cooling periods. This reduction is attributed to the SSPCM's rapid phase transition, which is facilitated by Miami's consistently warmer climate. The ability of the SSPCM to quickly shift from a transparent to an opaque state helps mitigate heat gains, thus lowering the interior temperature effectively. In Vancouver, the SSPCM results in a slightly lower reduction of around  $0.8^\circ\text{C}$  at  $T_c = 30^\circ\text{C}$  and  $\Delta T_c = 1^\circ\text{C}$  (Figure 4.7a) during peak cooling periods compared to Miami. This reduced cooling effect is due to Vancouver's milder summer temperatures, which influence the phase transition dynamics of the SSPCM. The SSPCM still provides significant benefits by capturing and storing solar radiation during the day, although the temperature reduction is less pronounced than in Miami. In Montreal, the SSPCM with  $T_c = 25^\circ\text{C}$  and  $\Delta T_c = 5^\circ\text{C}$  (Figure 4.7c) demonstrates a more substantial reduction in interior surface temperature, achieving nearly  $2^\circ\text{C}$  during peak cooling periods. This greater cooling effect is a result of the SSPCM's high latent heat storage capacity, which efficiently captures and stores solar energy, thus preventing excessive heat from entering the building. During daylight hours, the SSPCM's ability to maintain a cooler interior is pronounced, while at night, the stored heat is gradually released, causing a rise in temperature. Additionally, lower  $\Delta T_c$  values cause sharper interior surface temperature gradients. Overall, the DGW-SSPCM system exhibits its greatest effectiveness in Montreal's summer conditions, providing superior thermal comfort by significantly reducing interior temperatures. This underscores the importance of tailoring  $T_c$  and  $\Delta T_c$  values to the

local climate to optimize the performance of SSPCMs and enhance summer thermal comfort. Each city's specific climatic conditions affect the SSPCM's ability to manage heat gains and losses, highlighting the need for careful selection of system parameters to achieve optimal results.

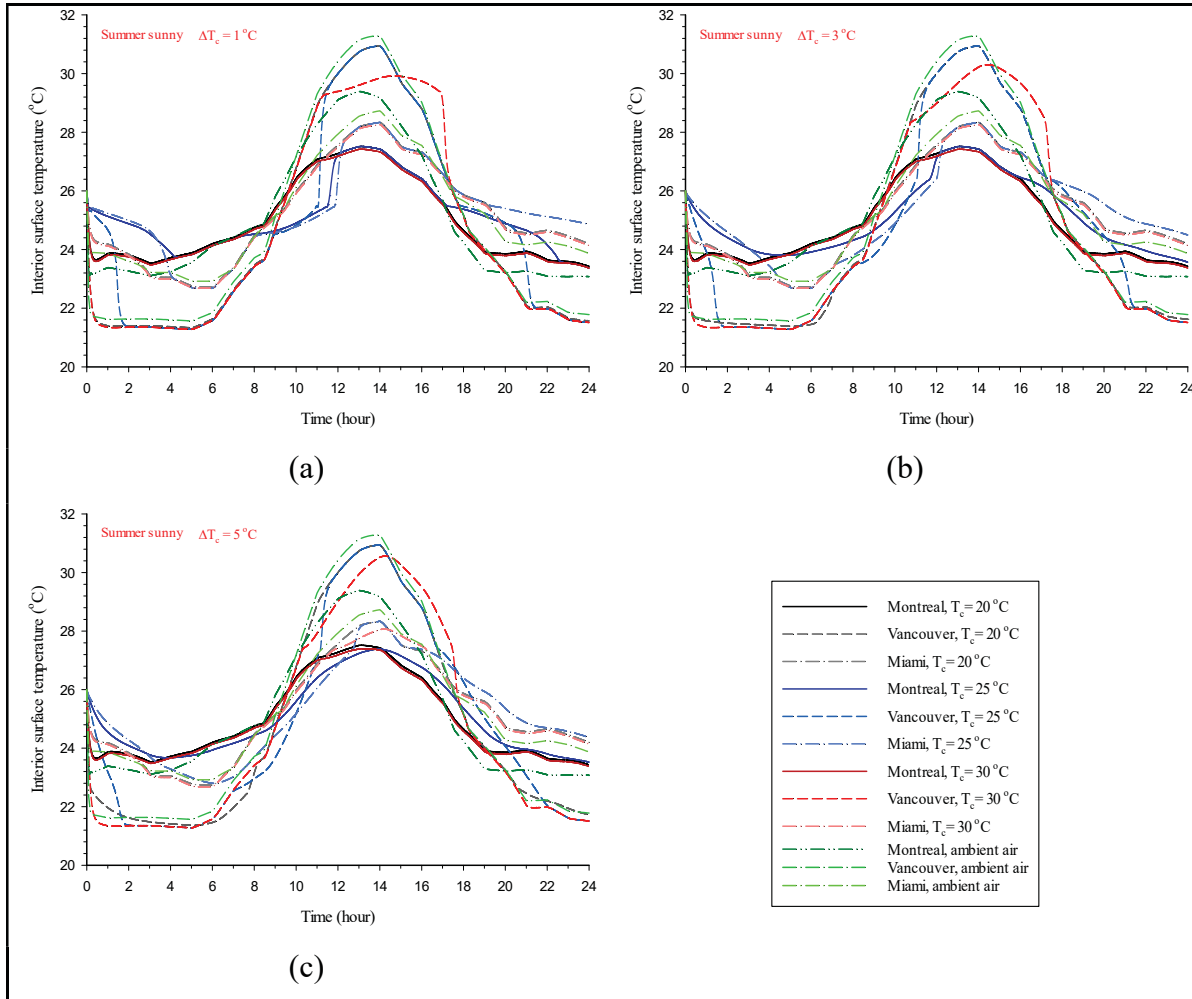


Figure 4.7 Variations of the interior surface temperature of SSPCM under summer sunny conditions for (a)  $\Delta T_c = 1^\circ\text{C}$ , (b)  $\Delta T_c = 3^\circ\text{C}$ , (c) and  $\Delta T_c = 5^\circ\text{C}$ , across Montreal, Vancouver, and Miami

Figure 4.8 illustrates the variations in interior surface temperature during summer cloudy conditions across the three studied cities. In Miami, the SSPCM shows a significant reduction in interior surface temperature, maintaining cooler temperatures more effectively due to the warmer climate. The SSPCM's capacity to store heat throughout the day and release it in the evening results in a more noticeable smoothing of temperature fluctuations and improved

thermal comfort during peak hours. This highlights the SSPCM's effectiveness in managing temperature variations and reducing cooling loads in Miami's warmer conditions.

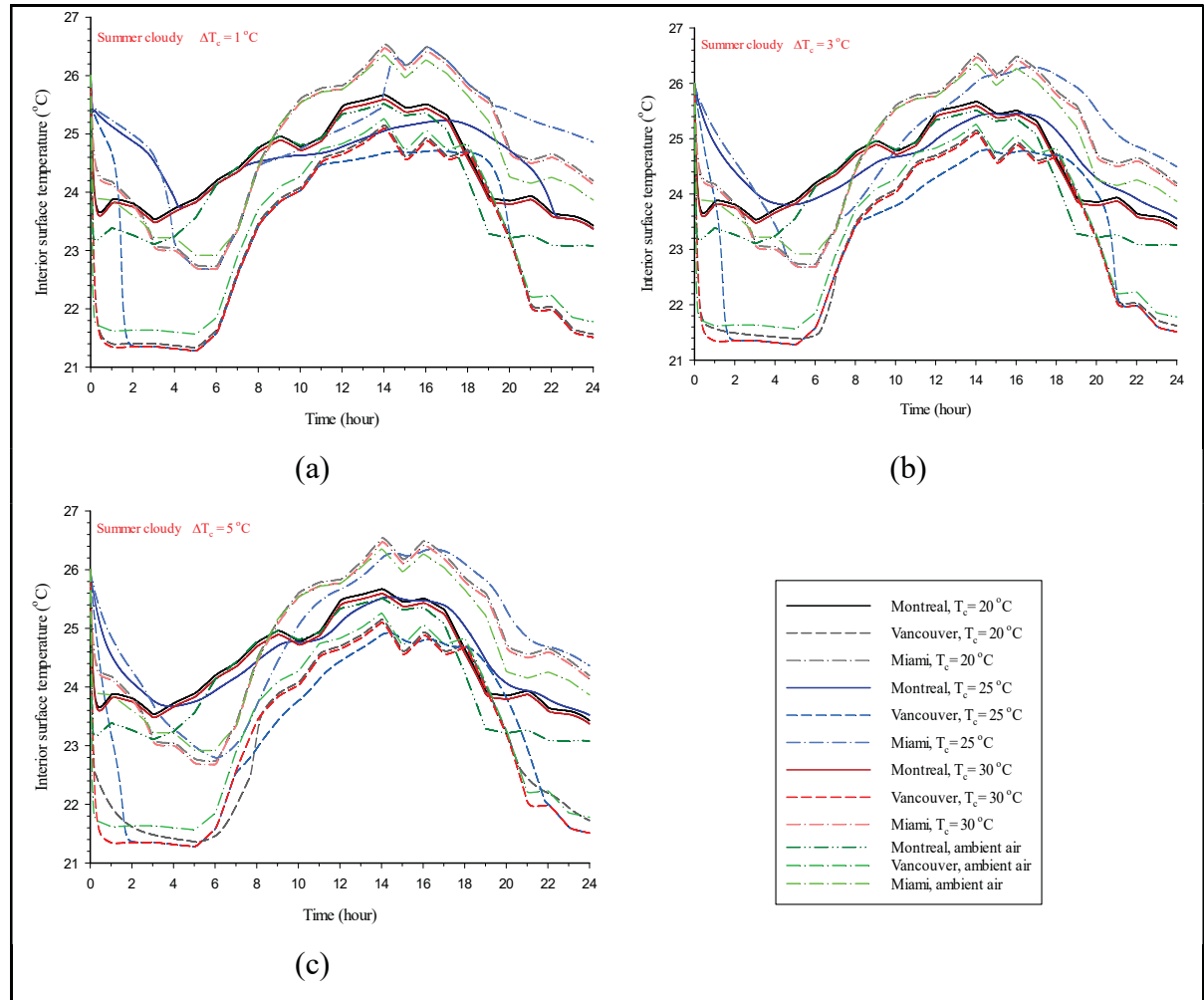


Figure 4.8 Variations of the interior surface temperature of SSPCM under summer cloudy conditions for (a)  $\Delta T_c = 1^\circ\text{C}$ , (b)  $\Delta T_c = 3^\circ\text{C}$ , (c) and  $\Delta T_c = 5^\circ\text{C}$ , across Montreal, Vancouver, and Miami

In Vancouver, the SSPCM also contributes to lowering the interior surface temperature, although the impact is less pronounced compared to Miami. Here, the SSPCM similarly absorbs heat during the day and releases it at night, helping to moderate temperature fluctuations and enhance comfort. The milder summer temperatures in Vancouver result in a less significant reduction in temperature compared to Miami, but the SSPCM still plays a crucial role in stabilizing interior temperatures and improving overall comfort. In Montreal, the SSPCM with  $T_c = 25^\circ\text{C}$  and  $\Delta T_c = 1^\circ\text{C}$  (Figure 4.8a) leads to a reduction of approximately

1°C in interior surface temperature during peak load hours. The SSPCM's ability to absorb and store heat throughout the day and release it in the evening helps to moderate temperature swings and improve thermal comfort. Despite the effectiveness of the SSPCM in Montreal, the overall impact on temperature reduction is less compared to Miami, reflecting the colder climate's influence on the system's performance. Overall, the DGW-SSPCM system demonstrates its greatest benefit in Miami, where it effectively manages temperature variations and improves thermal comfort during summer cloudy conditions. The system's performance varies across the cities, with Miami experiencing the most pronounced benefits, followed by Vancouver and Montreal. This variation underscores the importance of selecting appropriate SSPCM parameters to optimize performance based on local climatic conditions.

Figure 4.9 presents the variations in the interior surface temperature of the double-glazed window equipped with SSPCM under winter sunny conditions across the three cities studied. In Miami, the SSPCM demonstrates a significant impact on managing heat storage due to the city's warmer winter temperatures. The SSPCM releases stored heat more effectively, causing a notable rise in interior temperature from early evening through midnight. This ability to maintain higher interior temperatures is crucial for comfort during the cooler winter evenings in Miami.

In Vancouver, the SSPCM also shows a beneficial effect, though the temperature increase is less pronounced compared to Miami. The milder winter temperatures in Vancouver influence the extent of heat storage and release by the SSPCM. Nevertheless, a notable increase in interior temperature occurs in the early evening at  $T_c = 20^\circ\text{C}$ , highlighting the system's effectiveness in enhancing comfort as heating demands rise. In Montreal, the SSPCM has a significant impact on reducing solar heat ingress during the day. At  $T_c = 15^\circ\text{C}$ , the SSPCM captures and stores heat throughout daylight hours and releases it in the evening, resulting in a substantial increase in interior temperature. This effect is particularly noticeable when compared to the DGW-REF system, especially during peak heating periods when the material undergoes a full phase change.

The SSPCM thus plays a crucial role in improving thermal comfort in Montreal's colder winter conditions. Overall, the DGW-SSPCM system proves effective across all studied cities, with each location benefiting from the system's ability to manage interior surface temperatures based on local winter conditions. In Miami, the system maintains higher interior temperatures effectively, while in Vancouver, it contributes to enhanced comfort in the early evening. In Montreal, the SSPCM significantly improves comfort by managing heat storage and release during peak heating times. These observations emphasize the importance of tailoring SSPCM configurations and  $T_c$  values to optimize performance according to specific climatic conditions.

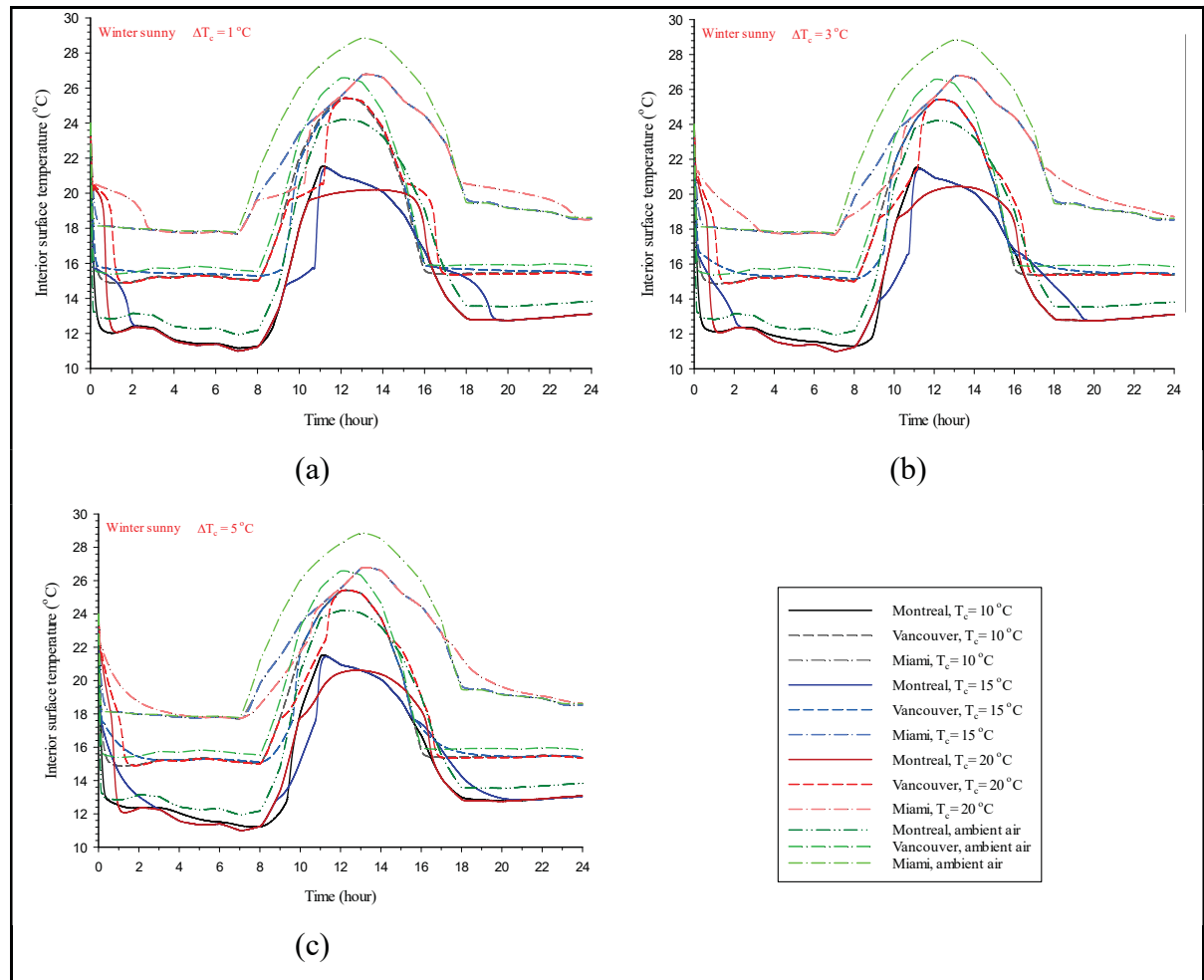


Figure 4.9 Variations of the interior surface temperature of SSPCM under winter sunny conditions for (a)  $\Delta T_c = 1^\circ\text{C}$ , (b)  $\Delta T_c = 3^\circ\text{C}$ , (c) and  $\Delta T_c = 5^\circ\text{C}$ , across Montreal, Vancouver, and Miami

Figure 4.10 depicts the variations in interior surface temperature for the double-glazed window equipped with SSPCM during winter cloudy conditions across the three cities studied. Under these conditions, the absence of direct solar radiation significantly affects the SSPCM's ability to manage interior temperatures. In Miami, the SSPCM demonstrates a notable performance even under cloudy conditions due to the city's warmer winter climate. The warmer ambient temperatures allow the SSPCM to complete its phase transition during the day. Consequently, it effectively stores heat and gradually releases it as the outdoor temperatures drop in the evening. This ability to retain and release heat results in increased interior surface temperatures, enhancing thermal comfort during the cooler evening hours.

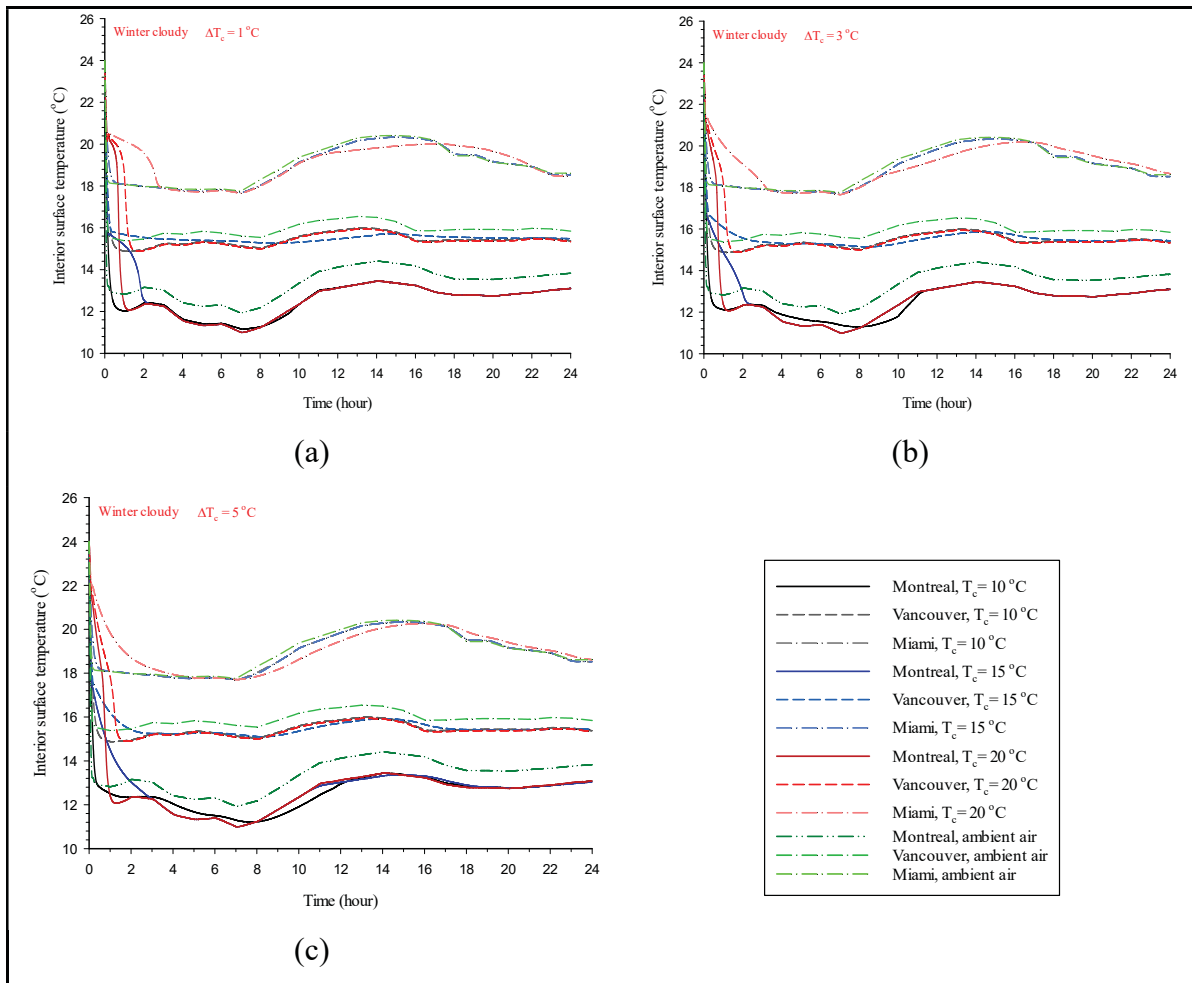


Figure 4.10 Variations of the interior surface temperature of SSPCM under winter cloudy conditions for (a)  $\Delta T_c = 1^\circ\text{C}$ , (b)  $\Delta T_c = 3^\circ\text{C}$ , (c) and  $\Delta T_c = 5^\circ\text{C}$ , across Montreal, Vancouver, and Miami



In Vancouver, the SSPCM's performance is less pronounced compared to Miami. The reduced solar radiation during cloudy days limits the SSPCM's capacity to fully engage in its heat storage and release processes. Although the system still manages to store some heat, it does not achieve a full phase transition, leading to less significant improvements in interior temperature regulation and comfort. In Montreal, the SSPCM's effectiveness is notably diminished under cloudy conditions. The lack of direct solar energy prevents the system from undergoing a complete phase change, which is crucial for its thermal management capabilities. As a result, the SSPCM's ability to store and release heat is significantly reduced, leading to less effective temperature regulation and lower thermal comfort.

In general, this figure highlights how the SSPCM's performance varies with local climatic conditions during winter cloudy weather. While the system performs relatively well in Miami due to its warmer temperatures, it struggles to maintain effective temperature regulation in colder regions like Vancouver and Montreal. This underscores the importance of considering ambient conditions when assessing the performance of SSPCMs in building applications.

#### **4.4.3      *Evaluation of energy efficiency: losses and savings***

This section provides a detailed assessment of how the proposed glazing system performs in terms of thermal energy across different sky conditions, focusing on three climatically distinct cities: Miami, Vancouver, and Montreal. The performance of the DGW-SSPCM is compared to a DGW-REF system to highlight the impact of the SSPCM under varying temperature conditions.

Figure 4.11 presents the thermal energy variations for each scenario under summer sunny conditions in these cities, offering a clear visual comparison of the energy performance. In Miami, the energy outcomes for the DGW-SSPCM system differ significantly from those in the other cities. Under Miami's hot and humid summer conditions, the DGW-SSPCM system results in energy losses in all scenarios when compared to the DGW-REF system. This is largely due to the elevated ambient temperatures in Miami, which exceed those found in Vancouver and Montreal, limiting the SSPCM's ability to effectively store and release thermal energy. The energy losses (averaged across the three  $\Delta T_c$ s) for  $T_c = 20^\circ\text{C}$ ,  $25^\circ\text{C}$ , and  $30^\circ\text{C}$

compared to DGW-REF system are 12.2 kJ, 13.0 kJ, and 5.0 kJ, respectively. The smallest energy losses occur when the SSPCM remains transparent all day at  $T_c = 30^\circ\text{C}$ , as this configuration minimizes heat absorption. However, even with  $T_c$  set to  $30^\circ\text{C}$ , the system still underperforms relative to the DGW-REF system due to Miami's extreme heat, which causes the SSPCM to release stored thermal energy into the building during the night, thereby increasing cooling demands.

