The Prediction of Liquid Leak Rates through Packing Seals

by

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THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
IN PARTIAL FULFILLMENT FOR A MASTER'S DEGREE
WITH THESIS IN MECHANICAL ENGINEERING
M.A.Sc.

MONTREAL, NOVEMBER 24, 2021

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

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ACKNOWLEDGMENT

I want to thank Prof. Hakim A. Bouzid from the bottom of my heart for accepting me as a master student and for generously and patiently giving me his endless knowledge, far from any complexity. Whenever there was a question or a problem in the thesis process, he helped me to solve it. Indeed, one of my honors in graduating life