In Vancouver, the DGW-SSPCM system performs better, demonstrating energy savings across all scenarios compared to the DGW-REF system. The city's more temperate summer conditions allow the SSPCM to store and release thermal energy more efficiently, making it well-suited to Vancouver's climate. The energy savings (averaged across the three  $\Delta T_c$ s) for  $T_c = 20^\circ\text{C}$ ,  $25^\circ\text{C}$ , and  $30^\circ\text{C}$  compared to DGW-REF system are 16.8 kJ, 10.8 kJ, and 20.8 kJ, respectively. The highest energy savings occur when  $T_c$  is set at  $30^\circ\text{C}$ , as the SSPCM remains opaque for most of the day, blocking a significant portion of solar radiation. However, the trade-off here is a reduction in visual clarity, which may not be suitable for all building applications. For a balance between energy efficiency and transparency,  $T_c = 20^\circ\text{C}$  offers a more optimal solution, allowing the SSPCM to remain transparent throughout the day while still providing considerable energy savings. This makes the DGW-SSPCM system particularly effective in Vancouver, where the milder temperatures and moderate solar radiation enable the system to optimize its latent heat storage capacity.

In Montreal, the DGW-SSPCM system also outperforms the DGW-REF system in terms of energy savings, albeit to a slightly lesser degree compared to Vancouver. Montreal's climate allows the SSPCM to block solar energy effectively, leveraging its latent thermal storage capability to reduce heat transfer into the building. The energy savings (averaged across the three  $\Delta T_c$ s) for  $T_c = 20^\circ\text{C}$ ,  $25^\circ\text{C}$ , and  $30^\circ\text{C}$  compared to DGW-REF system are 10.4 kJ, 7.6 kJ, and 17.4 kJ, respectively. The greatest energy savings occur at  $T_c = 30^\circ\text{C}$ , where the SSPCM remains opaque, blocking solar radiation and reducing heat gain. However, the lack of visual transparency at this temperature makes it less practical for fenestration systems where visibility is important. For Montreal, the most balanced scenario is when  $T_c$  is set to  $20^\circ\text{C}$ , where the SSPCM remains transparent, ensuring both effective energy savings and clear visibility.

throughout the day. At  $T_c = 25^\circ\text{C}$ , the SSPCM experiences a full phase transition, but the energy savings are lower than those at  $T_c = 20^\circ\text{C}$  due to the release of stored thermal heat during the nighttime. This release of latent heat back into the interior space results in lower overall energy efficiency, particularly when compared to the  $20^\circ\text{C}$  scenario, where the material stays transparent and maintains a steady thermal performance throughout the day. This analysis underscores the necessity of considering local climatic conditions when designing and implementing SSPCM glazing systems. While the DGW-SSPCM system proves effective in cooler climates like Vancouver and Montreal, it struggles in hotter environments like Miami, where its energy-saving potential is diminished. Tailoring the design of SSPCM systems to the specific thermal demands of each region is crucial to maximizing their effectiveness and ensuring they meet both energy efficiency and functional requirements.

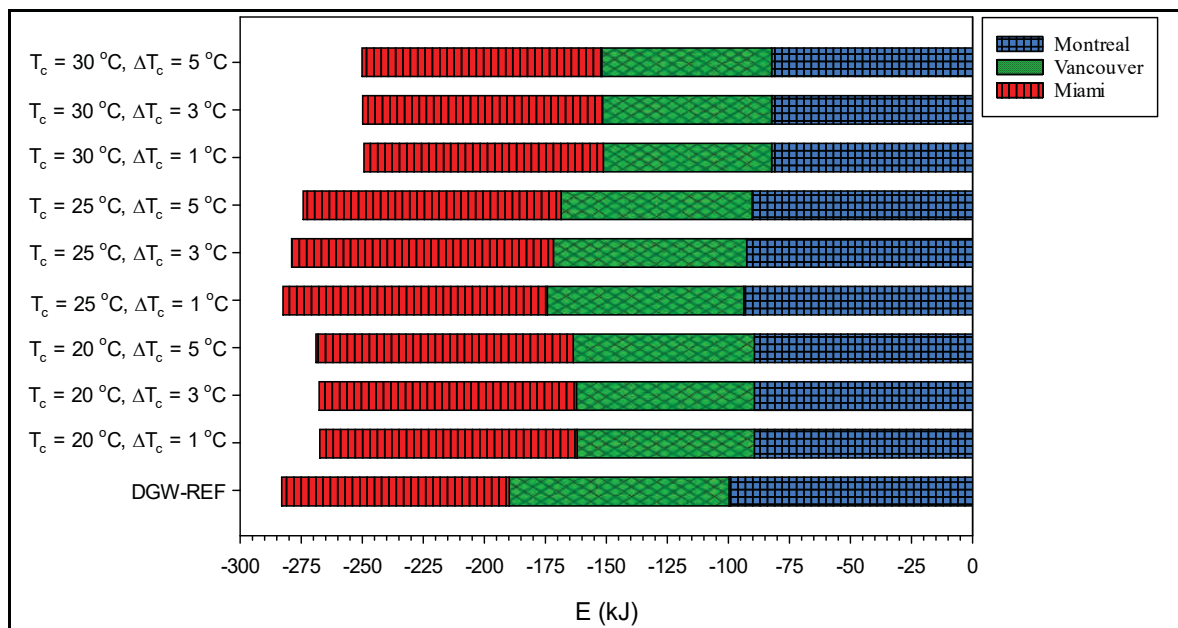


Figure 4.11 The thermal energy performance across three studied cities under summer sunny conditions

Figure 4.12 provides a comprehensive view of the thermal energy variations across different scenarios under summer cloudy conditions for the three cities studied—Miami, Vancouver, and Montreal. In Miami, where summer temperatures are consistently high, the absence of direct solar radiation exacerbates the challenges faced by the SSPCM-DGW system. Under cloudy conditions, the SSPCM's ability to store and release thermal energy is diminished,

leading to energy losses in all scenarios. In Miami, the energy losses (averaged across the three  $\Delta T_c$ s) for  $T_c = 20^\circ\text{C}$ ,  $25^\circ\text{C}$ , and  $30^\circ\text{C}$  compared to DGW-REF system are 33.6 kJ, 34.9 kJ, and 27.5 kJ, respectively. The smallest energy losses occur at  $T_c = 30^\circ\text{C}$ , where the SSPCM remains transparent, minimizing unwanted heat gain or loss. However, even in this optimal scenario, the DGW-SSPCM system is unable to provide energy savings compared to the DGW-REF system, highlighting the limitations of SSPCM technologies in Miami's warm climate, especially under cloudy conditions when the solar energy available for storage is reduced. Similarly, in Montreal, the DGW-SSPCM system also experiences energy losses across all scenarios under cloudy summer conditions, although these losses are generally more pronounced than in Miami.

Montreal's comparatively cooler summer temperatures are offset by the absence of direct solar radiation on cloudy days, reducing the effectiveness of the SSPCM. In Montreal, the energy losses (averaged across the three  $\Delta T_c$ s) for  $T_c = 20^\circ\text{C}$ ,  $25^\circ\text{C}$ , and  $30^\circ\text{C}$  compared to DGW-REF system are 45.1 kJ, 47.1 kJ, and 39.7 kJ, respectively. As in Miami, the smallest energy losses in Montreal occur when  $T_c$  is set at  $30^\circ\text{C}$ , allowing the SSPCM to remain transparent throughout the day, thereby minimizing heat transfer. However, despite this relative improvement, energy losses remain significant under cloudy conditions, demonstrating that the DGW-SSPCM system's performance is highly dependent on the presence of direct solar radiation. The results suggest that while the system offers some advantages under sunny conditions, it struggles to perform optimally in the absence of consistent solar exposure, as is common on cloudy days.

In contrast, Vancouver presents a different scenario due to its milder summer climate. Unlike Miami and Montreal, where energy losses are observed across all scenarios, Vancouver's cooler temperatures allow the DGW-SSPCM system to perform more effectively under cloudy conditions. The thermal energy values in Vancouver remain positive, meaning that the DGW-SSPCM system consistently conserves energy by reducing the amount of air-conditioned air lost from the building. In Vancouver, the energy savings (averaged across the three  $\Delta T_c$ s) for  $T_c = 20^\circ\text{C}$ ,  $25^\circ\text{C}$ , and  $30^\circ\text{C}$  compared to DGW-REF system are 17.3 kJ, 22.4 kJ, and 15.7 kJ, respectively. The highest energy savings occur when  $T_c$  is set at  $25^\circ\text{C}$ , a scenario in which the

SSPCM undergoes a partial phase transition, allowing it to optimize its latent heat storage and release capabilities throughout the day. In addition, scenarios where the lowest  $\Delta T_c$  values are employed achieve slightly greater energy savings within the  $T_c = 25^\circ\text{C}$  configuration, although the difference is relatively minor. This trend underscores the importance of the SSPCM's transition temperature,  $T_c$ , in influencing the overall energy performance of the glazing system, with a more pronounced effect than the variation in  $\Delta T_c$ .

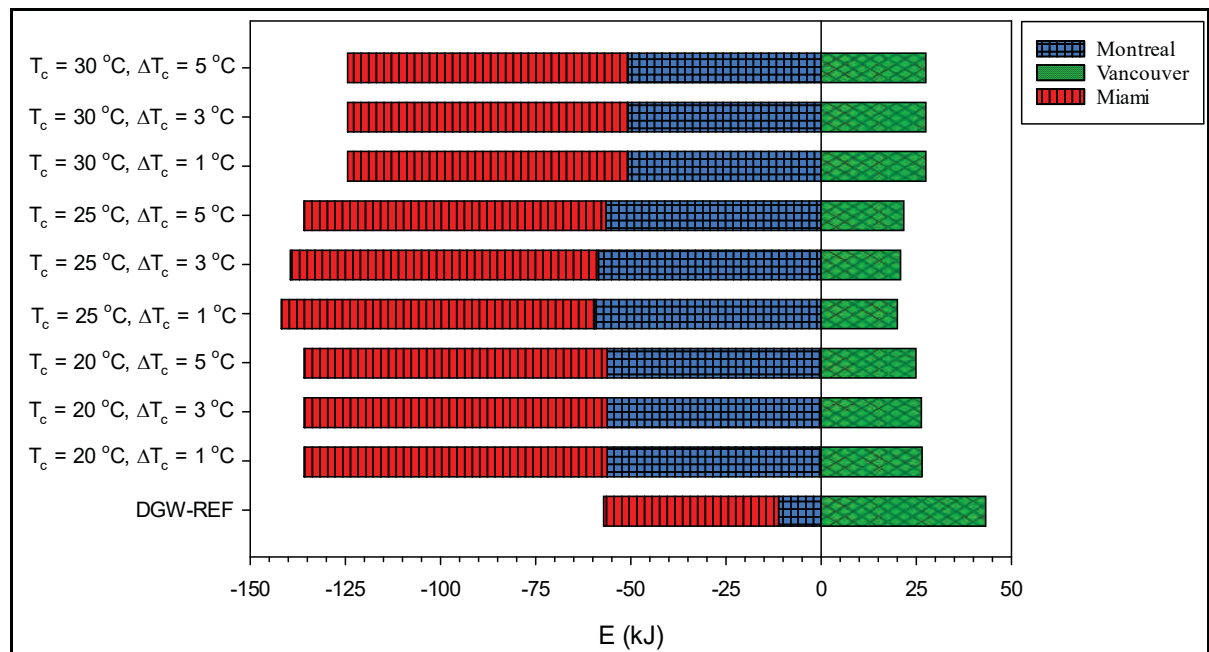


Figure 4.12 The thermal energy performance across three studied cities under summer cloudy conditions

Figure 4.13 presents the thermal energy across all scenarios studied under winter sunny conditions in the three cities. The data indicates that energy losses are observed in every case under these conditions. The energy losses (averaged across the three  $\Delta T_c$ s) for  $T_c = 10^\circ\text{C}$ ,  $15^\circ\text{C}$ , and  $20^\circ\text{C}$  compared to DGW-REF system are 86.4 kJ, 66.4 kJ, and 64.4 kJ for Montreal; 23.9 kJ, 16.8 kJ, and 7.1 kJ for Vancouver; and 71.8 kJ, 71.8 kJ, and 62.0 kJ for Miami, respectively.

Across all cities, the data for winter sunny conditions reveal a consistent pattern of energy loss, suggesting that the SSPCM's capacity to block direct solar radiation during the day outweighs the heat it releases into the interior at night, resulting in an overall energy deficit. The scenario with the smallest energy loss is observed when  $T_c = 20^\circ\text{C}$ , where the SSPCM undergoes a

phase transition, allowing it to release stored heat at night and maintain transparency for a longer period during the day. Although variations in  $\Delta T_c$  have a minimal effect on energy performance, higher  $\Delta T_c$  values contribute to reduced energy loss due to the extended periods of charging and discharging. Vancouver exhibits lower energy losses compared to Montreal and Miami, likely due to its winter temperatures being intermediate. This highlights the need for tailored designs in glazing systems with thermal energy storage materials, as various parameters significantly impact both energy performance and visual quality.

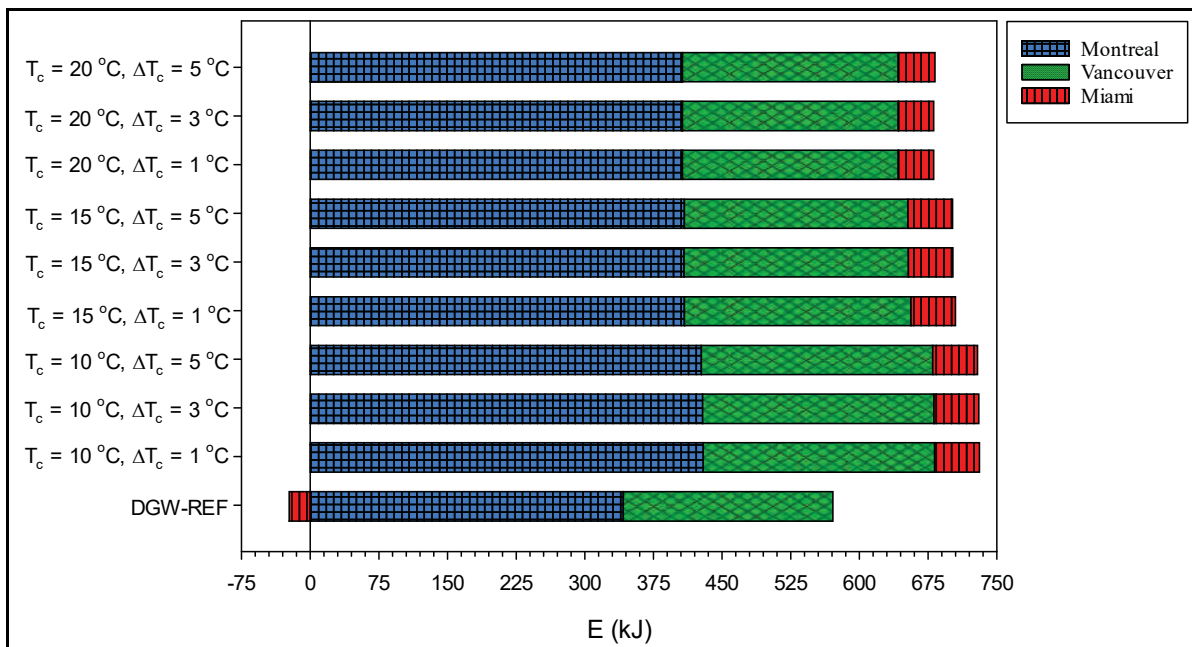


Figure 4.13 The thermal energy performance across three studied cities under winter sunny conditions

Figure 4.14 reveals that under winter cloudy conditions, the fenestration system performs differently, leading to energy savings in all three cities. With no direct solar irradiation, the SSPCM not only releases its stored heat into the indoor environment during the night but also acts as an insulating layer. This helps to retain the warm air inside the building, contributing to the overall energy savings.

The energy savings (averaged across the three  $\Delta T_c$ s) for  $T_c = 10^\circ\text{C}$ ,  $15^\circ\text{C}$ , and  $20^\circ\text{C}$  compared to DGW-REF system are as follows: 12.2 kJ, 38.9 kJ, and 39.3 kJ for Montreal; 30.0 kJ, 39.3 kJ, and 50.5 kJ for Vancouver; and 42.8 kJ, 42.8 kJ, and 54.1 kJ for Miami, respectively. The

analysis reveals that the highest energy savings occur at  $T_c = 20^\circ\text{C}$  due to the SSPCM's phase transition throughout the day. Among the cities studied, Miami leads in energy savings, followed by Vancouver, with Montreal ranking third. When comparing the energy saved and lost in the highest-saving scenario, it is evident that in Montreal and Miami, the energy lost on sunny days is nearly 1.7 and 1.2 times greater, respectively, than the energy saved on cloudy days. In contrast, Vancouver experiences a much higher ratio, with energy saved on cloudy days being approximately 7.1 times greater than the energy lost on sunny days. Therefore, the DGW-SSPCM system proves to be most effective in Vancouver during winter for achieving significant energy savings.

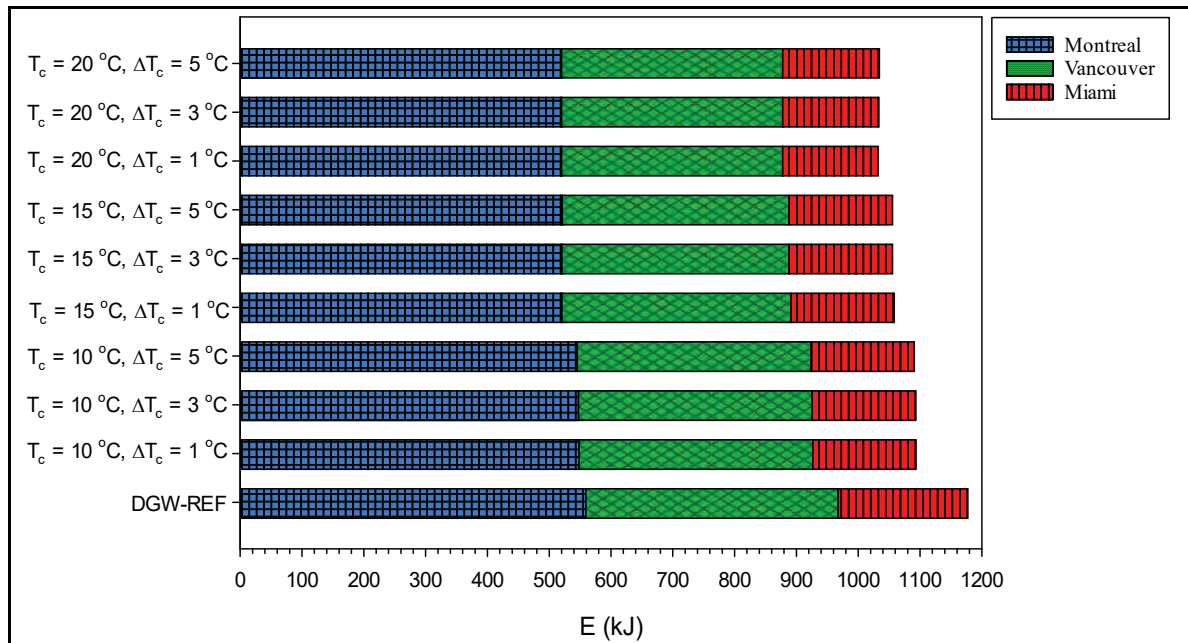


Figure 4.14 The thermal energy performance across three studied cities under winter cloudy conditions

## 4.5 Conclusion

In recent years, the growing urgency to combat global warming has driven substantial efforts toward decarbonization, particularly within the building sector, which is widely recognized as a significant source of CO<sub>2</sub> emissions. As a major contributor to energy consumption and carbon output, the building industry has become a focal point for introducing innovative technologies aimed at improving energy efficiency. One such technology is the integration of



solid-solid phase change material (SSPCM) into double-glazed windows (DGWs), which presents a promising solution for reducing energy use in building envelopes. This study investigates the potential of DGW-SSPCM systems in enhancing energy performance across a variety of climates, offering a novel approach to sustainable building design.

The research involved a detailed analysis of the SSPCM's behavior under varying climate conditions, including extreme temperatures and different weather patterns, to assess its performance across multiple regions. Numerical simulations were conducted to evaluate the system's effectiveness during both the hottest and coldest days of the year, as well as under both sunny and cloudy conditions. The study focused on three cities with distinct climates: Montreal, Vancouver, and Miami. These locations were chosen to represent a wide spectrum of temperature variations, allowing for a comprehensive assessment of the DGW-SSPCM system's adaptability to diverse environments.

The results revealed notable differences in energy performance across the three cities. Under sunny summer conditions, the DGW-SSPCM system showed significant energy savings of 17.5% in Montreal and 23.5% in Vancouver, while in Miami, energy losses of 5.3% were recorded. This suggests that the system is more beneficial in cooler or temperate climates where summer solar gains are more manageable. On cloudy summer days, Vancouver was the only city where substantial energy savings were observed, reaching 53.6%. In contrast, both Montreal and Miami experienced energy losses of 35.6% and 36.3%, respectively, indicating that the SSPCM's effectiveness is highly dependent on the weather patterns of each region.

During winter sunny conditions, the system exhibited energy losses across all three cities, as the SSPCM blocked the direct solar radiation that would have otherwise contributed to heating the buildings. The losses were most pronounced in Miami (270%), followed by Montreal (18.8%) and Vancouver (3.1%). However, under winter cloudy conditions, the DGW-SSPCM system performed favorably in all cities. The material's ability to retain indoor heat led to energy savings of 7.0% in Montreal, 12.4% in Vancouver, and 26.2% in Miami. These findings underscore the importance of considering both seasonal and daily weather variations when designing energy-efficient glazing systems.



A particularly noteworthy aspect of this system is its ability to maintain visual clarity during office hours, which makes it an attractive option for commercial buildings. The DGW-SSPCM design allows for complete transparency, ensuring that natural light can enter the building without compromising thermal performance. This dual benefit of energy efficiency and visual transparency is a key feature that enhances the applicability of DGW-SSPCM systems in modern architecture, especially in office and retail spaces where daylighting is a priority.

In general, the influence of the SSPCM's transient temperature on energy savings outweighs that of the transient temperature range. Among the different scenarios, the DGW-SSPCM system shows the greatest effectiveness in Vancouver. On the other hand, in Montreal and Miami, its performance is less favorable due to local weather conditions, leading to increased energy losses. These observations emphasize the importance of considering specific climate factors when designing energy-efficient glazing systems. Moreover, when the DGW-SSPCM system completes its full phase transition, it retains full visual clarity during office hours, making it particularly advantageous for commercial buildings.

For future studies, it is essential to address the current gaps in data related to solid-solid phase change materials (SSPCMs) to fully explore their potential in energy-efficient thermal design applications. A more thorough investigation into their thermophysical and optical properties is required, as existing information remains limited. Additionally, the scarcity of manufacturers producing SSPCMs further restricts experimental research, making it a key area for development. Future research should prioritize hands-on, experimental studies that focus on the integration of SSPCMs into building envelope systems, where experimental data is notably scarce. Expanding both the availability of data and the production of SSPCMs will be critical in unlocking their full range of applications in the building sector.



## CHAPTER 5

### COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF ENERGY AND OPTICAL PERFORMANCE IN FENESTRATION SYSTEMS INCORPORATING SOLID-SOLID PHASE CHANGE MATERIALS

Hossein Arasteh <sup>a</sup>, Wahid Maref <sup>a</sup>, Hamed H. Saber <sup>b</sup>

<sup>a</sup> Department of Construction Engineering, École de technologie supérieure,  
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C1K3

<sup>b</sup> Deanship of Research and Industrial Development, and Mechanical Engineering  
Department at Jubail Industrial College, Royal Commission of Jubail and Yanbu, Jubail  
Industrial City, 31961, Saudi Arabia

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#### Abstract

This study investigates the energy and optical performance of a double-glazed window system incorporating a solid-solid phase change material (DGW-SSPCM) compared to a conventional reference system (DGW-REF). Transient CFD simulations were conducted using ANSYS FLUENT for the hottest and coldest days in Montreal, Canada, under sunny and cloudy conditions across four glazing orientations. A 2 mm SSPCM layer was applied to the interior pane, and natural convection (NC) within the glazing air gap was modeled using the solidification/melting and Discrete Ordinates models. Results show that NC has negligible effects during summer due to weak buoyancy-driven airflow, making its inclusion unnecessary for accurate energy and optical analysis under warm conditions. In winter, however, NC significantly impacts the phase change behavior and total energy performance of the system, with heat losses being underestimated by 10 to 23 percent when NC is not considered. This behavior is supported by air gap velocity vector analyses, which show well-defined convective loops in winter with air velocities reaching up to 0.14 m/s, Reynolds numbers up to 57, and Rayleigh numbers exceeding  $10^4$ , while summer flows remain weak and conduction-dominated. While the DGW-SSPCM system offers no substantial energy savings in summer

due to nighttime thermal discharge, it achieves winter energy savings of up to 7.6 percent and improves indoor thermal comfort. The optical analysis in this study has demonstrated that benefiting from the full cycle of the SSPCM phase transition allows the glazing to remain fully transparent during office hours, making it particularly practical for commercial buildings. The south-facing configuration, incorporating an SSPCM layer with a transition temperature of 15 °C on the interior pane, is identified as the optimal setup. This design ensures full transparency and thermal neutrality throughout the year during office hours, while maximizing latent heat utilization for effective thermal regulation in winter. These findings highlight the potential of SSPCM-integrated glazing systems as a passive strategy for enhancing energy efficiency and indoor comfort in heating-dominated climates, particularly in commercial buildings with daytime occupancy.

**Keywords:** Building Energy; Solid-Solid Phase Change Material; Glazing System; Zero Energy Buildings; Computational Fluid Dynamics.

## 5.1 Introduction

Most individuals spend the majority of their time inside buildings. As living standards have improved, the role of buildings in global energy use has grown substantially, now accounting for nearly 40 percent of total consumption and up to 35 percent of greenhouse gas emissions, both of which contribute directly to climate change (Németh et al., 2021). In response to this issue, global sustainability agendas advocate for immediate efforts to address climate impacts. Various technological and design-based solutions have emerged to improve indoor thermal conditions. These range from passive architectural strategies and enhanced cooling methods to energy-efficient air conditioning systems and renewable energy integration (National Research Council Canada (NRC), 2020).

The building envelope, which functions as the interface between internal spaces and external weather conditions, is responsible for over half of the total energy consumption in buildings (Sadineni et al., 2011). Ensuring thermal stability indoors requires careful envelope design. Traditionally, this was accomplished by incorporating heavy construction materials to boost the building thermal mass and inertia. However, the widespread adoption of lightweight

construction systems has resulted in many buildings underperforming in terms of thermal efficiency (Roberz et al., 2017). Consequently, improving envelope performance has become a key focus of recent studies. The building envelope consists of opaque and transparent components, each playing a distinct role in thermal performance. Opaque elements include walls, roofs, and floors, while transparent parts comprise windows, curtain walls, and skylights. Among these, fenestration systems are particularly critical, as they are responsible for the majority of heat loss (up to 60 percent) thereby significantly affecting the overall energy efficiency of buildings (Ming et al., 2024). A promising passive solution to this challenge is the incorporation of PCMs into glazing systems. Our recent research (Arasteh et al., 2023), extensively reviewed the integration of PCMs into glazing systems, demonstrating their potential to enhance thermal performance while reducing visual transparency

Moghaddam et al. (2023) reviewed glazing solutions for nearly zero-energy buildings and proposed an approach for selecting optimal systems. They found that considering energy performance, thermal comfort, cost, and environmental impact together enable informed glazing choices, and future studies could include glare and visual comfort. Ceviz et al. (2023) found that adding phase change material in horizontal double-glazing improves energy storage and thermal comfort, with a 30 percent area ratio of PCM to double-glazed test elements providing the best balance between cooling duration and light transmittance. Lu et al. (2023) evaluated double-layer and multilayer phase change material glazing and found that the optimal configurations depend on climate, improving thermal regulation and energy savings.

Nsaif et al. (2024) found that adding phase change material along with blinders in triple-glazed windows reduced interior temperatures and increased time lag, though PCM solidification leakage remains a challenge. Uribe et al. (2024) developed and validated a heat transfer model for double-clear PCM glazing and integrated it into EnergyPlus (U.S. Department of Energy, 2017). They found that PCM glazing increases the thermal inertia, and reduces the cooling energy consumption by up to 9.1 percent and the cooling peak loads by up to 10.5 percent. Shaik et al. (2024) tested double-pane glazing filled with organic phase change materials and found that the 30-degree liquid mixture best reduced heat gain, energy costs, and carbon emissions while allowing natural daylight, whereas the solid-state mixtures blocked daylight.

Hu et al. (2024) found that 10 mm PCM glazing reduced temperature fluctuations, delayed peak temperatures, and maintained adequate daylighting, while thicker layers (15 and 20 mm) lowered energy storage and daylight performance.

Yuan et al. (2025) showed that triple-glazed windows with PCM and silica aerogel improve thermal regulation and energy savings subjected to cold and tropical climates. The cold climates benefit from reduced heat loss, while tropical climates achieve up to 74.8 percent energy savings. Future work should address durability, PCM stability, and extreme climate performance. Zhang et al. (2025) showed that the optical properties of PCM glazing units are strongly affected by the thermal parameters and layer thickness of the PCMs. They indicated that the common assumption in previous studies that optical properties are independent of thermal parameters is not valid, and the design strategies for such glazing units should be revised accordingly.

In another study by Zhang et al. (2025), they showed that during phase change, the transmittance and reflectance of PCM glazing units vary linearly, with most changes occurring in the solid-liquid stage and notable changes in the solid-solid stage. Also, they have showed that an optimized radiative transfer model based on their findings reduced calculation errors compared to previous models. Mandev (2025) found that integrating PCM in double-glazed windows improved the thermal regulation but reduced the natural light. A 45 percent area ratio of PCM to window cut light transmittance by about one-third highlighting a trade-off between thermal comfort and visual transparency.

As provided above, the use of PCMs can regulate heat transfer through phase changes, either from solid to liquid, referred to as SLPCMs, or from solid to solid, referred to as SSPCMs. The present study adopts SSPCMs in glazing configurations due to their distinct advantages over SLPCMs. These advantages include low subcooling effects, reduced material degradation, consistent optical behavior, the ability to be applied without encapsulation, absence of leakage, minimal phase segregation, small volumetric changes, and high thermal stability. Unlike SLPCMs, SSPCMs remain in a solid state throughout the phase transition and can be directly applied to the surface or pane of a multi-glazed window at a defined thickness. This configuration allows the low thermal conductivity of the intermediate air or inert gas layer to

be preserved, maintaining the insulating function between indoor and outdoor environments. In contrast, SLPCMs, when used to fill the air gap, reduce the system thermal resistance due to their relatively higher thermal conductivity. Although encapsulation can address this drawback by stabilizing the SLPCM in a solid state, the performance still depends on containment and material compatibility. SSPCMs undergo a phase transition between a semi-crystalline (opaque) and an amorphous (transparent) state, wherein only the soft segments melt while the hard segments (polymeric backbones with significantly higher melting temperatures) retain structural stability. This transition allows the material to remain solid as the soft segments undergo phase change, anchored by the hard segments. Detailed descriptions of the SSPCM phase transition mechanism are available in (Fallahi et al., 2017).

Although numerous studies have examined the application of SLPCMs in glazing systems, research focusing on SSPCMs in smart glazing remains limited. Raj et al. (2020) presented a review that outlined the development of SSPCMs and recent progress in their thermophysical properties. The study provided an extensive compilation of organic, polymeric, organometallic, and commercially available SSPCMs, including data on phase transition temperatures, melting points, molecular structures, and thermal behavior. This compilation serves as a valuable reference for professionals exploring SSPCM integration across a range of thermal energy applications. Another review (Fallahi et al., 2017) examined the relationship between molecular configurations, phase transition mechanisms, and thermal characteristics of SSPCMs. The study categorized SSPCMs into four primary groups: polymeric, organic, organometallic, and inorganic. It also offered guidelines for material selection based on specific thermal, mechanical, and physical requirements, supported by detailed listings within each category.

Guldentops et al. (2018) evaluated the performance of SSPCMs in a passive building enclosure system installed on the south-facing facade of a structure in central Massachusetts. The analysis, conducted through a finite element model, considered both summer and winter scenarios to identify optimal seasonal configurations. The study emphasized the importance of refining extinction coefficients and phase transition temperatures to ensure year-round effectiveness. In a separate investigation, Gao et al. (2021) conducted a numerical study

involving a thin SSPCM layer integrated on the interior surface of a double-glazed window. Since EnergyPlus could not directly simulate latent thermal storage, an equivalent model was developed. Results indicated that a 3 mm SSPCM layer improved energy performance in warm, mixed, and cold climates, offering better results than conventional low-emissivity glazing.

Ma et al. (2022) investigated a composite glazing system combining silica aerogel with SSPCM for use in extremely cold regions of China. EnergyPlus was used for thermal analysis and Radiance for daylighting assessment. As with previous studies, an equivalent SSPCM model was required. Key influencing parameters identified through sensitivity analysis included transition temperature, latent heat, absorption coefficient, and refractive index. The study recommended a 10 mm aerogel layer to achieve energy savings while meeting daylighting requirements.

Wang et al. (2023) developed an inverse modeling approach to determine temperature-dependent equations for extinction coefficients and refractive indices of SSPCMs in the translucent phase. Constant values were used for the opaque and transparent phases, and the optical parameters derived were used in the current analysis.

More recently, Zhang et al. (2024) investigated SSPCM glazing windows as an alternative to SLPCM to avoid liquid leakage issues. Through a parametric study in cold weather, they found that the melting temperature and latent heat of the PCM strongly affect thermal performance, energy saving potential, and inner surface temperature, while optical properties such as absorption coefficient and refractive index have smaller effects. Optimal values yielded the highest energy saving efficiency of 15.38 percent. Also, their study highlights guidelines for SSPCM design, noting that longer-term evaluations are needed for practical applications.

The reviewed literature highlights a clear gap in the application of SSPCMs in glazing systems, particularly in relation to energy performance assessment as well as optical evaluation through three-dimensional modeling. While SSPCMs offer latent heat storage benefits without the drawbacks of liquid-phase formation and moisture-related risks within the building envelope, existing numerical studies are limited. Most prior investigations have either employed



EnergyPlus, which lacks the capability to accurately capture phase transition phenomena and thus requires equivalent modeling approaches, or utilized two-dimensional models that assume the SSPCM fully occupies the air gap in the glazed units. To address these limitations, a three-dimensional CFD model using the finite volume method is developed in this study to evaluate the energy and optical performance of a double-glazed window system incorporating SSPCMs.

The model accounts for all modes of heat transfer in the double-glazed system, including natural convection (NC) that has resulted due to buoyancy-driven flow within the air gap. In this study, the SSPCM layer is positioned onto the interior surface of the air gap-facing glass pane, enabling the material to maintain elevated temperatures and remain in its transparent state throughout the year. This study aims to provide a more comprehensive understanding of DGW-SSPCM behavior under various climatic and operational scenarios via 3D CFD modeling. Following model validation, a parametric study was conducted to compare the performance of the DGW-SSPCM system with and without accounting for NC effects. The analysis was carried out under both sunny and cloudy conditions for the cold-dominant climate of Montreal. Simulations were performed for the four principal window orientations (north, east, south, and west) on the coldest and hottest days of the year 2022. This investigation also aims to evaluate the influence of NC on the heat transfer and fluid flow characteristics of the system across different façade orientations.

## **5.2 Methodology**

### **5.2.1 Model Geometry**

This study investigates two window configurations across four orientations: North, East, South, and West. The first configuration is a conventional DGW with an air gap, designated as DGW-REF. The second, referred to as DGW-SSPCM, incorporates a 2 mm layer of SSPCM applied to the inner surface of the interior glass pane. Both glazing systems consist of two glass panes, each measuring 200 mm by 200 mm with a thickness of 4 mm. In the DGW-REF setup, the panes are separated by a 16 mm air gap, as shown in Figure 5.1a. For the DGW-SSPCM

configuration, the air gap is reduced to 14 mm to accommodate the SSPCM layer while preserving the total thickness of the window unit, as shown in Figure 5.1b.

### 5.2.2 *Material properties*

The glazing system examined in this study consists of two clear glass panes, each 4 mm thick and possessing an emissivity of 0.9 (ASHRAE, 2021). The corresponding thermophysical and optical properties of the glass were sourced from (Gowreesunker et al., 2013), while the selected SSPCM was adopted based on the material specifications provided in (*PCM Products*, 2024). Optical characteristics of the SSPCM, including refractive index along with absorption and scattering coefficients, were determined using the correlations proposed in (P. Wang et al., 2023). Table 5.1 summarizes the thermophysical properties of all materials utilized in the simulations. In this study, one SSPCM material was used with identical thermophysical properties for both transition temperatures, set to 15 °C for winter and 25 °C for summer.

For the SSPCM used in this study, the refractive index and extinction coefficient are specified as  $1.11 \text{ m}^{-1}$  and  $25.73 \text{ m}^{-1}$  for the transparent phase, and  $5.33 \text{ m}^{-1}$  and  $152.82 \text{ m}^{-1}$  for the opaque phase, respectively, based on values reported in (P. Wang et al., 2023).

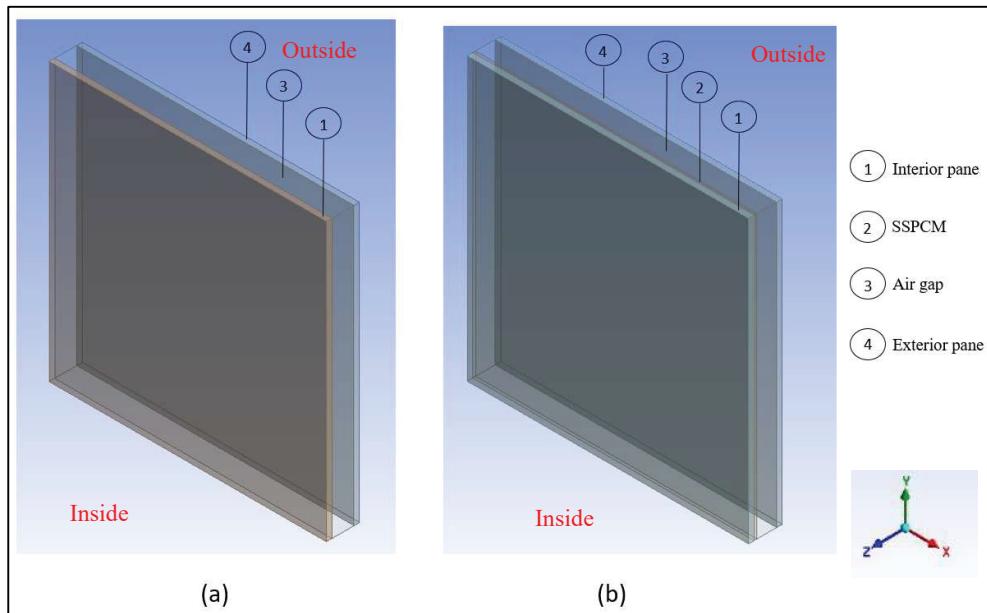


Figure 5.1 Current study model geometry: (a) DGW-REF and (b) DGW-SSPCM

Table 5.1 Thermophysical and optical properties of materials

| Material | Density<br>(kg/m <sup>3</sup> ) | Specific<br>heat<br>(J/kgK) | Thermal<br>conductivity<br>(W/mK) | Absorption<br>coefficient<br>(1/m)             | Scattering<br>coefficient<br>(1/m)          | Refractive<br>index                          |
|----------|---------------------------------|-----------------------------|-----------------------------------|------------------------------------------------|---------------------------------------------|----------------------------------------------|
| Air      | f (P, T)                        | 1006.43                     | 0.0242                            | 0                                              | 0                                           | 1                                            |
| Glass    | 2500                            | 840                         | 1.3                               | 19                                             | 0                                           | 1.5                                          |
| SSPCM    | 1055                            | 1630                        | 0.36                              | 33.80 ( $\beta = 1$ )<br>25.73 ( $\beta = 0$ ) | 0 ( $\beta = 1$ )<br>119.02 ( $\beta = 0$ ) | 1.11 ( $\beta = 1$ )<br>5.33 ( $\beta = 0$ ) |

To evaluate the optical behavior of the SSPCM in its intermediate (translucent) state, Equations (5.1) and (5.2) are employed. These equations compute the average optical properties as functions of the transparency fraction, a term adopted in place of the conventional "liquid fraction" since SSPCMs do not undergo a liquid phase. The transparency fraction,  $\beta$ , quantifies the proportion of the material in the transparent state, where  $\beta = 0$  corresponds to a fully opaque material and  $\beta = 1$  indicates full transparency. A transparency fraction of zero implies that the SSPCM temperature is at or below the lower boundary of the transition temperature range, referred to as the *opaqueus* temperature (analogous to the *solidus* temperature in solid-liquid phase change materials, SLPCMs), indicating a fully opaque phase. In contrast, a value of one signifies that the temperature has reached or exceeded the upper boundary, referred to as the *transparentus* temperature (analogous to the *liquidus* temperature in SLPCMs), resulting in a fully transparent phase. Intermediate values of  $\beta$  between 0 and 1 reflect a translucent state, comparable to the mushy zone observed in SLPCMs.

$$\sigma_{a,cell} = 33.8\beta + 25.73(1 - \beta) \quad (5.1)$$

$$\sigma_{s,cell} = 119.02(1 - \beta) \quad (5.2)$$

It should be noted that the transparency level of 1.0 corresponds to the SSPCM being in its fully transparent phase, which is similar to the fully liquid phase of a SLPCM. This does not mean that the material is permanently or fully transparent, but rather that it has reached the phase where light can pass through with minimal scattering. Therefore, reporting a transparency of 1.0 in this study indicates that the material is at its maximum transparent state during the phase transition.

### 5.2.3 Governing equations

The modeling of SSPCM is based on the enthalpy-porosity method within the ANSYS Fluent software (*ANSYS FLUENT*, 2021). A very high viscosity is assigned to the SSPCM to suppress internal flow, ensuring a nearly static state. Simulations are conducted for both cases, with and without NC-in the air gap of the DGW for both configurations: DGW-SSPCM and DGW-REF. This approach allows for accounting for the effect of NC in the air gap to accurately assess the energy performance of both DGW-SSPCM and DGW-REF systems. The analysis uses the climate of Montreal as a representative cold-dominant city to assess the potential energy savings relative to conventional glazing systems

The governing equations, including the Discrete Ordinates (DO) model for radiation and the solidification/melting model for representing SSPCM phase transitions, are:

- Mass conservation equation (*ANSYS FLUENT*, 2021):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad (5.3)$$

- Momentum conservation equation (*ANSYS FLUENT*, 2021):

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\mu \nabla \vec{v}) + \rho \vec{g} + S_m \vec{v} \quad (5.4)$$

In Equations (5.3) and (5.4),  $\rho$ ,  $t$ ,  $\vec{v}$ ,  $p$ , and  $\mu$  represent density, time, velocity vector, pressure, and dynamic viscosity, respectively. It is important to note that the source term “ $S_m \vec{v}$ ” is included on the right-hand side of Equation (5.4) as part of the solidification/melting (i.e., SSPCM in this study) model. The term  $S_m$  is defined as the negative of the porosity function ( $A_m(\beta)$ ), as described by (Brent et al., 1988). This porosity function is formulated to ensure that the momentum equations resemble the Carman-Kozeny equations (Heijs and Lowe, 1995), which are commonly used to describe fluid flow in porous media.

- Energy equation (*ANSYS FLUENT*, 2021):

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (k \nabla T) + S_h \quad (5.5)$$

In Equation (5.5), the enthalpy of the PCM,  $H$ , is calculated as the sum of the sensible enthalpy,  $h_s$ , and latent heat,  $\Delta H$  as:

$$H = h_s + \Delta H \quad (5.6)$$

where,

$$h_s = h_{s,ref} + \int_{T_{ref}}^T c_p dT \quad (5.7)$$

In Equation (5.6), the fractional latent heat of the PCM,  $\Delta H$ , is defined based on the material's latent heat of fusion,  $L$ . As provided in Equations (5.8) and (5.9), the value of  $\Delta H$  ranges from 0 in the opaque phase ( $\beta = 0$ ), to  $L$  in the transparent phase ( $\beta = 1$ ), and takes intermediate values between 0 and  $L$  when the temperature lies within the transition range,  $T_{opaqueus} < T < T_{transparentus}$ , corresponding to the translucent phase.

$$\Delta H = \beta L \quad (5.8)$$

In this study, the transparency fraction is calculated as follows:

$$\beta = \begin{cases} 0 & \text{if } T \leq T_{opaqueus} \\ 1 & \text{if } T \geq T_{transparentus} \\ \frac{T - T_{opaqueus}}{T_{transparentus} - T_{opaqueus}} & \text{if } T_{opaqueus} < T < T_{transparentus} \end{cases} \quad (5.9)$$

The term  $S_h$  in Equation (5.5) represents the volumetric heat source or sink associated with the phase change and is defined as:

$$S_h = -\frac{\partial(\rho\Delta H)}{\partial t} \quad (5.10)$$

- Radiation equation:

In this study, the Discrete Ordinates (DO) model is employed to simulate radiative heat transfer due to its comprehensive capability in radiation modeling within ANSYS Fluent (*ANSYS FLUENT*, 2021). The model facilitates accurate representation of radiation scattering and absorption across a wide range of optical thicknesses. It operates by transforming the radiative transfer equation into a set of transport equations for radiation intensity, which are solved over a finite number of discrete solid angles (*ANSYS FLUENT*, 2021). While the DO model improves accuracy, it also increases computational demand by requiring the solution of additional equations, thereby extending the simulation time.

For a position vector, the radiative transfer equation for a medium that absorbs, emits, and scatters radiation at position  $\vec{r}$  in the direction  $\vec{s}$  is given as follows (*ANSYS FLUENT*, 2021):

$$\frac{dI(\vec{r}, \vec{s})}{ds} + (\sigma_a + \sigma_s)I(\vec{r}, \vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \phi(\vec{s}, \vec{s}') d\Omega' \quad (5.11)$$

The DO model treats the radiative transfer equation in the direction  $\vec{s}$  as a field equation, expressed as follows (*ANSYS FLUENT*, 2021):

$$\begin{aligned} & \nabla \cdot (I(\vec{r}, \vec{s})\vec{s}) + (\sigma_a + \sigma_s)I(\vec{r}, \vec{s}) \\ &= an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \phi(\vec{s}, \vec{s}') d\Omega' \end{aligned} \quad (5.12)$$

In Equations (5.11) and (5.12),  $I$ ,  $n$ ,  $\vec{r}$ ,  $\vec{s}$ ,  $\vec{s}'$ ,  $\phi$ ,  $\Omega'$ , and  $\sigma$  indicate radiation intensity, refractive index, position vector, direction vector, scattering direction vector, phase function, solid angle, and the Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ ), respectively.

The energy performance of the different glazing systems in this study are evaluated using the Equation (5.13). The area-averaged heat flux in this equation has been calculated in the interior surface of the glazing system.

$$E = q''_{avg} \times t \times A \quad (5.13)$$

$$\langle q'' \rangle_A = q''_{avg} = \frac{1}{A} \int_A q''(x, y) dA \quad (5.14)$$

#### 5.2.4 Initial and boundary conditions

The glazing system analyzed in this study is evaluated across four orientations (North, East, South, West) in Montreal, Quebec, Canada, located at  $45.52^\circ\text{N}$  latitude and  $73.42^\circ\text{W}$  longitude. The selected dates representing the coldest and hottest days of the year are found to be in January 22 and July 21, 2022, respectively. Montreal follows GMT-5 during Eastern Standard Time (EST) and GMT-4 during Eastern Daylight Time (EDT). According to the Köppen–Geiger climate classification (Beck et al., 2018), Montreal falls under the Dfb category, indicating a humid continental climate characterized by warm summers and no distinct dry season. Simulations are conducted under both sunny and cloudy conditions for the identified extreme days. The climatic inputs used in the analysis include hourly wind speed (*Historical Climate Data in Canada*, 2023), ambient temperature (*Historical Climate Data in Canada*, 2023), direct solar irradiation (*ANSYS FLUENT*, 2021), and diffuse solar irradiation (*ANSYS FLUENT*, 2021).

The initial temperature is set to  $18^\circ\text{C}$  for all the studied cases. In our previous study (Arasteh et al., 2024b), the DGW-SSPCM system reaches a stabilized energy and optical state after two simulation days, showing the influence of the initial conditions on the system performance is negligible beyond this point. Accordingly, in this study, all simulations are carried out over a

48-hour period, with the first 24 hours serving as a preconditioning phase to eliminate the influence of initial conditions, and the subsequent 24 hours used for performance analysis.

The side surfaces of the window system, including the exterior top, bottom, front, and back, are treated as thermally insulated or adiabatic, indicating that no heat transfer occurs through these boundaries. The interfaces between adjacent material layers are modeled using coupled thermal boundary conditions and semi-transparent radiation boundary conditions. These conditions ensure continuity of temperature and heat flux across both real and shadow surfaces, while also allowing incoming radiation to be transmitted through the interface. All material layers are assumed to be in perfect thermal contact, which means that thermal contact resistance at each interface is set to zero.

Mixed thermal boundary conditions, consisting of both convection and radiation, are applied to the indoor and outdoor surfaces of the window. Therefore, it is necessary to define parameters such as the heat transfer coefficient, free stream temperature, surface emissivity, and radiation temperature for these surfaces. In order to account for solar radiation in the numerical model, semi-transparent radiation boundary conditions are used. This requires defining direct and diffuse solar irradiance, along with beam direction vectors in the x, y, and z directions for both indoor and outdoor boundaries. The emissivity of standard clear glass is set to 0.9 (ASHRAE, 2021) across all boundaries. A sunshine factor of 1 is used to represent sunny conditions, while a value of 0 is used for cloudy conditions, resulting in zero direct solar irradiation under overcast skies.

For the thermal and radiation boundary conditions on the indoor surface of the window, the heat transfer coefficient is specified as  $8.7 \text{ W/m}^2\cdot\text{K}$  (Chen et al., 2023). The free stream temperature and external radiation temperature on the indoor surface of the window are set to  $26^\circ\text{C}$  for summer and  $22^\circ\text{C}$  for winter (Chen et al., 2023). No solar radiation is applied to the indoor surface to avoid modeling direct or diffuse solar gains from indoor sources. For the outdoor surface boundary conditions, all parameters except emissivity are implemented into ANSYS Fluent using User Defined Functions (UDFs) written in the C programming language, in accordance with the Fluent framework, to simulate a complete 24-hour period. These UDFs apply piecewise linear functions to input hourly weather data. Hourly ambient temperature



values are used for the free stream temperature, and the radiation boundary conditions are defined using hourly values of direct and diffuse solar irradiation, along with corresponding beam direction vectors. The hourly heat transfer coefficient, determined based on wind speed, and the external radiation or sky temperature, calculated from ambient temperature, are evaluated using Equations (5.15) and (5.16) (Goia et al., 2012).

$$h_a = 5.62 + 3.9 v_{wind} \quad (5.15)$$

$$T_{sky} = 0.0552 T_{air,o}^{1.5} \quad (5.16)$$

In Equation (5.15),  $h_a$  is expressed in W/m<sup>2</sup>K and  $v_{wind}$  in m/s. In Equation (5.16), both  $T_{sky}$  and  $T_{air,o}$  are given in Kelvin

### 5.3 Numerical model

#### 5.3.1 Modeling approach

The commercial CFD software ANSYS Fluent (version 2022 R1) is employed to perform three-dimensional simulations using the finite volume method. The computational geometry is generated in Design Modeler, and meshing is carried out using Ansys Meshing. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm is used for velocity-pressure coupling. A second-order upwind scheme is applied for the discretization of pressure, momentum, and energy equations, while the Discrete Ordinates (DO) radiation model and transient formulation are discretized using a first-order upwind scheme and a first-order implicit scheme, respectively. The convergence criteria are set to  $10^{-6}$  for mass conservation, x-velocity, y-velocity, and z-velocity, and to  $10^{-9}$  for both the energy equation and DO radiation intensity.

To prevent direct interaction between the SSPCM and the adjacent air gap, a 0.001 mm thick transparent glass layer is inserted at their interface, addressing the software inability to simulate direct contact between distinct media. This artificial layer is defined with zero absorption and scattering coefficients, a refractive index of 1, and high thermal conductivity, ensuring that it

has no impact on the system energy or optical behavior. NC within the air gap is modeled by incorporating a gravitational body force,  $\rho \vec{g}$  (with  $g_x = 0.0 \text{ m/s}^2$ ,  $g_y = -9.81 \text{ m/s}^2$ , and  $g_z = 0.0 \text{ m/s}^2$ ), applied only to the air gap. This allows buoyancy-driven flow to be captured without influencing other materials in the domain. It should be noted that the momentum equation need not be solved in the SSPCM to reduce computational time, and the SSPCM can be treated as a solid domain. Accordingly, the model was re-run with the volume force applied only to the air gap. This approach significantly reduced computational time while yielding results identical to those obtained when the momentum equation was solved throughout the entire domain.

A constant transition range of  $1^\circ\text{C}$  is used for the phase change process, with transition temperatures of  $15^\circ\text{C}$  for winter and  $25^\circ\text{C}$  for summer. These values are selected based on previous studies (Arasteh et al., 2024a), which showed that they enable complete phase transition of the SSPCM. This setup allows full utilization of the material's latent heat storage capacity and facilitates the evaluation of system performance under both heating and cooling conditions.

In this research, the solidification/melting model traditionally applied to solid-liquid phase change materials (SLPCMs) is adapted for use with solid-solid phase change materials (SSPCMs). The primary distinction lies in the absence of a liquid phase in SSPCMs during the phase change process, which eliminates NC effects. By neglecting gravity and assigning a high viscosity to the liquid phase of the SLPCM, its behavior can be approximated to that of an SSPCM.

Assumptions considered in the numerical model are as follows:

1. The SSPCM layer is treated as a solid domain with no internal flow; the momentum equation is not solved within this layer.
2. The thermophysical properties of the SSPCM were considered identical for both cases with transition temperatures of  $15^\circ\text{C}$  (winter) and  $25^\circ\text{C}$  (summer) to isolate the effect of the transition temperature on the optical and energy performance of the glazing system.

3. Gravity is applied only to the air gap by specifying a source term ( $\rho g$ ) in the y-momentum equation ( $g_x = 0$ ,  $g_y = -9.807 \text{ m/s}^2$ , and  $g_z = 0$ ) to capture the NC effects and buoyancy-driven flow.
4. Air in the gap is treated as a compressible gas to account for the natural convection inside the air layer.
5. Thermophysical properties of air and SSPCM are assumed constant, except for the density variation of air, which drives buoyancy effects.
6. Radiative heat transfer is modeled using the Discrete Ordinates (DO) method.
7. Heat conduction in glass and SSPCM is solved in three dimensions, with phase change in the SSPCM captured using the solidification/melting model.
8. The SSPCM transition temperature is fixed, and hysteresis effects are neglected.
9. Initial condition effects were eliminated by discarding the first 24 hours of the simulation; all reported results correspond to the second 24-hour period of the 48-hour run to ensure that initial condition influences were eliminated from the numerical results.
10. Moisture transfer and condensation within the air gap are not accounted for in this study.
11. All interfaces between all layers of SSPCM, air gap and glass are assumed to be in perfect thermal contact (i.e., no interfacial thermal resistances at these interfaces)

### 5.3.2 *Numerical model validation*

To validate the numerical model incorporating the Discrete Ordinates (DO) radiation model and the solidification/melting model in glazing systems, transient numerical results over a 12,000-second simulation period are compared with experimental data reported by Gowreesunker et al. (2013). Their study investigated transmittance variations in PCM-filled glazing units over time. A specialized experimental setup was developed to monitor radiation effects during the mushy phase, which cannot be captured using a spectrophotometer alone. The setup was housed in an environmental chamber with controlled air temperature, and a 150 W metal halide lamp emitting diffuse neutral white light was used as the radiation source. The test specimen was a regular double-glazed unit measuring 20 cm by 20 cm, with an overall

thickness of 24 mm. It consisted of two 4 mm glass panes separated by a 16 mm air gap. In the PCM-filled configuration, the air gap was replaced with RT27. The initial air gap temperature and irradiation level were set at 13°C and 950 W/m<sup>2</sup>, respectively.

The experimental transmittance data from (Gowreesunker et al., 2013) is used to validate the numerical model. This data is illustrated in Figure 5.2a by the black dashed curve, with corresponding uncertainty bounds indicated by gray dashed curves. In Figure 5.2, transmittance is defined as the ratio of radiation flux transmitted through the front and back surfaces. The post-processing procedure for transmittance calculation in the present study follows the same equations and methodology described in the study of (Gowreesunker et al., 2013) and is represented in Equations (5.17) to (5.19). The simulation results, represented by the red curve, show strong agreement with the experimental measurements, remaining within the defined margin of error. The transmittance trends observed in both datasets also exhibit consistent behavior over time. Some discrepancies between the numerical and experimental results are noticeable in certain regions of the curve. These are attributed to the enthalpy-porosity model, which assumes a linear relationship between temperature and liquid fraction within the phase change range. This model treats the mushy region as a porous medium, with porosity directly dependent on local temperature. Although this linearization simplifies the melting and solidification modeling, it introduces limitations, particularly where the experimental data indicate non-linear transitions. As shown in Figure 5.2b, the numerical results fall within a  $\pm 10$  percent range of the experimental values, thereby validating the model. This level of agreement confirms the model's suitability for simulating glazing systems incorporating SSPCMs in the present study.

$$d' = (\sigma_a + \sigma_s)s \quad (5.17)$$

$$\tau_{PCM} = 10^{-d'} \quad (5.18)$$

$$\sigma_a = \sigma_s \left[ \frac{\tau_{PCM,liquid} - \tau_{PCM,solid}}{1 - \tau_{PCM,solid}} \beta + \frac{1 - \tau_{PCM,liquid}}{1 - \tau_{PCM,solid}} \right] \quad (5.19)$$

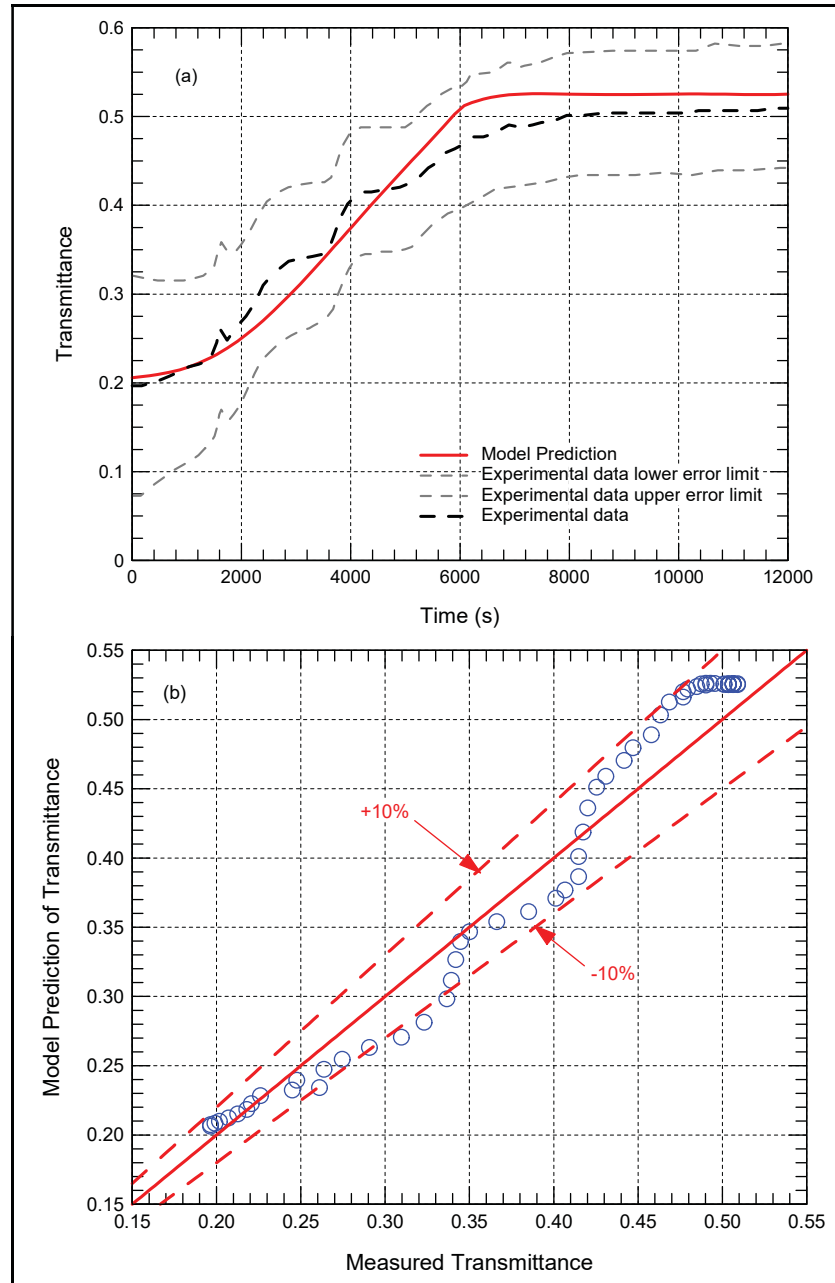


Figure 5.2 Current numerical model results compared to the experimental data (Gowreesunker et al., 2013)

### 5.3.3 Grid and time-step sensitivity analysis

A grid and time-step sensitivity analysis are conducted to determine the optimal combination that ensures numerical accuracy while minimizing computational time. To evaluate the model sensitivity to spatial and temporal resolution, a series of simulations is performed using various mesh densities and time-step sizes. The time-averaged values of the air gap volume-averaged velocity (mm/s), air gap volume-averaged temperature (K), and glazing system heat energy (kJ) are presented in Tables 5.2 and 5.3, facilitating direct comparison across different mesh and time-step sizes. The error is calculated using Equation (5.20) for each mesh size and time-step. The goal is to confirm that the selected mesh and time-step adequately capture the key thermal and flow features of the system without introducing unnecessary computational load. Based on this analysis, a mesh containing 262,800 elements combined with a time-step of 300 seconds provide the most suitable compromise between accuracy and efficiency (i.e., the numerical solutions are approximately the same as those for finer mesh and smaller time-step). This configuration is therefore used for all simulations in the present study.

$$ith\ error = E_i = \frac{(F_{i+1} - F_i)}{F_i} \times 100 \quad (5.20)$$

where,  $F_i$  denotes the criterion parameter corresponding to each grid size and time step.

Table 5.2 Mesh sensitivity analysis

| No (i) | Number of Elements | v (mm/s) | Error (%) | $\bar{T}$ (K) | Error (%) | E (kJ) | Error (%) |
|--------|--------------------|----------|-----------|---------------|-----------|--------|-----------|
| 1      | 33,300             | 15.12    | 88.76     | 300.6         | 0.0019    | 299.99 | 0.22      |
| 2      | 55,125             | 28.54    | 65.59     | 300.6         | 0.0017    | 299.34 | 0.11      |
| 3      | 95,256             | 9.82     | 106.92    | 300.6         | 0.0011    | 299.01 | 0.00      |
| 4      | 158,661            | 20.32    | 64.07     | 300.6         | 0.0019    | 299.02 | 0.07      |
| 5      | 262,800            | 7.30     | 4.11      | 300.6         | 0.0015    | 298.80 | -0.01     |
| 6      | 360,672            | 7.00     | 3.43      | 300.6         | 0.0013    | 298.82 | 0.11      |
| 7      | 451,008            | 6.76     | 5.03      | 300.6         | 0.0003    | 298.49 | -0.01     |
| 8      | 627,200            | 6.42     | -         | 300.6         | -         | 298.52 | -         |

Table 5.3 Time-step study

| No (i) | Time-step size | v (mm/s) | Error (%) | $\bar{T}$ (K) | Error (%) | E (kJ) | Error (%) |
|--------|----------------|----------|-----------|---------------|-----------|--------|-----------|
| 1      | 1 hour         | 7.72     | 0.13      | 289.3         | 2.60      | 298.95 | 0.47      |
| 2      | 45 min         | 7.71     | 1.18      | 297.0         | 0.52      | 300.34 | -0.46     |
| 3      | 30 min         | 7.62     | 0.93      | 298.6         | 0.34      | 298.95 | -0.01     |
| 4      | 20 min         | 7.55     | 2.86      | 299.6         | 0.34      | 298.93 | -0.03     |
| 5      | 10 min         | 7.34     | 0.55      | 300.6         | 0.17      | 298.84 | -0.01     |
| 6      | 5 min          | 7.30     | -1.75     | 301.1         | 0.09      | 298.80 | 0.00      |
| 7      | 2.5 min        | 7.43     | -2.62     | 301.4         | 0.05      | 298.80 | 0.02      |
| 8      | 1 min          | 7.63     | 1.17      | 301.6         | 0.00      | 298.87 | 0.07      |
| 9      | 30 sec         | 7.72     | -         | 301.6         | -         | 299.08 | -         |

#### 5.4 Results and discussion

This study investigates the energy and optical performance of the DGW-SSPCM system during the hottest and coldest days of 2022 in Montreal, Canada, under both sunny and cloudy conditions. A parametric analysis is conducted to assess the influence of glazing orientation and the transient thermal response of the SSPCM on system behavior across the four principal orientations: north, east, south, and west. Natural convection (NC) from buoyancy-driven flow within the air gap is included in all simulations to ensure accurate assessment of glazing system performance. Additional simulations excluding NC are performed to evaluate its impact and to determine whether it can be reasonably neglected to reduce computational cost without significantly compromising accuracy. The following sections present the results in a structured manner: the optical performance is first examined through the transient evolution of the transparency fraction over time; this is followed by a detailed analysis of fluid flow and heat transfer within the air gap, including the temperature difference across the air gap surfaces, velocity vector distributions, and the evaluation of Reynolds number (Re) and Raileigh number (Ra). The definitions of Re and Ra are provided in the Nomenclature, where the characteristic length for Re is the air gap depth (16 mm for DGW-REF and 14 mm for DGW-SSPCM), and

for Ra it is the air gap height (200 mm). The discussion then moves to the thermal behavior of the system and concludes with an evaluation of the overall energy performance.

#### **5.4.1 *Optical performance***

Figure 5.3 illustrates the variation of the transparency fraction of the SSPCM in the glazing system over a 24-hour period for all orientations, with and without the consideration of NC, under both sunny and cloudy conditions during summer. The results indicate that the difference between the cases with and without NC is negligible. Throughout the summer period, the SSPCM completes its phase transition cycle across all orientations, regardless of whether the conditions are sunny or cloudy. During nighttime hours, the absence of solar radiation leads to a drop in the system temperature below the phase change freezing temperature threshold, resulting in the SSPCM remaining fully opaque. With sunrise, ambient temperature begins to rise, and the combined effect of direct and diffuse solar radiation contributes to the heating of the system. This thermal input triggers the phase transition by surpassing the melting temperature threshold of the soft segment within the molecular structure of the SSPCM, while the hard segment remains solid due to its higher melting point. As a result of this molecular structure, the material does not become liquid but instead gradually transitions to a transparent state. The latent heat storage capability of SSPCM moderates this process, as a defined quantity of energy must be absorbed to complete the phase transition from opaque to transparent.

In terms of orientation-specific behavior, the east-facing glazing system is the first to undergo phase change. It becomes fully transparent at approximately 6:00, begins transitioning back to the opaque phase around 18:00, and reaches full opacity by 22:00. The north-facing system follows, becoming fully transparent around 7:00, initiating its return to the opaque phase at approximately 21:00, and completing the transition by 23:00. The south-facing system reaches full transparency later in the day, around 10:00, while the west-facing system and the configuration under cloudy conditions achieve full transparency at approximately 14:00. These results suggest that the use of SSPCM in fenestration systems is particularly suited for commercial buildings. By tailoring the transition temperature, it is possible to achieve full transparency during typical office hours while simultaneously contributing to thermal regulation. This dual functionality supports visual comfort and energy efficiency during



working periods. However, for residential applications, the application of SSPCM in residential glazing may offer limited visual benefits.

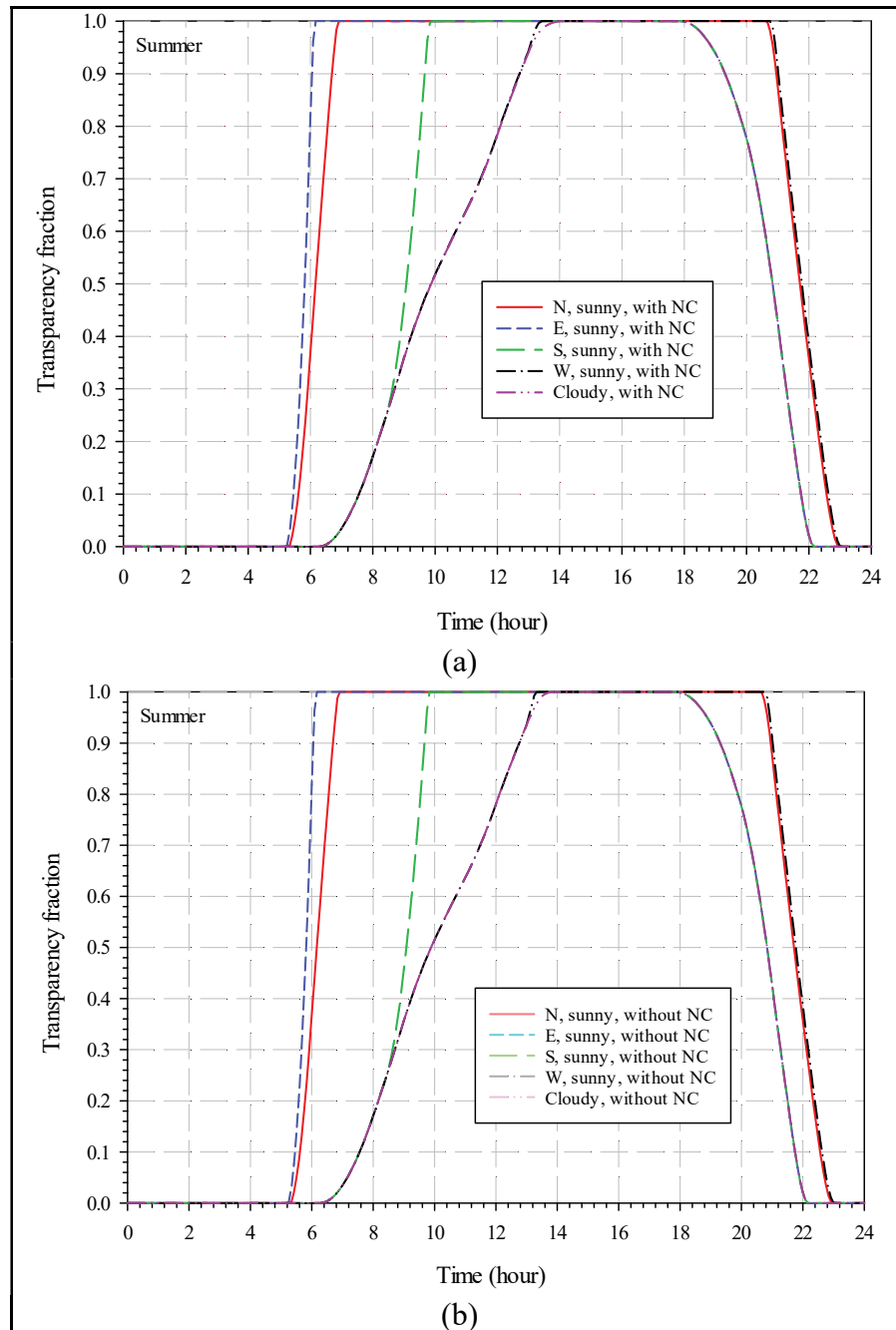


Figure 5.3 Transparency fraction variation over a 24-hour period for different orientations in DGW-REF and DGW-SSPCM, (a) with and (b) without NC, under summer conditions

Figure 5.4 presents the transparency fraction variation of the SSPCM in the glazing system over a 24-hour period for all orientations, considering both the presence and absence of NC, under sunny and cloudy winter conditions. Unlike the summer results, the winter cases show a noticeable difference between simulations with and without NC. During the winter season, the SSPCM remains in its opaque state throughout the entire day for both the cloudy and north-facing scenarios, indicating that the available solar energy is insufficient to trigger a phase change. This highlights the limited solar gain on these surfaces under such conditions, preventing the SSPCM from absorbing the heat energy required to initiate the transition to a transparent state. In contrast, the east, south, and west orientations experience a complete phase transition cycle. Among them, the south-facing window exhibits the most favorable performance, achieving full transparency from 9:00 to 16:00. This extended duration of daylight transmission enhances the glazing system potential for natural lighting and passive solar heating during the cold season, making it particularly suitable for commercial buildings.

When comparing the system behavior with and without NC, the initiation of the phase change in the south-facing configuration occurs at approximately the same time in both cases. However, the presence of NC delays the time SSPCM reaches the opaque phase by about 30 minutes. Conversely, once the ambient temperature begins to drop and the SSPCM starts transitioning back from transparent to opaque, the presence of NC accelerates the onset of this reverse phase change by approximately 30 minutes compared to the case without NC. These results demonstrate that while NC has a limited impact on the overall duration of the transparent state, it can influence the dynamics of the transition process. The presence of NC contributes to more gradual thermal responses. This behavior further emphasizes the importance of accounting for NC effects when evaluating the performance of SSPCM-integrated glazing systems in cold climates.

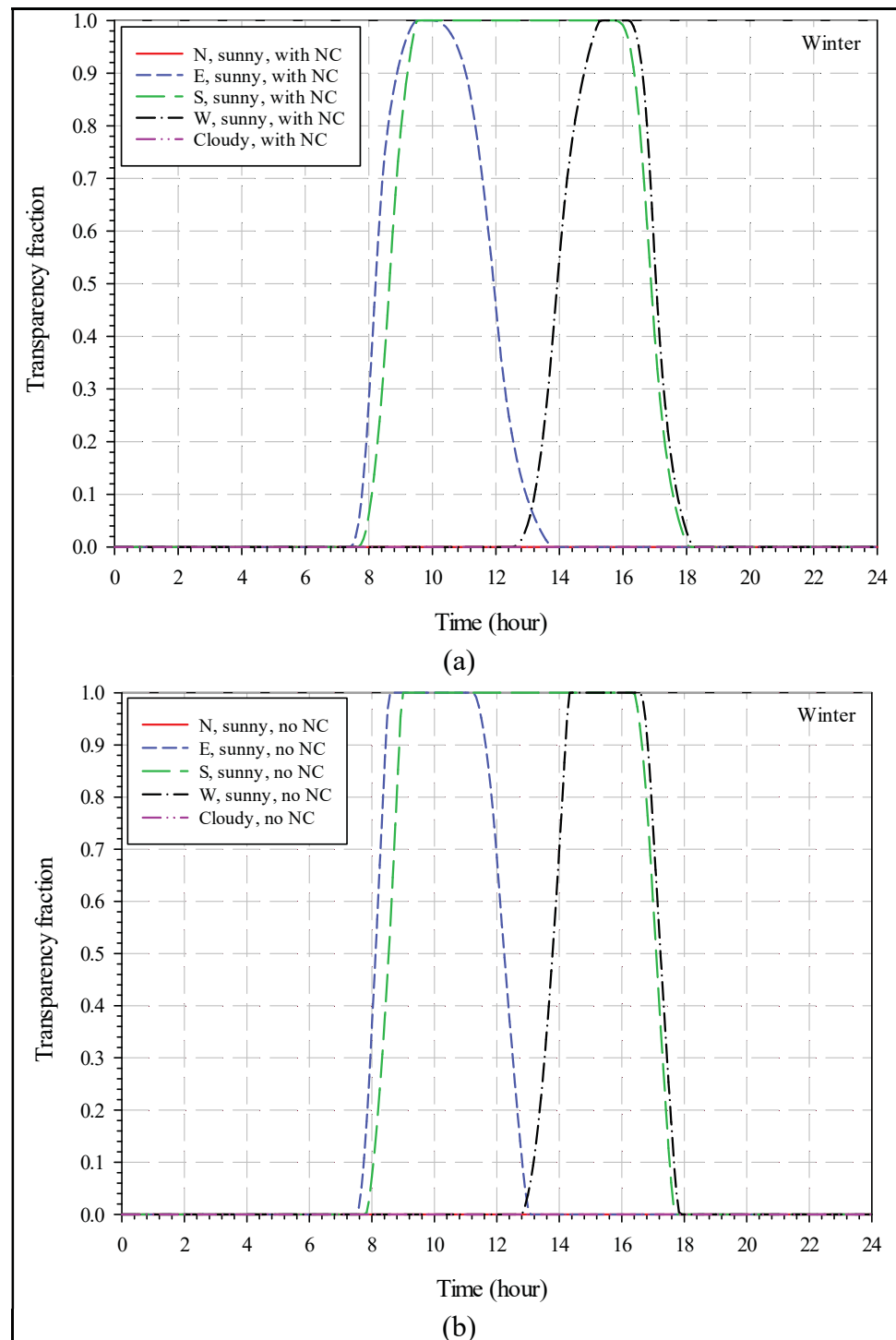


Figure 5.4 Transparency fraction variation over a 24-hour period for different orientations in DGW-REF and DGW-SSPCM configurations, (a) with and (b) without NC, under winter conditions

#### **5.4.2      *Fluid flow and heat transfer analysis within air gap***

This section analyzes the thermofluid behavior within the air gap of the glazing system under conditions where NC is present. Various parameters are examined to characterize the physical phenomena occurring inside the air gap and to establish a scientific basis for interpreting the system's energy performance under different seasonal and orientation-specific conditions.

##### **5.4.2.1      Temperature difference across air gap**

Figure 5.5 presents the hourly variation of the area-weighted temperature difference across the air gap between the two facing surfaces within the glazing system. The results are shown for both the DGW-REF and DGW-SSPCM systems under various seasonal conditions and orientations. As shown in Figure 5.5, the temperature difference is considerably higher in winter than in summer. During winter, values typically range from 15 °C to 30 °C, mostly remaining above 25 °C, while in summer, the temperature difference stays between 0 and 5 °C throughout the 24-hour period. This seasonal contrast reflects the stronger thermal gradient that exists during winter, when the indoor temperature is maintained at a much higher level than the cold exterior conditions, thereby intensifying buoyancy-driven flow. This would result in obtaining lower thermal performance.

The effect of orientation is clearly observed, particularly in winter. The south-oriented configuration shows the lowest temperature difference among all orientations. This can be attributed to higher solar irradiation on the south-facing exterior surface, which increases the temperature of that surface and brings it closer to the indoor design temperature, thus reducing the overall thermal gradient across the air gap. In contrast, the north orientation as well as cloudy condition, which receive less solar radiation, exhibit higher temperature differences.

Differences between the DGW-REF and DGW-SSPCM systems are also apparent. The phase change behavior of the SSPCM introduces a delay in thermal response, which becomes especially visible during the evening hours after approximately 16:00. As the ambient temperature drops, the SSPCM undergoes phase transition and releases the stored latent heat to the surrounding air gap.

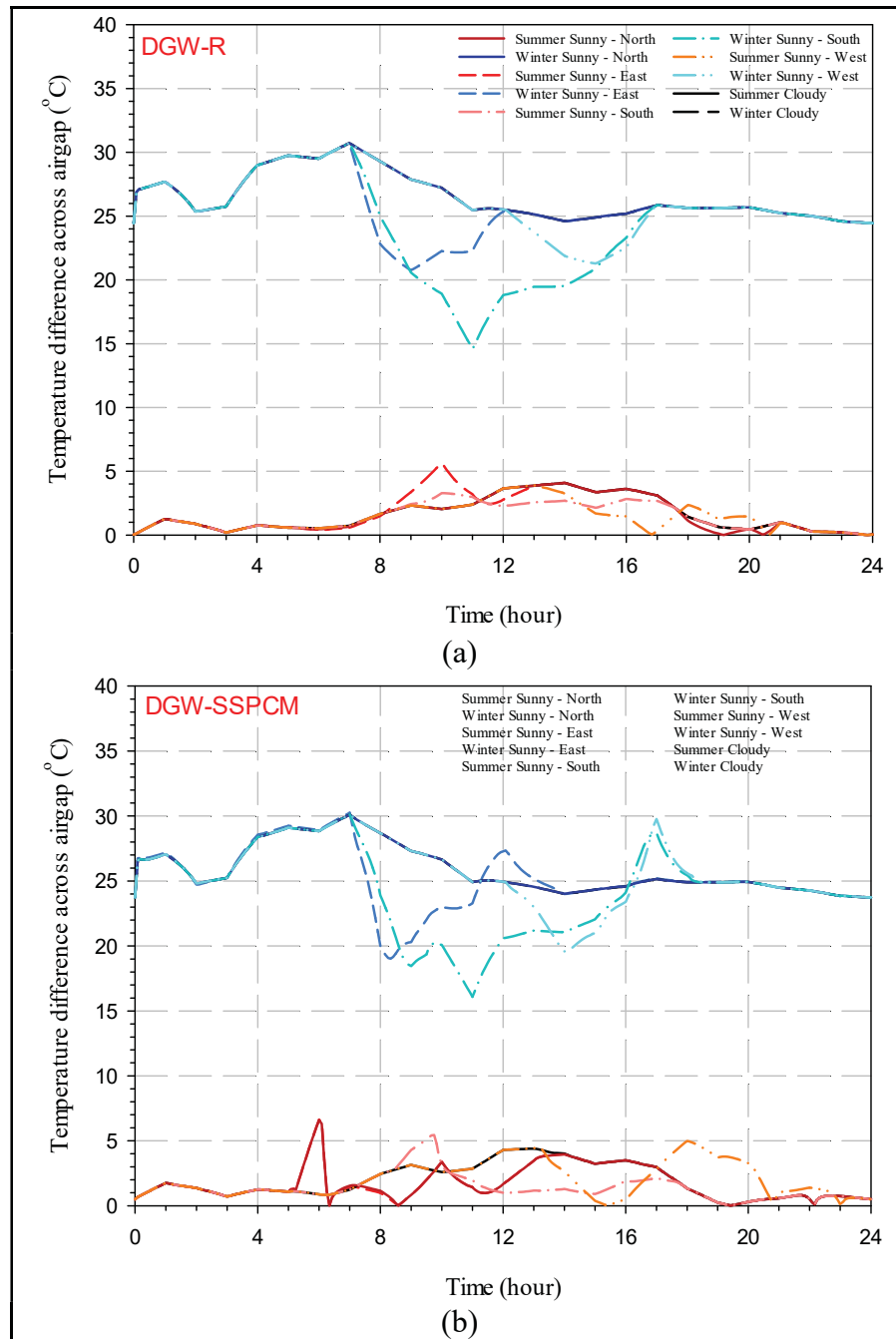


Figure 5.5 Transparency fraction variation over a 24-hour period for different orientations in DGW-REF and DGW-SSPCM configurations, (a) with and (b) without NC, under winter conditions

This process elevates the temperature of the SSPCM-facing surface, thereby causing both decrease and increase in the temperature difference compared to the DGW-REF system based

on the orientation. This behavior is most evident in winter, where the influence of latent heat release is more pronounced due to larger diurnal temperature swings.

#### 5.4.2.2 Airflow velocity behavior within the air gap

For south-oriented DGW-SSPCM system as example, Figures 5.6 and 5.7 present the velocity vector distribution within the air gap over a 24-hour simulation period for summer and winter design days, respectively. The vectors are colored according to the velocity magnitude, depicting the development and evolution of airflow induced due to buoyancy-driven. These visualizations are used to evaluate transient flow structures within the air gap, which result from the temperature difference between the two internal-facing surfaces of the air gap, as described in section 4.2.1. The results were obtained in a vertical slice passing through the mid-depth of the system (i.e.,  $x = W/2$ ), allowing a clear representation of the airflow pattern across the cavity height.

Figure 5.6 shows the velocity vector distribution within the air gap of the south-oriented DGW-SSPCM system during the summer design day. The results reveal that the flow field remains weak and largely inactive during the nighttime and early morning hours, specifically between 00:00 and 08:00. This is attributed to the minimal temperature difference between the opposing surfaces of the air gap during this period, which results in insignificant buoyancy forces to drive the air movement. Between 09:00 and 13:00, a slight increase in convective activity is observed, with upward motion developing near the sunlit exterior surface as solar irradiance induces surface heating. However, even during the peak solar hours from 11:00 to 14:00, the flow remains a quite weak where the velocity magnitudes do not exceed 0.05 m/s. The resulted flow lacks well-organized convective loops. After 15:00, as solar input decreases and the exterior surface temperature begins to decline, the flow velocity further diminishes. The air within the air gap becomes approximately stagnant, and vector density drops, reflecting a return to conduction-dominant heat transfer. These results are consistent with the low temperature differences reported earlier in Section 4.2.1 (e.g., see Figure 5.5) and confirm that NC plays a minimal role in heat transport within the glazing air gap under summer conditions.

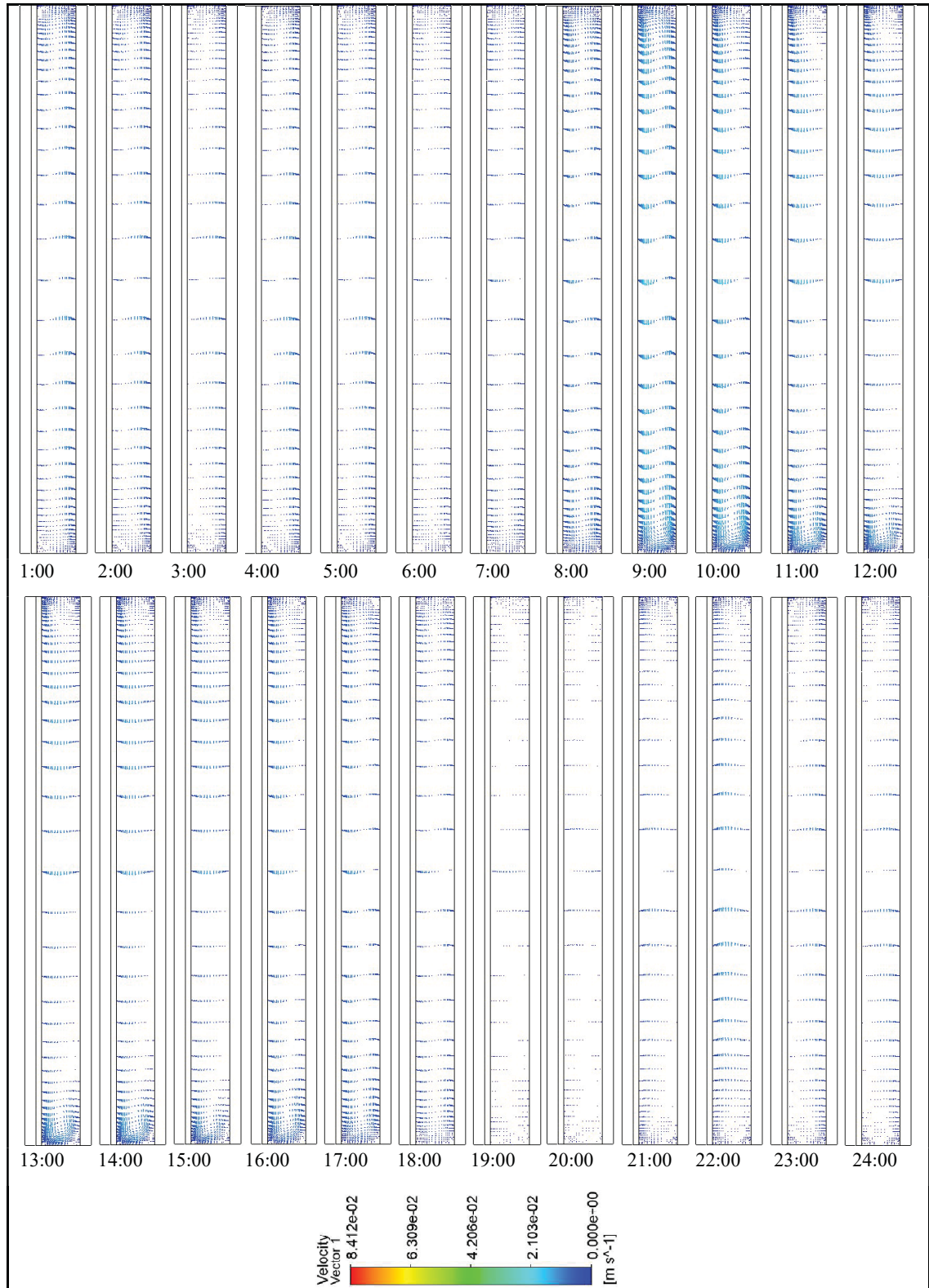


Figure 5.6 Velocity vector distribution within the air gap of the south-oriented DGW-SSPCM system over a 24-hour during summer period

Figure 5.7 shows the velocity vector distribution within the air gap of the south-oriented DGW-SSPCM system during the winter design day. The results indicate that strong convective loops occur between 17:00 and 07:00, corresponding to the period with the highest temperature difference between the two opposing air gap surfaces (see Figure 5.5). Note that the direction of the convection loop in winter is clockwise, whereas that in the summer is counter-clockwise. During this interval, the indoor surface remains consistently warm due to space heating, while the exterior surface temperature drops significantly, resulting in a strong thermal gradient across the air gap. This drives intensified buoyancy forces, leading to the formation of large, coherent convective loops at increased velocity magnitudes, with values reaching up to 0.14 m/s (about three times of that during the summer as shown in Figure 5.6). Between 08:00 and 16:00, a noticeable weakening in the air flow pattern is observed. As solar radiation begins to heat the exterior surface, its temperature rises and approaches the indoor setpoint, thereby reducing the temperature difference across the air gap. This leads to a diminished buoyancy effect, as reflected by the lower velocity magnitudes during daylight hours.

These observations confirm that the strength of the air flow within the air gap is primarily governed by the instantaneous temperature gradient between the glazing surfaces. The cooling of the exterior surface during nighttime, combined with the latent heat release from the SSPCM, enhances the thermal driving potential and promotes stronger convective motion. In contrast, daytime solar gains reduce the temperature gradient and thereby suppress the flow intensity. This diurnal variation highlights the dynamic interplay between solar radiation, phase change effects, and air gap flow behavior in determining the transient thermal performance of the system.

#### **5.4.2.3 Reynolds number**

Figure 5.8 illustrates the hourly variation of volume-averaged velocity within the air gap for both DGW-REF and DGW-SSPCM systems across different orientations and seasonal conditions. This figure clearly highlights a significant difference in air flow velocity between summer and winter. In both systems, air velocities during summer predominantly range from 5 to 15 mm/s, whereas in winter they increase considerably, reaching values between 40 and 50 mm/s.



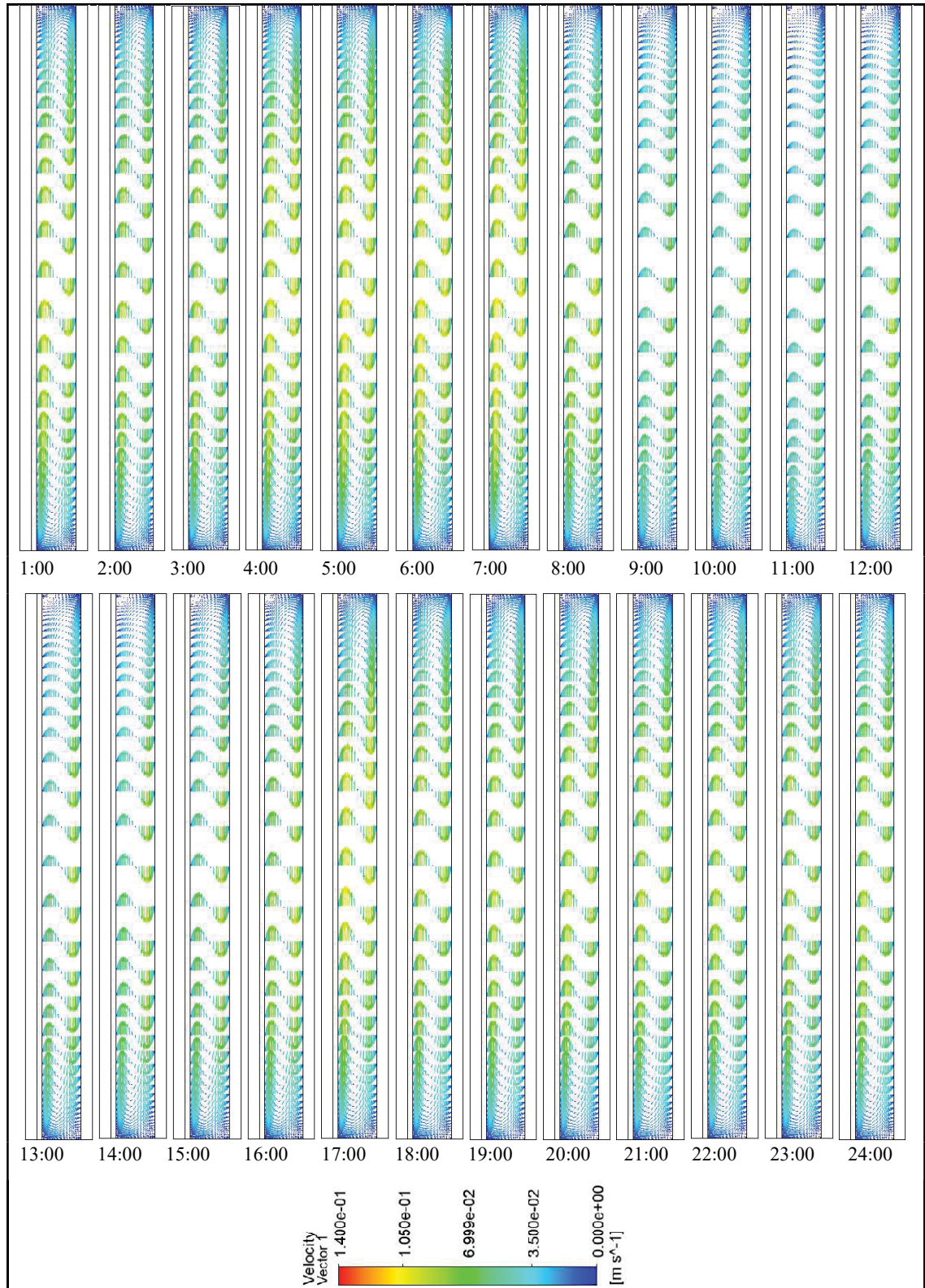


Figure 5.7 Velocity vector distribution within the air gap of the south-oriented DGW-SSPCM system over a 24-hour during winter period

This seasonal disparity is consistent with the temperature difference trends previously discussed (see Figure 5.5), confirming that natural convection is more intense during colder conditions due to a stronger thermal gradient across the air gap. This figure also reveals that during summer, the air gap flow velocity reaches its minimum during nighttime and gradually increases to its peak during the daytime, following the rise in solar radiation. In contrast, the opposite pattern is observed in winter, where the flow velocity is lowest during the day and highest during the night, corresponding to the stronger temperature difference that develops after sunset.

A comparison between Figures 5.8a and 5.8b reveals that the inclusion of the SSPCM results in a damping effect on the air gap velocity, particularly in winter. The latent heat storage of the PCM moderates temperature fluctuations within the air gap, reducing the temperature difference between the inner and outer surfaces. As a result, the buoyancy-driven airflow in the DGW-SSPCM system is slightly weaker than in the DGW-REF configuration. This effect is most evident in winter, where the thermal buffering capacity of the SSPCM limits the peak velocities observed in the reference system. Although a general reduction in velocity is observed with the use of SSPCM, certain cases, such as the west orientation, show localized increases in velocity, particularly in the late afternoon and evening. This behavior is attributed to the heat released by the SSPCM after solar gains are reduced, which temporarily enhances the temperature gradient and sustains convective flow. This effect is visible in both seasons, highlighting the dynamic thermal response introduced by the phase change process.

Figure 5.9 presents the Reynolds number values for the air within the glazing air gap for both DGW-REF and DGW-SSPCM systems. The Reynolds number in summer ranges between 5 and 20, whereas in winter it increases significantly, reaching values between 40 and 53 depending on orientation. This clear seasonal contrast highlights the enhanced convective activity under colder conditions, driven by the stronger thermal gradient between the interior and exterior air gap surfaces. Across all cases, the Reynolds number remains within the laminar regime, indicating that while flow intensity varies significantly with season and orientation, the airflow does not reach transitional or turbulent conditions. These values serve as quantitative confirmation of the natural convection behavior observed in the velocity vector

distributions and support the interpretation of flow regime characteristics in the subsequent analysis.

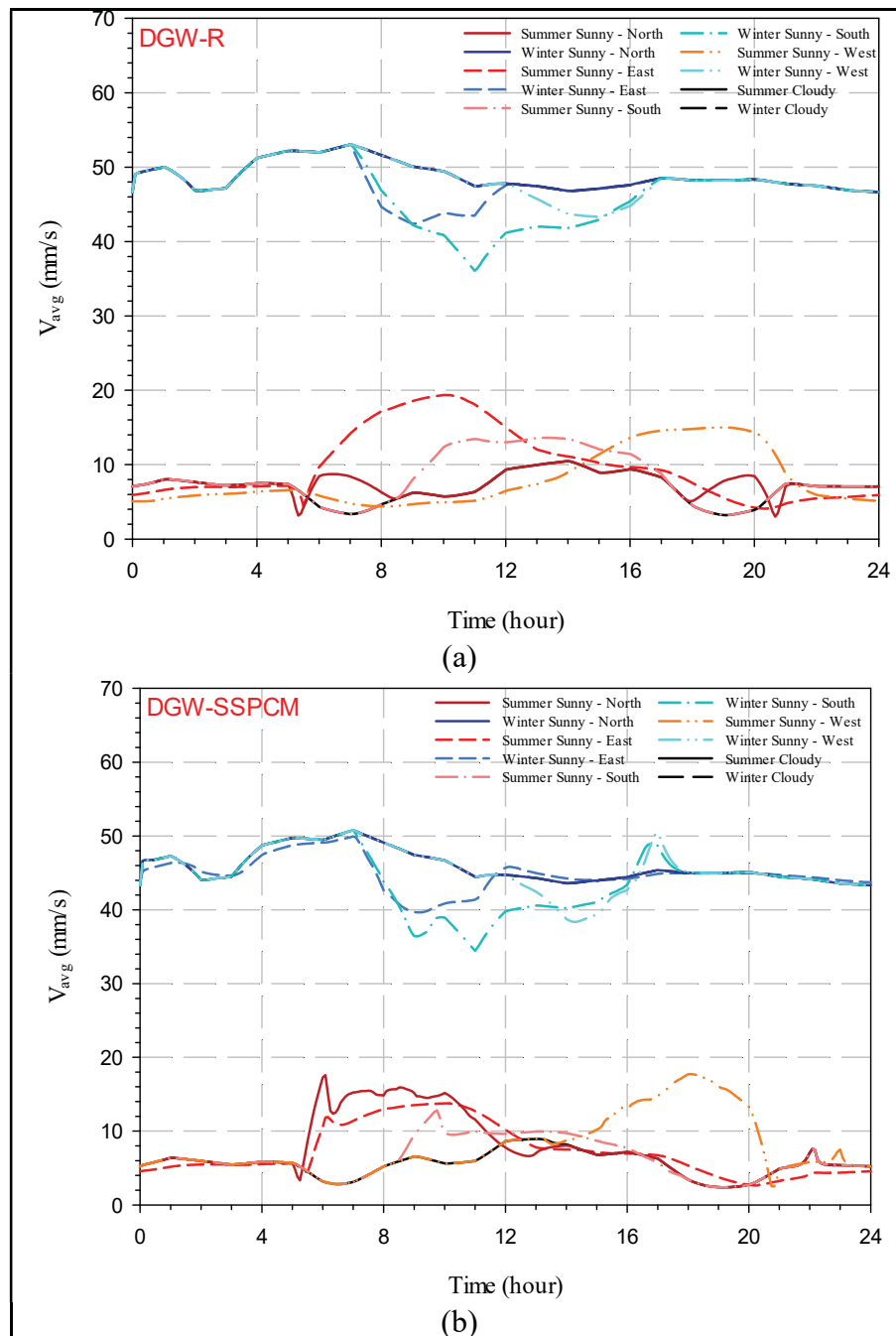


Figure 5.8 Variation of volume-averaged air velocity within the glazing air gap over a 24-hour period in (a) DGW-REF and (b) DGW-SSPCM systems under summer and winter conditions

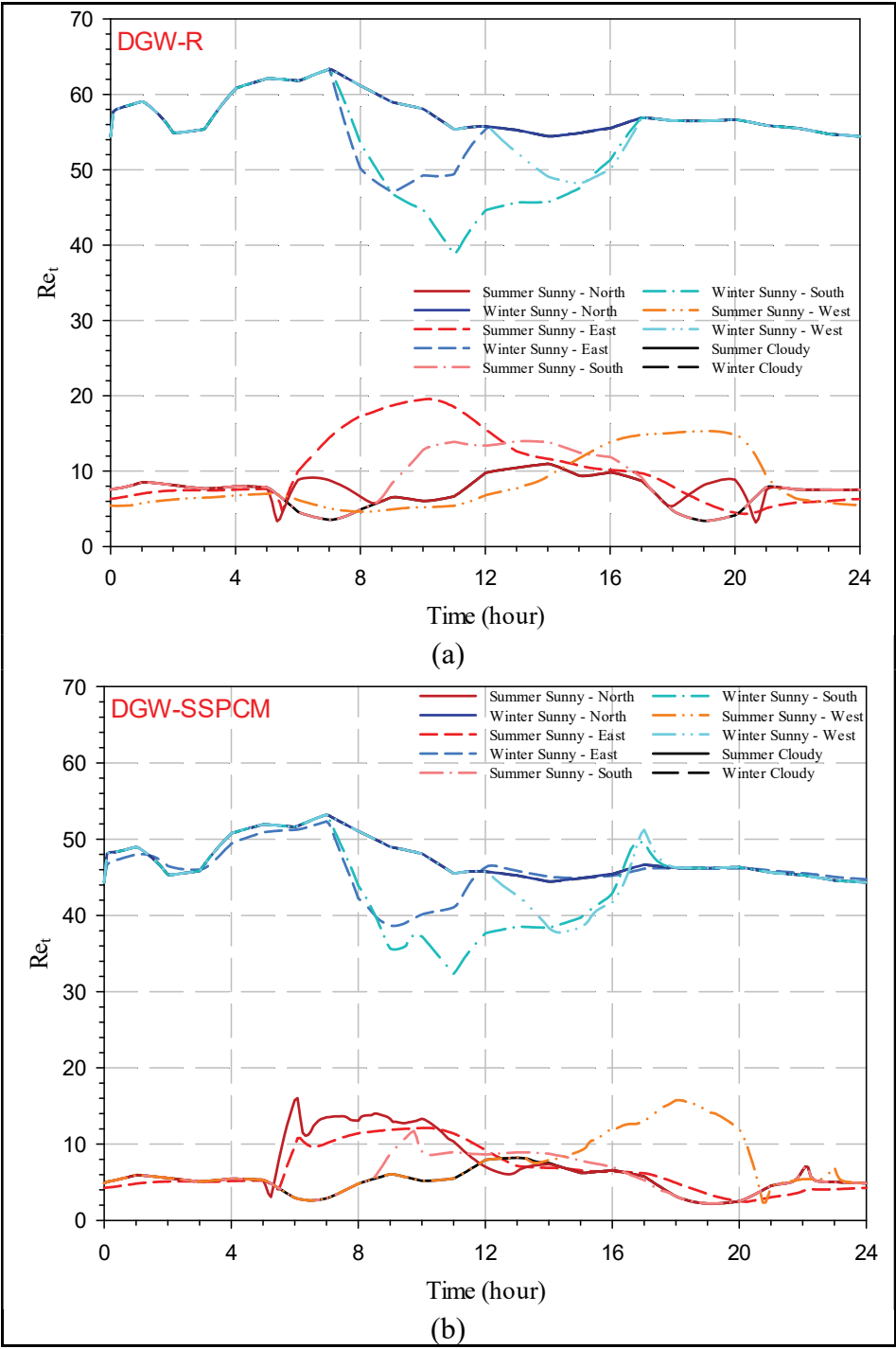


Figure 5.9 Variation of Reynolds number within the glazing air gap over a 24-hour period in (a) DGW-REF and (b) DGW-SSPCM systems under summer and winter conditions

Figure 5.10 presents the time-averaged values of the air gap flow velocity for all simulated cases across both seasons. The time-averaged velocity is substantially higher in winter for all cases, ranging from approximately 44.0 to 48.8 mm/s, compared to only 5.6 to 9.8 mm/s in summer. This seasonal disparity reaffirms the significant enhancement of NC during cold conditions due to the larger temperature difference between the indoor and outdoor surfaces. The DGW-REF system consistently exhibits slightly higher velocities than DGW-SSPCM in winter, reflecting the moderating influence of the PCM, which reduces the temperature gradient and suppresses convective flow to some extent. In summer, however, the difference between the two systems is minimal.

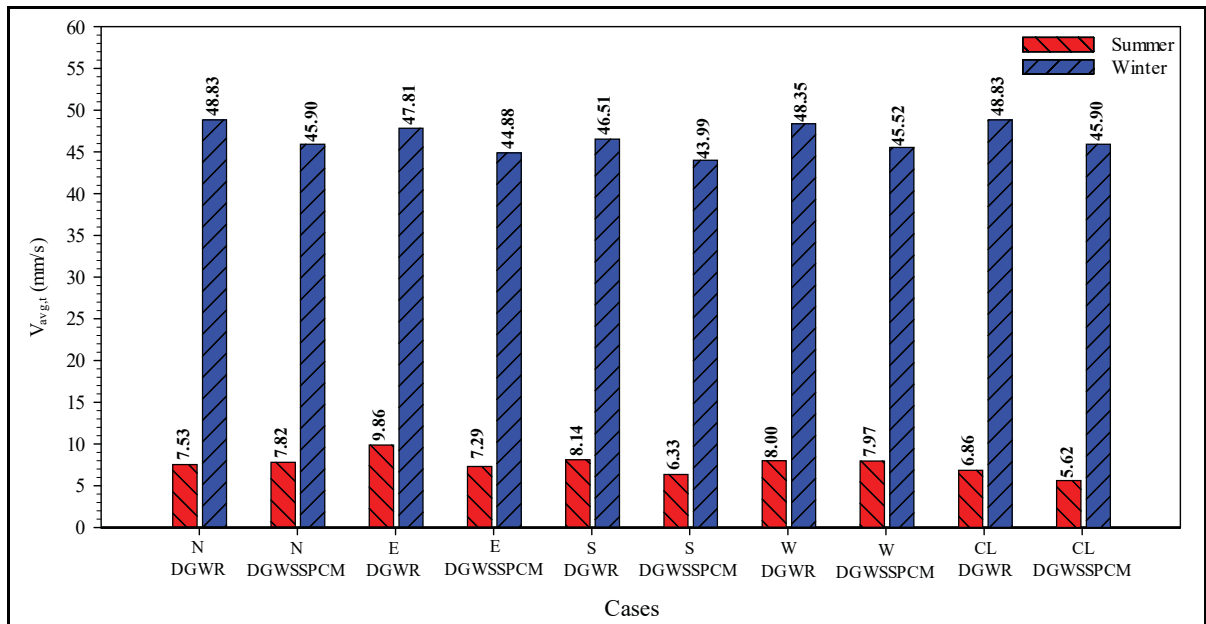


Figure 5.10 Time-averaged of the volume-averaged air velocity within the glazing air gap for all orientations in DGW-REF and DGW-SSPCM systems under summer and winter conditions

Figure 5.11 illustrates the corresponding time-averaged values of the air gap flow Reynolds number for all simulated cases across both seasons. In winter, time-averaged Reynolds numbers lie between approximately 44 and 49, confirming that the air gap flow remains in the laminar natural convection regime but with strong and sustained buoyancy-driven motion. In summer, the average Reynolds numbers remain well below 10.

The highest values for the time-averaged velocity and Reynolds number occur in the north and cloudy cases during winter for both DGW-REF and DGW-SSPCM systems. In summer, however, the highest values are observed in the east-facing configuration for DGW-REF and the west-facing configuration for DGW-SSPCM.

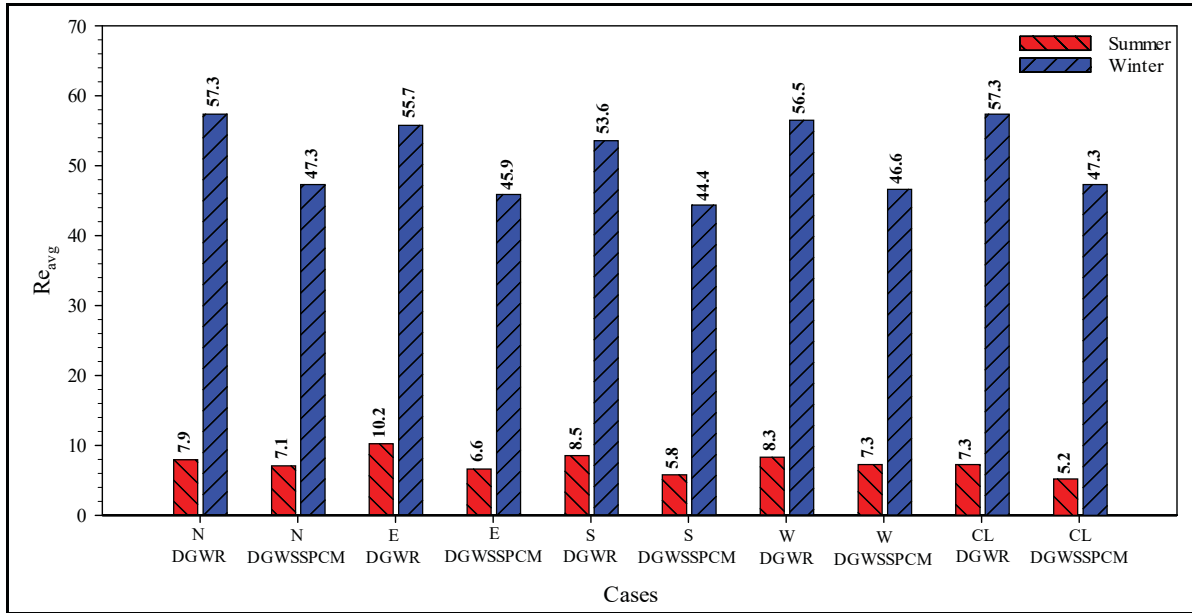


Figure 5.11 Time-averaged of the volume-averaged air velocity within the glazing air gap for all orientations in DGW-REF and DGW-SSPCM systems under summer and winter conditions

#### 5.4.2.4 Rayleigh number

Figure 5.12 presents the Rayleigh number values for the air within the glazing air gap for both DGW-REF and DGW-SSPCM systems. The Ra is defined as  $Ra = \frac{g\beta'\Delta Td^3}{\nu\alpha}$ , where “d” denotes the air gap depth, which is used as the characteristic length in this study (Dalal et al., 2009; Tafakkori and Fattahi, 2021). The most noticeable observation is the significantly higher fluctuation intensity of the Rayleigh number in summer compared to the relatively stable values in winter. These fluctuations are even more pronounced in the DGW-SSPCM system than in the DGW-REF system, likely due to the dynamic phase change behavior of the PCM. Despite this, the overall Rayleigh number magnitudes remain nearly identical between the two systems with and without PCM in both seasons.

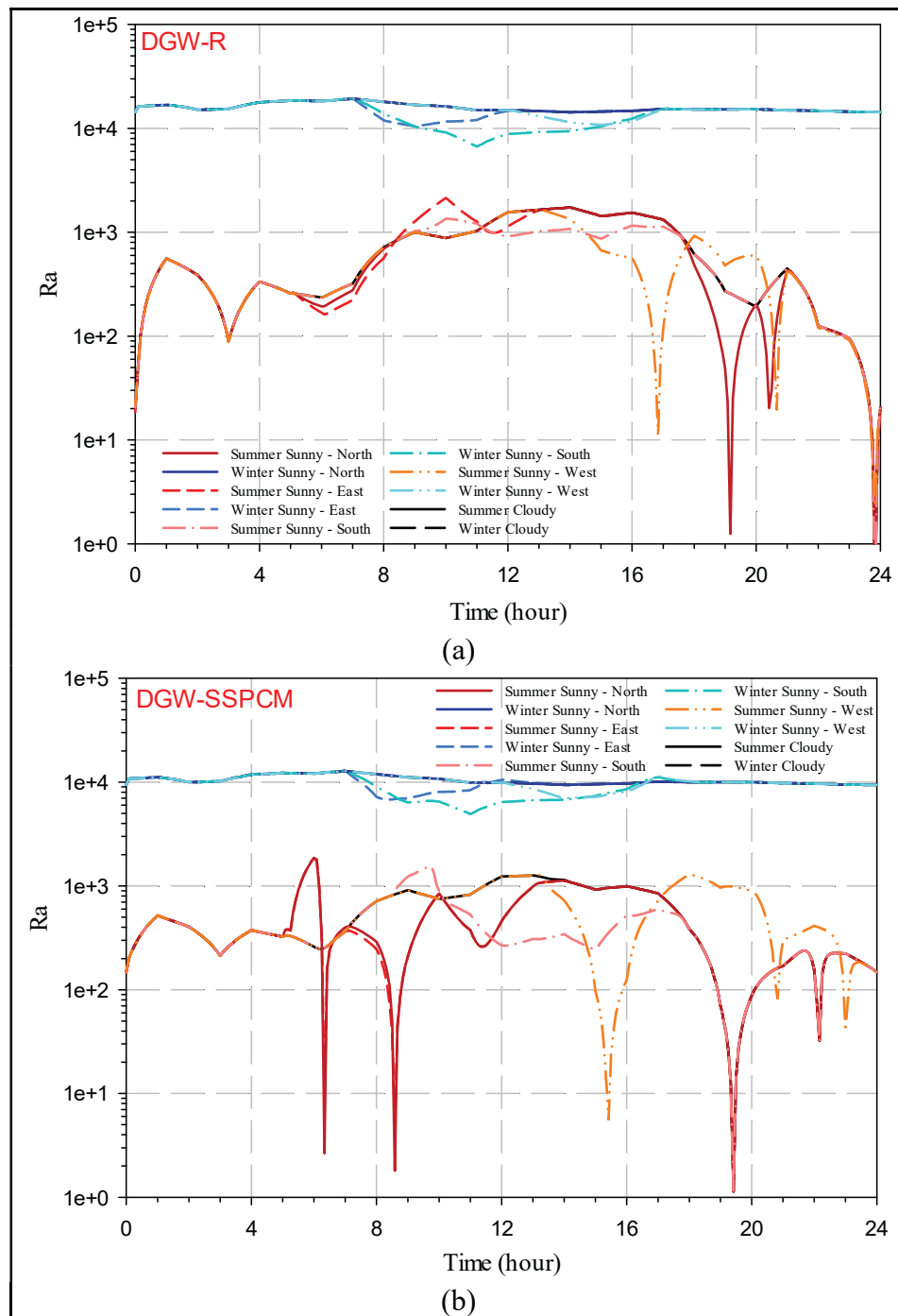


Figure 5.12 Variation of the Rayleigh number within the glazing air gap over a 24-hour period in (a) DGW-REF and (b) DGW-SSPCM systems under summer and winter conditions



The Rayleigh number is a dimensionless parameter that governs the stability and transition from purely conductive to convective heat transfer, with higher values indicating the dominance of buoyancy-induced fluid motion over thermal diffusion. In this context, this figure shows that during summer, the Rayleigh number fluctuates mostly between  $10^2$  and  $10^3$ . In contrast, during winter, the Rayleigh number consistently fluctuates around  $10^4$ , clearly indicating the higher dominance of buoyancy-induced fluid motion over thermal diffusion in cold conditions. In this study, as the Rayleigh numbers for all systems with and without PCM were well below  $10^5$ , the air flow in the glazing systems is laminar.

By factoring out all of the constant values in the Rayleigh number formulation, based on the assumptions applied for air properties in the present study, it can be expressed in the form  $Ra = C \cdot \Delta T / T^3$ , where  $C$  is a constant and equal to  $1.16 \times 10^{10} \text{ K}^2$  for DGW-SSPCM and  $7.79 \times 10^9 \text{ K}^2$  for DGW-REF. This expression highlights that the Rayleigh number is directly proportional to the temperature difference across the air gap ( $\Delta T$ ) and inversely proportional to the cube of the volume-averaged temperature within the air gap ( $T^3$ ), highlighting its high sensitivity to thermal boundary conditions. Consequently, the higher temperature differences and lower average air gap temperatures in winter lead to substantially greater Rayleigh numbers and more intense buoyancy-driven convection compared to summer conditions. Furthermore, abrupt variations in temperature ( $T$ ) during summer, driven by the onset of intense solar irradiation, lead to frequent fluctuations in the Rayleigh number.

Figure 5.13 presents the time-averaged Rayleigh number for each simulated case, comparing seasonal and system-based variations. As expected, winter values are significantly higher across all orientations and both glazing systems, with values ranging from approximately  $0.9 \times 10^4$  to  $1.6 \times 10^4$ . In contrast, summer values remain below  $7.4 \times 10^2$ , indicating higher conduction-dominated heat transfer within the air gap. The highest Rayleigh numbers are observed in the north and cloudy cases during winter for both DGW-REF and DGW-SSPCM systems. These cases correspond to the largest temperature differences between the two air gap surfaces due to minimal solar gain on the exterior surface. Among all orientations, however, the south-facing cases consistently show the lowest values in winter, as solar heating raises the exterior surface temperature and reduces the thermal gradient. Additionally, the use of SSPCM



leads to a slight reduction in the Rayleigh number across most winter cases. This is attributed to the PCM's ability to absorb and release heat, moderating the surface temperature difference and slightly lowering the buoyancy potential. In summer, the difference between the DGW-REF and DGW-SSPCM systems is negligible.

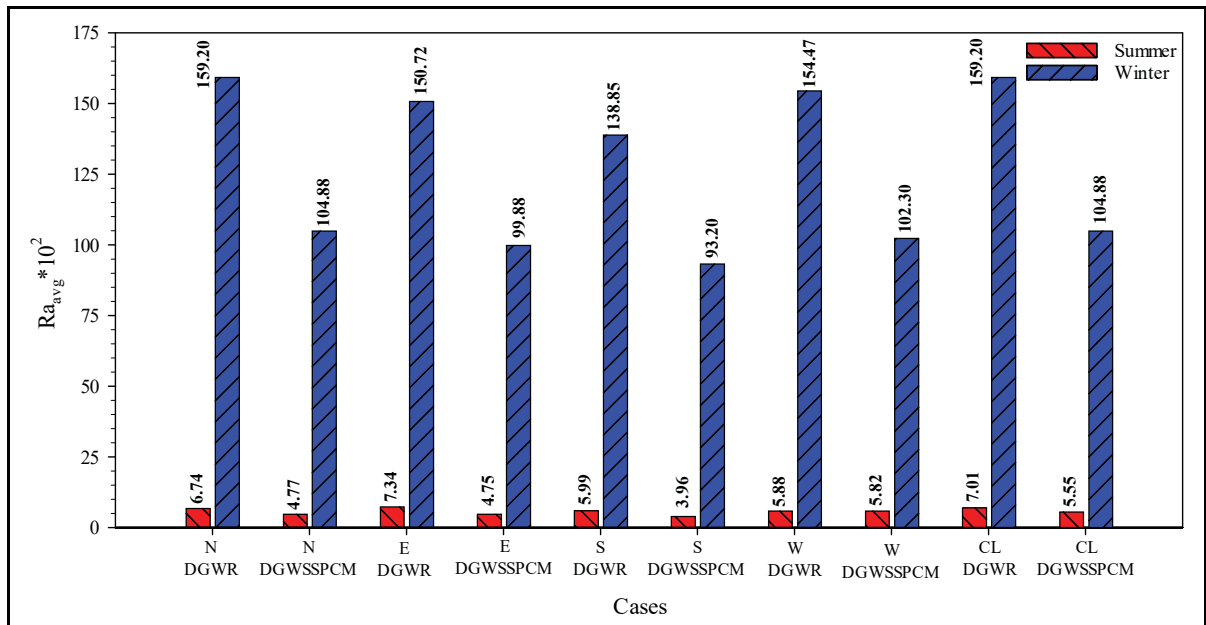


Figure 5.13 Time-averaged Rayleigh number within the glazing air gap for all orientations in DGW-REF and DGW-SSPCM systems under summer and winter conditions

It should be noted that the effect of the air gap difference between DGW-REF and DGW-SSPCM is reflected implicitly in the results. The air gap depth ( $d$ ) is directly used as the characteristic length in the  $Re$  and  $Ra$  calculations ( $d = 16$  mm for DGW-REF and  $d = 14$  mm for DGW-SSPCM), and it also influences the airflow velocity, which enters the  $Re$  calculation. Consequently, the impact of the 2 mm reduction in the air gap is implicitly captured in the velocity,  $Re$ , and  $Ra$  results.

#### 5.4.3 Thermal analysis

This section presents the thermal performance evaluation of the DGW-SSPCM system across all studied configurations, with and without the inclusion of NC within the glazing air gap. In cases where NC is not considered, the air layer remains stagnant, and heat transfer occurs only

through conduction and radiation. When NC is included in the model, convection is introduced as an additional heat transfer mechanism, which can enhance the overall thermal response of the system, resulting in lower energy performance. The objective of this comparative analysis is to assess the impact of NC on the system energy behavior, with particular attention to seasonal and orientation-dependent effects. It is important to recognize that incorporating NC significantly increases computational cost, typically by a factor of four to five compared to simulations that neglect it. Therefore, identifying scenarios where NC has a negligible influence can offer an opportunity to simplify the future simulations, reduce computation time, and maintain acceptable accuracy.

Figure 5.14 illustrates the area-weighted average of interior surface temperature for the DGW-REF system during summer for various orientations, with and without the inclusion of NC within the air gap. The results show that the impact of NC on the interior surface temperature remains negligible across all orientations and under both sunny and cloudy conditions. This observation is consistent with the previously noted minimal influence of NC on the transparency fraction, which is attributed to the weak buoyancy-driven airflow within the air gap during summer.

Under cloudy conditions, where direct solar radiation is absent, the interior surface temperature remains relatively stable, ranging between 22 °C and 26 °C throughout the day. In contrast, under sunny conditions, surface temperatures vary depending on orientation, with distinct peak periods corresponding to solar exposure. The east-facing configuration reaches its maximum surface temperature around 8:00, peaking at approximately 37.5 °C. The west-facing window exhibits a peak near 17:00, reaching about 36.5 °C. For the south-facing orientation, the highest surface temperature occurs around midday (13:00), reaching up to 32 °C. The north-facing configuration shows two moderate peaks, one in the early morning around 6:00 and another in the evening around 20:00, with surface temperatures rising to approximately 28 °C.

Figure 5.15 presents the area-weighted average of interior surface temperature for the DGW-REF system during winter for different glazing orientations, with and without the inclusion of NC. The results indicate that NC has a noticeable impact on the interior surface temperature across all orientations and under both sunny and cloudy conditions.

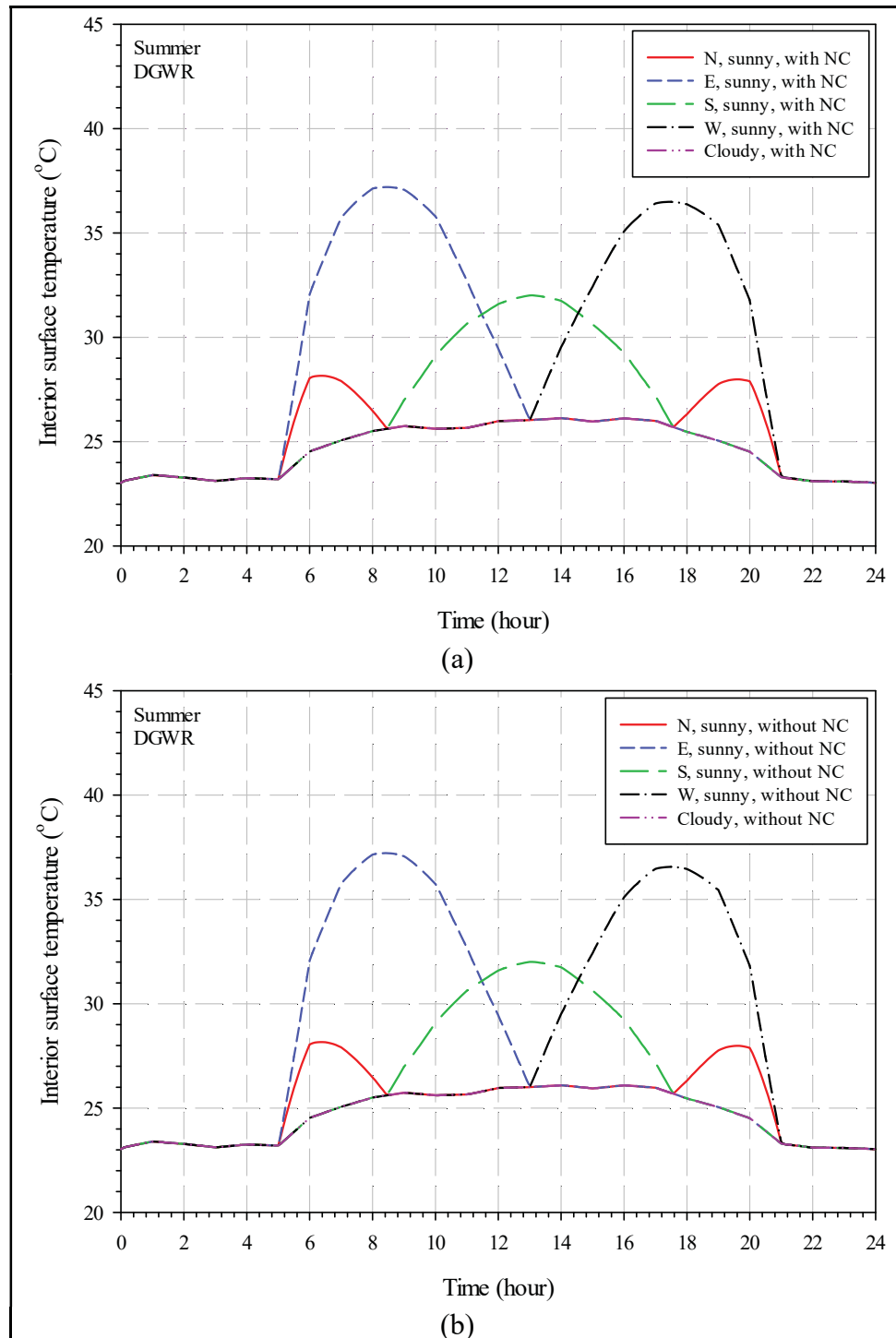


Figure 5.14 Interior surface temperature variation over a 24-hour period for different orientations in DGW-REF configurations, (a) with and (b) without NC, under summer conditions

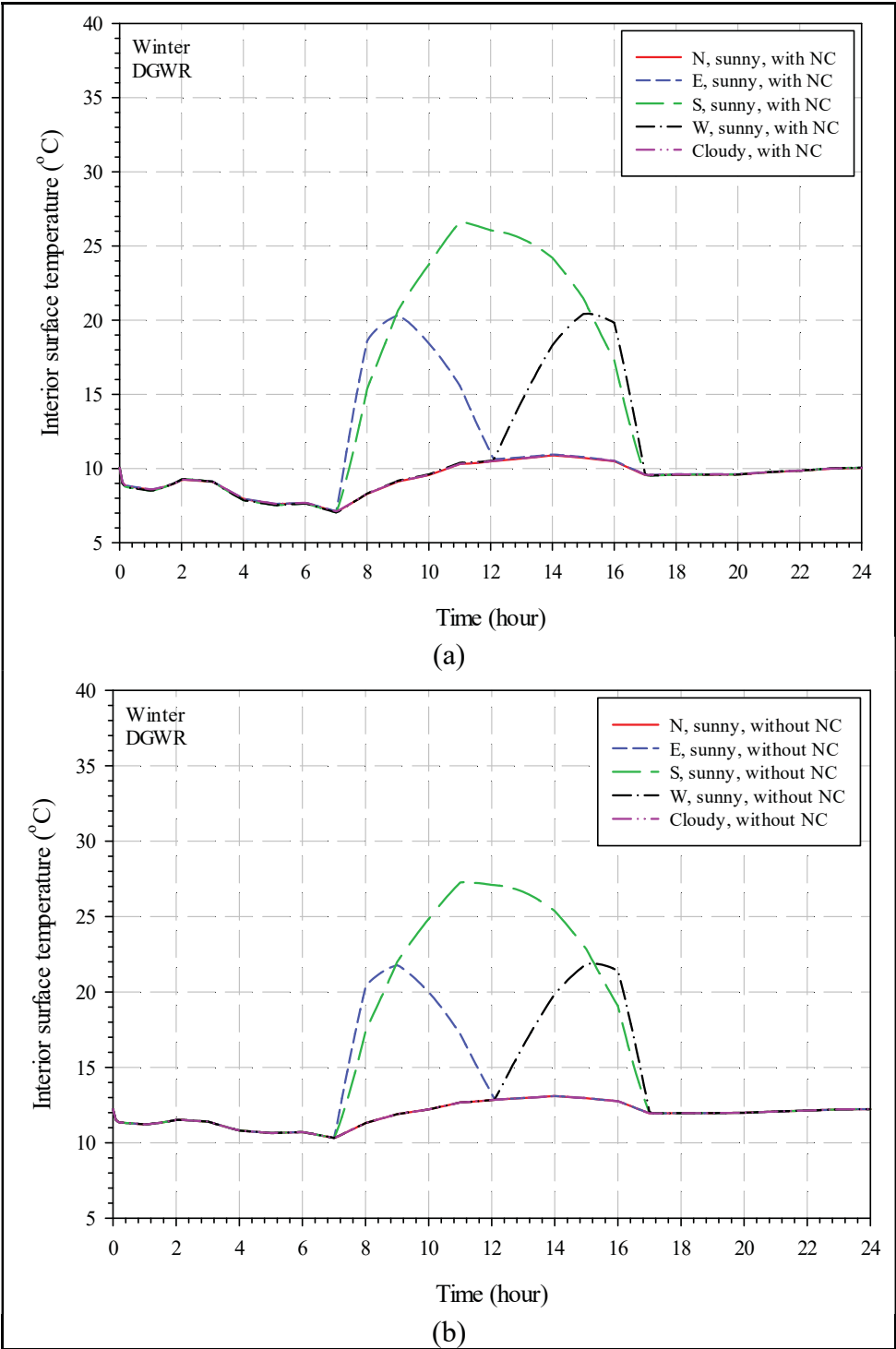


Figure 5.15 Interior surface temperature variation over a 24-hour period for different orientations in DGW-REF configurations, (a) with and (b) without NC, under winter conditions

This behavior aligns with the previously observed significant influence of NC on the transparency fraction, which is driven by the strong buoyancy-induced airflow within the glazing air gap during winter. Figure 5.15 also shows that for the north-facing configuration and under cloudy conditions, the interior surface temperature remains relatively low and stable throughout the day, ranging between 7 °C and 11 °C with no distinct peak. When NC is considered, the interior surface temperature is approximately 3.5°C lower than the case without NC. This reduction further confirms the enhanced heat transfer within the system resulting from the addition of a new heat transfer mode, namely convection, which becomes active when NC is considered. In contrast, the other three orientations (east, south, and west) exhibit distinct peaks in surface temperature during the day under sunny conditions. Among these, the south-facing configuration reaches the highest peak, with the inner surface temperature rising to approximately 27 °C around midday.

Figure 5.16 illustrates the area-weighted average of interior surface temperature for the DGW-SSPCM system during summer for various glazing orientations, with and without the inclusion of NC within the air gap. Similar to the DGW-REF configuration, the influence of NC on interior surface temperature remains negligible across all orientations and under both sunny and cloudy conditions. This observation is consistent with the limited buoyancy-driven flow within the air layer during summer, as discussed previously. A comparison between the results provided in Figure 5.10 and Figure 5.8 reveals that the incorporation of SSPCM introduces a delay in the rise of interior surface temperature following the onset of solar irradiation. This delay, attributed to the latent heat absorption of the SSPCM during phase transition, is particularly evident in the south-facing configuration, where solar exposure is more sustained. In addition, this delay contributes in enhancing the indoor air quality. Aside from this delay in temperature rise, the overall trend of interior surface temperature variation throughout the day in the DGW-SSPCM system closely follows that of the DGW-REF system. However, during peak hours, the interior surface temperatures for the east-, south-, and west-facing orientations are slightly higher in the DGW-SSPCM system, reaching approximately 39.5 °C, 38.5 °C, and 33 °C, respectively. This increase can be associated with the thermal storage behavior of the SSPCM, which absorbs and releases heat over time, influencing short-term surface temperature dynamics.

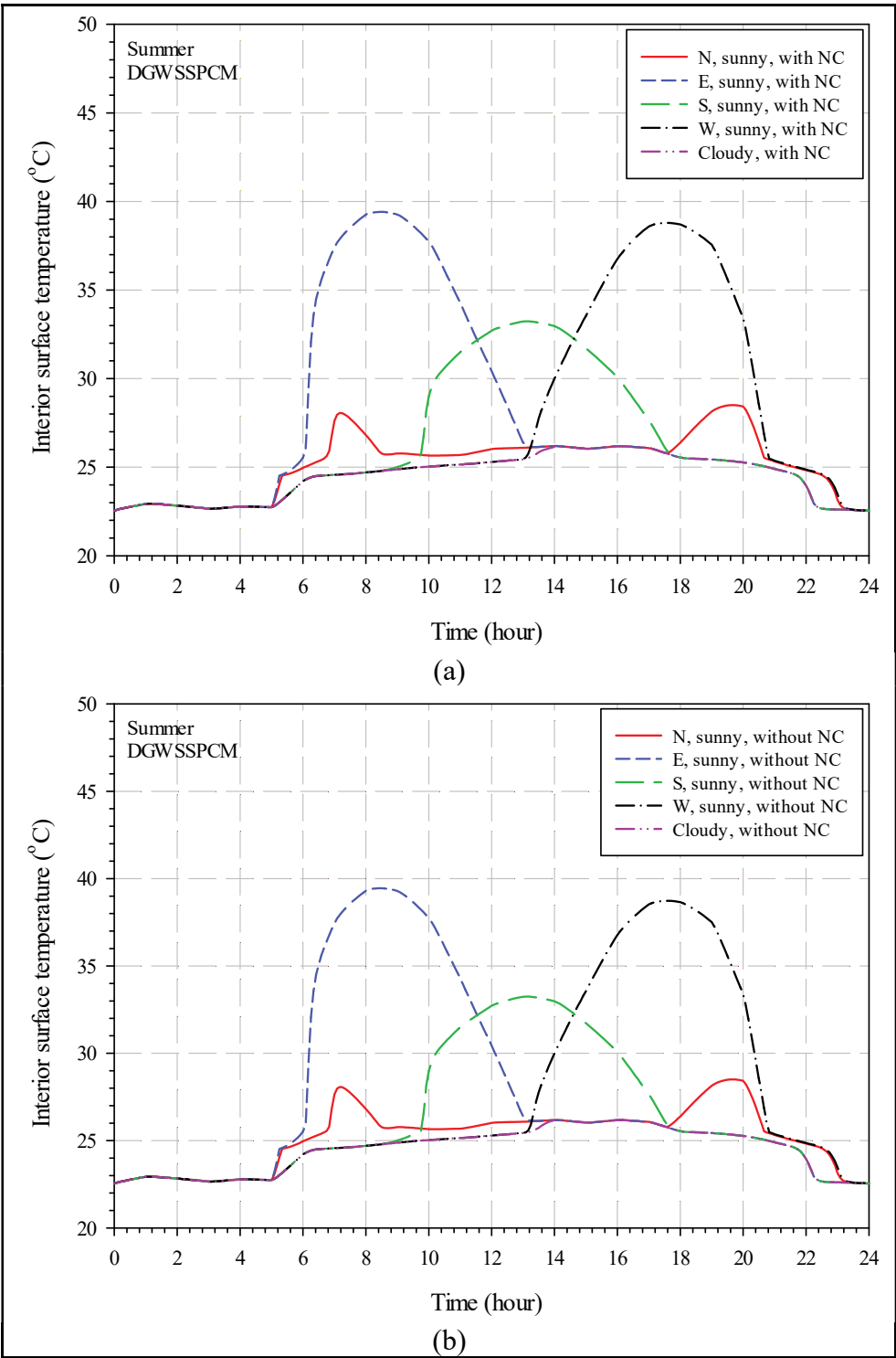


Figure 5.16 Interior surface temperature variation over a 24-hour period for different orientations in DGW-SSPCM configurations, (a) with and (b) without NC, under summer conditions

Under cloudy conditions and in the north-facing orientation, the peak surface temperatures are nearly identical between the DGW-SSPCM and DGW-REF systems, due to the absence or limitation of direct solar radiation. Consequently, the proposed DGW-SSPCM system results in a slight reduction in indoor thermal comfort compared to the DGW-REF system during summer. Furthermore, the inclusion of NC in the thermal modeling of both DGW-SSPCM and DGW-REF systems is not essential for accurately predicting indoor thermal comfort under summer conditions, given the minimal impact observed on surface temperatures.

Figure 5.17 presents the area-weighted average of interior surface temperature for the DGW-SSPCM system during winter for various glazing orientations, with and without the inclusion of natural convection (NC) within the air gap. Like the behavior observed in the DGW-REF configuration under winter conditions, the impact of NC on interior surface temperature is notable in all cases. In the north-facing and cloudy scenarios, the inclusion of NC results in an approximate 2 °C decrease in interior surface temperature compared to the cases without NC. For the other orientations, the temperature difference between the NC and non-NC cases varies throughout the day, typically ranging between 1 and 3 °C. The most prominent influence of NC occurs during the phase when the SSPCM is releasing stored heat. When NC is considered, the temperature increase on the interior surface becomes more gradual, reflecting a smoother and more distributed heat release. This effect is attributed to the enhanced convective heat transfer within the air layer, which improves thermal distribution across the surface.

In addition, the interior surface temperatures of the DGW-SSPCM system are generally higher than those of the DGW-REF system shown in Figure 5.9. This confirms the thermal buffering capacity of the SSPCM and its effectiveness in enhancing indoor thermal comfort during winter conditions. Among the orientations, the east-, west-, and south-facing windows display distinct peaks in surface temperature, with the south-facing configuration reaching the highest value. The interior surface temperature in this case peaks around midday, reaching approximately 29 °C, as a result of direct solar exposure combined with latent heat release from the SSPCM. These results demonstrate the combined benefits of solar gain and latent thermal storage in achieving improved energy performance and occupant comfort in winter conditions.

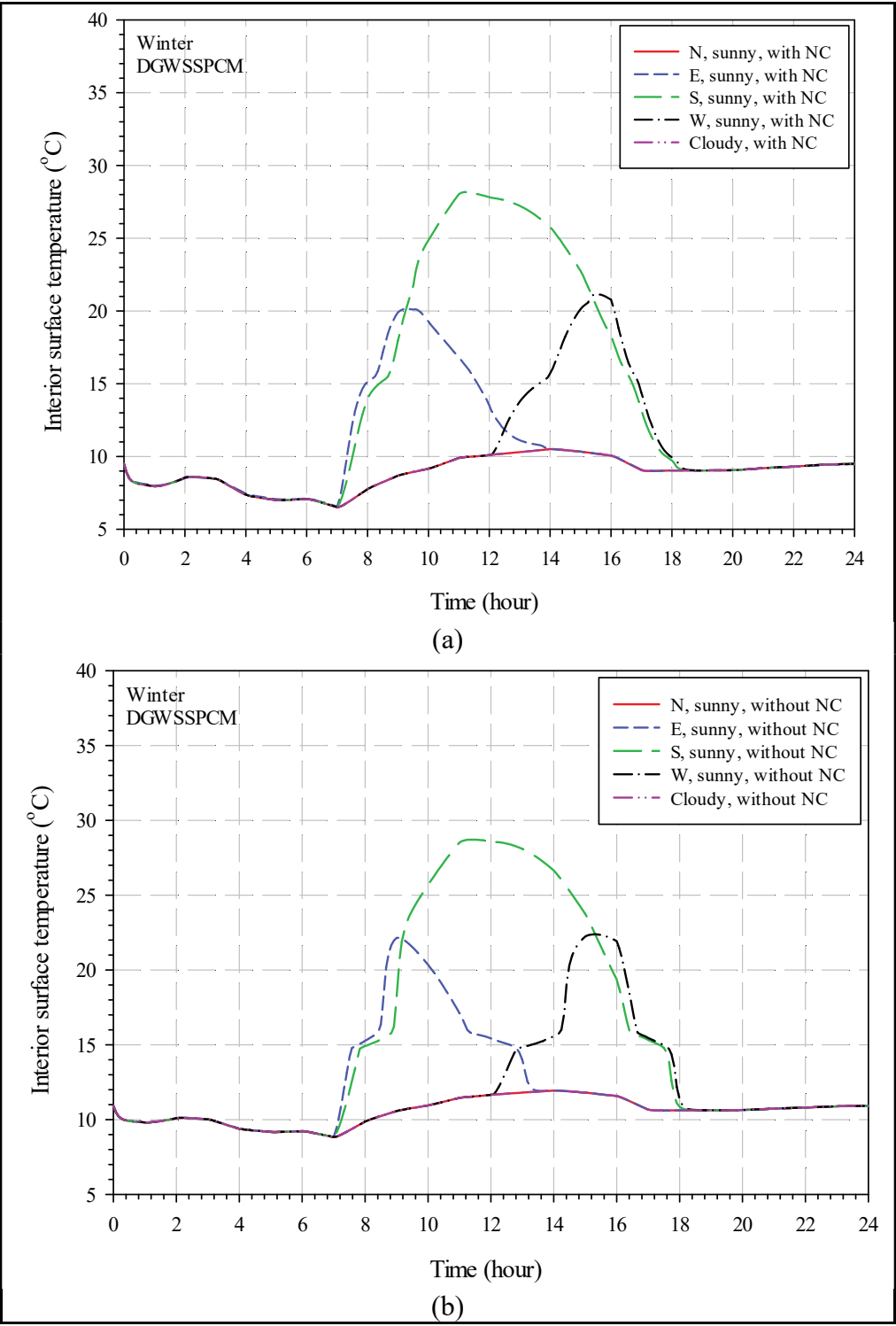


Figure 5.17 Interior surface temperature variation over a 24-hour period for different orientations in DGW-SSPCM configurations, with and without NC, under winter conditions



Overall, the proposed DGW-SSPCM system improves indoor thermal comfort compared to the DGW-REF configuration during winter. Additionally, incorporating NC in the thermal modeling of both systems is essential for accurately capturing indoor thermal conditions in the cold season, due to the significant influence observed on interior surface temperatures.

#### 5.4.4 *Energy analysis*

Figures 5.18 and 5.19 illustrate the total energy transfer for both DGW-REF and DGW-SSPCM configurations across four orientations under sunny and cloudy conditions with and without the effect of natural convection (NC) in the air gap of the glazing systems. Figure 5.18, corresponding to summer conditions, shows heat transfer from the outdoor environment into the indoor space, which represents the energy cooling load. In this context, when the energy value of the DGW-SSPCM values fall below those of DGW-REF, this indicates improved energy efficiency related to the energy cooling savings. Figure 5.19, representing winter conditions, displays the reverse heat transfer direction (from indoors to outdoors), which represents the energy heating load. In the cold season, lower energy values correspond to reduced heat loss, indicating improved energy efficiency related to the energy heating savings.

During summer, the data presented in Figure 5.18 reveal that the total energy transferred across all orientations under cloudy conditions remains nearly the same between DGW-REF and DGW-SSPCM systems. This behavior is largely attributed to the installation of the SSPCM layer on the interior surface of the glazing. During daytime hours, the SSPCM absorbs incident solar energy and stores it as latent heat, effectively not only dampening interior temperature fluctuations (see Figure 5.16) but also reducing peak cooling demand. However, as ambient temperatures decline in the evening, the stored energy is released back into the indoor environment. While this delayed heat release can be beneficial in cooler climates, it contributes to internal heat gains that may be undesirable in warm conditions, particularly during the nighttime. As a result, the energy savings achieved by limiting heat gain during the day are counterbalanced by the additional heat released at night. This thermal compensation leads to approximately the same cumulative heat energy values over the full 24-hour cycle for both DGW-SSPCM and DGW-REF configurations.

When comparing different orientations, the east-facing configuration exhibits the highest transmitted heat energy, reaching 297 kJ. This is followed by the west-facing window at 287 kJ, the south-facing window at 195 kJ, and the north-facing window at 112 kJ. The lowest transmitted heat energy is observed under cloudy conditions, with a value of 54 kJ. These results highlight the significant influence of solar exposure and orientation on the thermal performance of glazing systems during summer, emphasizing the need for orientation-specific design strategies to maximize the energy performance.

Figure 5.18 demonstrates that the influence of NC is negligible across all orientations and under cloudy conditions. Therefore, when modeling DGW-REF and DGW-SSPCM systems under summer climatic conditions in Montreal, the inclusion of NC is not essential. Neglecting NC in these scenarios is recommended, as its influence on the total energy transfer through the glazing system is minimal. Additionally, omitting NC consideration under summer conditions in Montreal can significantly reduce computational demands by a factor of four to five, without compromising the accuracy of energy performance predictions.

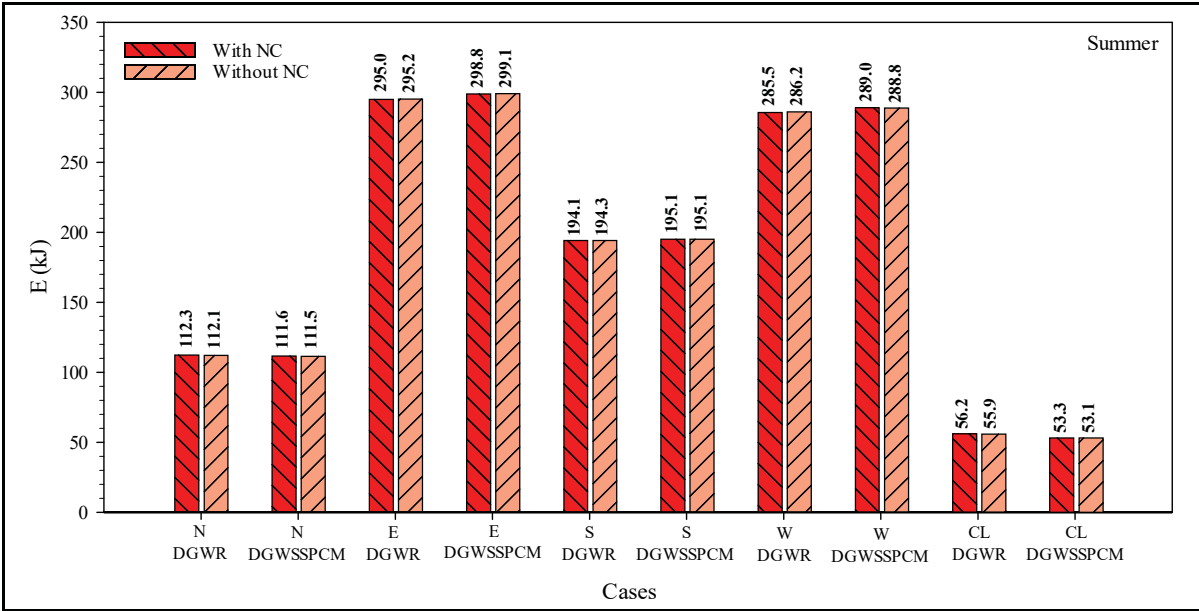


Figure 5.18 Energy cooling load for DGW-REF and DGW-SSPCM configurations in four orientations, North, East, West, and South, with and without NC, during summer

Figure 5.19 illustrates the total energy transferred through the DGW-REF and DGW-SSPCM systems, with and without considering NC, for various glazing orientations under both sunny and cloudy winter conditions. In contrast to the summer results, the winter data clearly show that the DGW-SSPCM configuration leads to consistent energy savings across all scenarios as a result of reducing heat loss through the fenestration system. This improvement is primarily attributed to the ability of the SSPCM to absorb solar energy and heat from the indoor air in the form of latent heat during the day and gradually release it back to the indoor space as outdoor temperatures decline. This behavior enables the system to passively regulating indoor temperatures and as well reducing the demand for active heating. Moreover, the effect of NC on the total transferred heat energy is pronounced during the winter season. The enhanced buoyancy-driven flow intensifies heat exchange within the air gap, further impacting the thermal performance of the glazing system. Therefore, accurately capturing NC effects is critical in winter conditions to avoid underestimating energy transfer.

The quantified energy savings for the DGW-SSPCM system relative to the DGW-REF configuration are as follows: 21.7 kJ (3.5 percent) for the north-facing window, 17.8 kJ (3.6 percent) for the east-facing window, 19.1 kJ (3.8 percent) for the west-facing window, 18.7 kJ (7.6 percent) for the south-facing window, and 21.1 kJ (3.4 percent) under cloudy conditions. These values demonstrate the DGW-SSPCM system capacity to improve energy efficiency in heating-dominated climates such as Montreal.

Figure 5.19 also demonstrates that incorporating NC as an additional mode of heat transfer leads to increased energy loss compared to scenarios where NC is not considered. Specifically, for the DGW-REF configuration, the total heat transfer is lower when NC is excluded, with the differences quantified as follows: 86.9 kJ (14.2 percent) for the north-facing window, 80.1 kJ (16.2 percent) for the east-facing window, 73.6 kJ (29.9 percent) for the west-facing window, 83.8 kJ (16.5 percent) for the south-facing window, and 86.4 kJ (14.1 percent) under cloudy conditions. Similarly, for the DGW-SSPCM configuration, the reduction in total heat transfer when NC is not considered is: 62.1 kJ (10.5 percent) for the north-facing window, 57.9 kJ (12.1 percent) for the east-facing window, 53.5 kJ (23.5 percent) for the west-facing window, 60.6 kJ (12.4 percent) for the south-facing window, and 62.2 kJ (10.5 percent) under

cloudy conditions. These results indicate that neglecting NC leads to an underestimation of total energy transfer by approximately 14 to 20 percent in the DGW-REF system and by 10 to 23 percent in the DGW-SSPCM system.

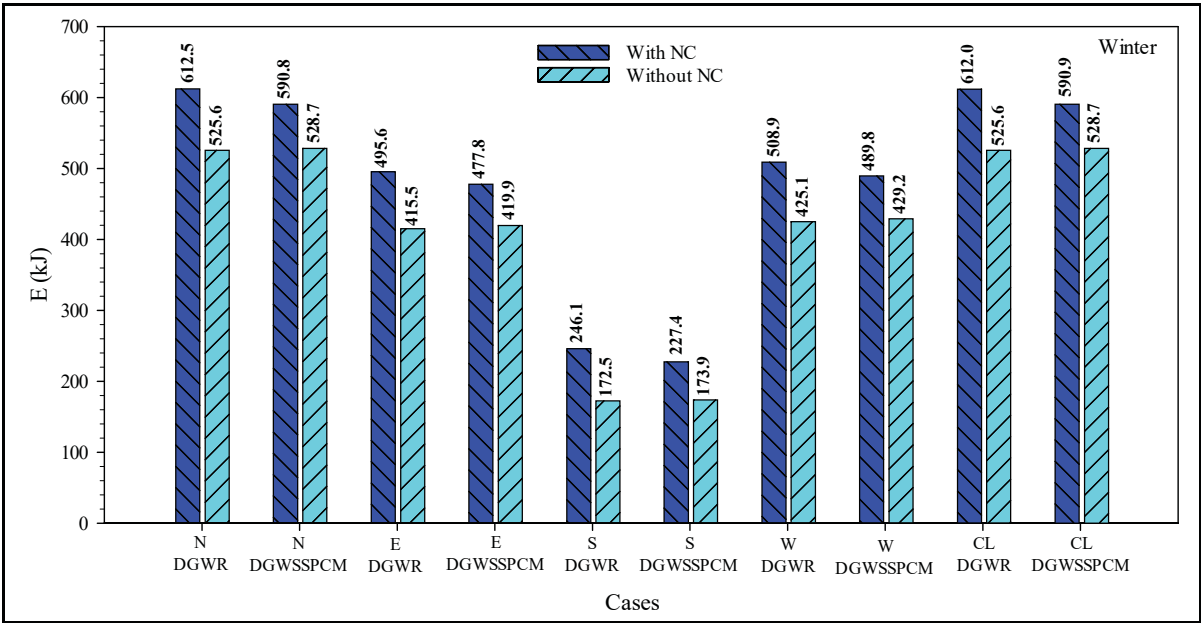


Figure 5.19 Energy heating load for DGW-REF and DGW-SSPCM configurations in four orientations, North, East, West, and South, with and without NC, during winter

Overall, for the weather condition of Montreal, the south-facing configuration is identified as the most effective option, as it provides the highest energy savings during the winter period while also maintaining full visual transparency during typical office hours. Based on the climatic conditions and simulation results, the optimal window design is a double-glazed unit incorporating a thin layer of SSPCM with a transition temperature of 15°C, applied to the interior pane within the air gap and oriented toward the south. This configuration is recommended because the selected transition temperature ensures that the SSPCM remains fully transparent throughout the summer season, thereby preserving daylight availability and visual comfort. As demonstrated in the analysis, enabling a phase transition in summer does not result in a meaningful improvement in the thermal performance of the glazing system. In contrast, during winter, the SSPCM plays a significant role in reducing heat loss while maintaining visual transparency during the hours of occupancy. This dual benefit highlights

the potential of the proposed system to enhance both energy efficiency and indoor environmental quality in cold climates.

## 5.5 Conclusion

This study investigated the energy and optical performance of a double-glazed window system incorporating a solid-solid phase change material (DGW-SSPCM) in comparison with a conventional reference system (DGW-REF). Simulations were conducted under both sunny and cloudy conditions on the hottest and coldest days of year 2022 in Montreal, Canada, across the four main orientations (north, east, south, west). The aim was to evaluate the effectiveness of integrating a 2 mm SSPCM layer on the interior side of the glazing and assess the influence of Natural Convection (NC) within the window air gap, using detailed transient CFD modeling with the ANSYS FLUENT software. Both radiative and phase change phenomena were modeled using the Discrete Ordinates (DO) and solidification/melting models, respectively. The key findings are as follows:

- Velocity analysis shows weak, conduction-dominant flow in summer (max 0.05 m/s) and organized convective loops in winter (up to 0.14 m/s).
- Airflow remains laminar in all cases, with Reynolds numbers of 5–20 in summer and 40–53 in winter. Highest values occur in north and cloudy cases during winter and in east (DGW-REF) and west (DGW-SSPCM) orientations in summer.
- Rayleigh numbers reflect seasonal contrasts, with steady  $\sim 1.3 \times 10^7$  in winter and fluctuating  $\sim 10^6$  in summer, emphasizing sensitivity to temperature differences across the air gap.
- In summer, NC has negligible impact on energy and optical performance, so neglecting it can save computational time.
- In winter, NC raises interior surface temperatures (up to 3°C), modifies SSPCM phase change, and affects transparency fraction, highlighting its importance for accurate predictions.

- DGW-SSPCM offers limited summer energy savings but reduces winter heat loss, achieving 3.4–7.6 percent savings compared to DGW-REF, with the south-facing orientation most efficient.
- Neglecting NC underestimates total energy transfer by 10–23 percent depending on system and orientation, underscoring the need to model convective effects in cold conditions.
- SSPCM improves indoor thermal comfort in winter and slightly increases peak summer surface temperatures, making it more suitable for heating-dominated climates and commercial applications.

Under the climate conditions of Montreal, the recommended configuration is a south-facing DGW-SSPCM system, with the SSPCM placed on the interior glazing pane and designed with a transition temperature of 15°C. This setup ensures that the material remains fully transparent and neutral in summer and activates its full latent heat potential during winter. The chosen configuration balances energy savings, thermal comfort, and daylight utilization, especially in commercial buildings with daytime occupancy.

Finally, integrating SSPCMs into glazing systems presents a promising passive solution to enhance energy efficiency and visual performance in cold climates. Future work should include annual-scale simulations with dynamic weather data to better quantify long-term benefits. Additionally, experimental validation under real-world conditions and development of SSPCMs with tunable or multi-stage transition behavior may further enhance adaptability and performance across broader climate contexts.

## CHAPTER 6

### DISCUSSION AND FUTURE WORK

This thesis develops a comprehensive and physically grounded understanding of solid–solid phase change material integration within double-glazed systems by framing these systems as coupled thermo-optical components whose performance is governed by the interaction of material behaviour, heat transfer mechanisms, solar radiation, and the simultaneous thermal and optical performance requirements of glazing systems. Throughout the thesis, SSPCM-enhanced glazing is evaluated not as an abstract energy concept but as a building envelope system that must simultaneously satisfy thermal performance objectives and optical requirements such as transparency, daylight availability, and visual connection to the outdoors. This integrated perspective enables the thesis to move beyond simplified performance claims and to clarify the conditions under which SSPCM glazing can realistically contribute to improving building energy efficiency, reducing building energy demand, and supporting carbon-free and greenhouse gas emission reduction strategies.

A central outcome of the thesis is the recognition that SSPCM glazing performance is inherently conditional and cannot be generalized across climates, seasons, or façade configurations. The presence of latent heat storage within a glazing system does not, by itself, guarantee energy savings. Instead, the effectiveness of SSPCM integration depends on whether the phase transition occurs at times when stored energy reduces net heat transfer while maintaining acceptable optical performance during occupied hours. When this alignment exists, SSPCM glazing can moderate heat flow and act as a thermal buffer. When the alignment is absent, the same system can block beneficial solar gains, introduce time-shifted heat release that does not coincide with demand, or compromise transparency. These outcomes are not contradictory; rather, they reflect the fundamental trade-offs associated with embedding latent thermal storage within transparent envelope components.

The thesis demonstrates that climatic forcing plays a dominant role in shaping these trade-offs. Variations in ambient temperature, solar availability, and sky condition determine whether

SSPCM behaviour aligns with heating or cooling demand. The analyses consistently show that SSPCM glazing responds differently under different weather conditions, even within the same season, because solar radiation influences both thermal input and optical activation of the material. This sensitivity highlights the limitations of performance assessments based on simplified seasonal averages or isolated representative days. SSPCM glazing effectiveness emerges from the cumulative interaction between weather patterns and material response rather than from a single dominant mechanism.

Transparency is treated throughout the thesis as a defining constraint rather than a secondary performance indicator. Unlike opaque PCM applications, glazing systems must maintain visual access and daylight during occupied hours to remain viable for real buildings. The thesis demonstrates that SSPCM-enhanced glazing can undergo phase transition while maintaining transparency during typical occupancy periods, provided that material properties and system configuration are carefully selected. This finding establishes that optical penalties are not an inevitable consequence of SSPCM integration but instead depend on design decisions at both the material and system levels. It also reinforces the importance of evaluating SSPCM glazing using metrics that explicitly reflect visual functionality rather than relying solely on thermal indicators.

Material properties emerge as decisive design variables. The thesis shows that transition temperature governs whether latent storage is activated at appropriate times relative to climatic forcing, while transition range influences how gradually thermal and optical properties evolve. This distinction has important implications for SSPCM selection and optimization. Prioritizing transition temperature enables alignment between phase change behaviour and building demand, while transition range affects visual stability and the extent of partial opacity experienced during operation. Together, these parameters link material-level decisions to occupant perception and acceptance, reinforcing the need for integrated material and system design.

Façade orientation further conditions SSPCM glazing behaviour by altering the timing and magnitude of solar exposure. The thesis demonstrates that SSPCM-enhanced glazing should not be applied uniformly across all façades of a building. Instead, selective deployment based



on orientation allows latent storage behaviour to align more effectively with both thermal demand and transparency requirements. This finding supports a broader design principle that SSPCM glazing should be used strategically rather than universally, and that its integration must respond to orientation-specific solar and thermal conditions.

The treatment of heat transfer mechanisms within the glazing cavity provides additional insight into SSPCM performance. The thesis shows that conduction, radiation, and natural convection interact differently depending on operating conditions and that convective effects are not uniformly dominant. In certain regimes, convection has limited influence on overall performance, allowing simplified modelling approaches without compromising accuracy. In other regimes, buoyancy-driven flow significantly affects temperature distribution, phase transition behaviour, and heat transfer rates. This distinction is critical for interpreting results and for guiding future modelling efforts, as it clarifies when simplifications are physically justified and when they lead to systematic misrepresentation of system behaviour.

Despite the depth of numerical analysis presented, the thesis also makes clear that modelling alone cannot establish readiness for real-world deployment. One of the most significant limitations identified is the scarcity of experimental data for SSPCM glazing systems, particularly regarding optical behaviour, phase transition kinetics, and long-term stability. Experimental validation is therefore essential to confirm the trends identified through simulation and to reduce uncertainty in material behaviour. Future research should prioritize experimental investigations conducted in academic laboratories and in collaboration with glazing manufacturers to characterize temperature-dependent thermophysical and optical properties under controlled conditions.

Long-term experimental studies represent a particularly important future direction. SSPCM-enhanced glazing is intended to operate through repeated daily and seasonal cycles, and its long-term performance cannot be inferred from short-duration tests. Extended experimental campaigns are needed to assess durability, ageing effects, consistency of optical response, and stability of thermal performance over time. Such data are essential to build confidence in SSPCM technologies and to support their adoption in real buildings.

Another critical future direction is the extension of analysis from component-level behaviour to real building operation. While the thesis establishes fundamental behaviour and design logic at the glazing level, real buildings introduce additional layers of complexity, including HVAC operation, internal heat gains, shading systems, and occupant interaction. Field studies and monitored building installations are necessary to evaluate how SSPCM glazing performs within this broader context. These studies would enable assessment of thermal comfort, daylight quality, glare response, and operational robustness under realistic conditions and would provide feedback for refining both design strategies and modelling assumptions.

From a modelling perspective, future work should focus on strengthening the link between laboratory measurements and numerical simulations. Implementing numerical models calibrated directly using experimentally measured SSPCM properties would reduce uncertainty and improve predictive reliability. At the same time, computational efficiency remains a practical concern. While detailed CFD modelling captures essential physical mechanisms, it is not feasible for whole-building analysis or large-scale parametric studies. Coupled modelling strategies that integrate high-fidelity component-level models with whole-building energy simulation tools represent a promising pathway. Such approaches can preserve accuracy where it is most critical while enabling broader analysis with manageable computational cost.

The solid-state nature of SSPCMs also opens additional avenues for exploration beyond conventional transparent glazing. Because SSPCMs do not undergo a liquid phase, they can be integrated into building envelope components without concerns related to leakage or containment. This characteristic enables alternative configurations in which SSPCM layers intentionally modulate transparency, allowing partial view obstruction or daylight attenuation during certain periods while remaining transparent during occupancy. Rather than being viewed solely as a limitation, this behaviour can be interpreted as a controllable architectural feature that supports glare control or privacy. In addition, SSPCM integration into opaque envelope elements, where optical constraints are relaxed, may allow latent storage benefits to be realized more consistently. These applications require further experimental and numerical investigation to establish feasibility and performance.

Across all these future directions, a recurring and fundamental requirement is the availability of comprehensive material property data. Progress in SSPCM-enhanced envelope systems depends on expanded characterization of thermophysical and optical properties across different SSPCM formulations and transition temperatures. Improved datasets are essential for reliable modelling, meaningful comparison between design options, and informed decision-making. Addressing this data gap represents a foundational step toward broader adoption of SSPCM technologies in building envelopes.

From a problem-solving perspective, integrating SSPCMs into double-glazed and multi-layer building envelope systems helps address a key challenge in building energy performance, namely the misalignment between thermal demand, solar availability, and the timing of energy use. By introducing latent heat energy storage directly within the building envelope, SSPCM-integrated systems offer a pathway to moderate heat transfer, reduce peak heating and cooling loads, and redistribute thermal energy over time without compromising the essential transparency and functionality of glazing systems. These characteristics position SSPCM-enhanced envelopes as a complementary strategy for improving building energy efficiency and supporting the development of net-zero energy buildings. While the effectiveness of SSPCM integration remains dependent on climate, configuration, and material properties, the ability to store and release energy passively at the envelope level contributes to more resilient and flexible building operation. When considered at scale, such improvements in building energy performance support broader efforts to reduce energy consumption, facilitate integration of low-carbon and renewable energy sources, and mitigate greenhouse gas emissions. In this context, SSPCM-integrated building envelopes represent a material-level solution that responds to both building-specific performance challenges and global objectives related to energy sustainability and decarbonization.



## CONCLUSION

This thesis establishes a comprehensive and physically consistent understanding of solid–solid phase change material integration in double glazing systems through a structured numerical and parametric investigation of their coupled thermal and optical performance. Using a validated numerical framework, the work systematically examines transient heat transfer, solar radiation effects, phase transition behaviour, and transparency evolution within SSPCM-enhanced glazing systems under realistic climatic boundary conditions. The analysis explicitly considers key design and operating parameters, including climate, façade orientation, seasonal conditions, sky condition, SSPCM transition temperature and transition range, and dominant heat transfer mechanisms within the glazing cavity.

A central contribution of this thesis lies in the breadth and coherence of the parametric analysis performed. The results demonstrate that the thermal and optical performance of SSPCM-integrated glazing systems is governed by the interaction between climatic forcing, solar availability, orientation-dependent exposure, and SSPCM material characteristics. Transition temperature is identified as a primary parameter controlling whether phase change aligns with building thermal demand, while transition range influences the smoothness of thermal response and the evolution of optical properties. The placement of the SSPCM layer within the glazing system further affects phase transition dynamics and energy behaviour. Through systematic comparison with reference glazing configurations, the thesis clarifies the conditions under which latent heat storage moderates heat transfer and those under which performance benefits are limited.

The findings confirm that SSPCM-enhanced glazing is a design-sensitive and context-dependent solution rather than a universally optimal one. When phase transition behaviour aligns with thermal demand and solar exposure while maintaining transparency during occupied hours, SSPCM integration enhances thermal inertia and moderates heat transfer without compromising visual performance. Conversely, misalignment between these factors can reduce the effectiveness of SSPCM or introduce penalties associated with altered solar transmission and the timing of thermal energy release. These outcomes reflect inherent trade-

offs associated with integrating SSPCM into transparent building envelope systems and highlight the importance of climate-responsive and orientation-specific design.

An important methodological outcome of this thesis concerns the role of natural convection within the glazing cavity. The results demonstrate that the influence of natural convection is strongly dependent on seasonal operating conditions. For the climatic conditions of Montreal, natural convection is shown to have a negligible effect on thermal performance under summer conditions, allowing it to be neglected without compromising the accuracy of numerical predictions. In contrast, under winter conditions, natural convection significantly affects temperature distribution, phase transition behaviour, and heat transfer rates and must therefore be accounted for to accurately represent system behaviour. This distinction provides clear guidance for future numerical modelling of SSPCM-enhanced glazing systems and supports informed selection of modelling assumptions based on operating regime.

Overall, this thesis provides a rigorous and realistic assessment of SSPCM-integrated glazing systems by integrating thermal behaviour, optical performance, climate dependency, and dominant heat transfer mechanisms within a unified parametric framework. By clarifying the governing parameters, identifying inherent trade-offs, and establishing when specific modelling assumptions are valid, the work delivers practical insight for the analysis and design of SSPCM-enhanced multi-layer glazing systems. The conclusions presented form a solid foundation for extending experimental investigation, enhancing numerical modelling capabilities, and supporting informed application of SSPCMs in advanced building envelope technologies.

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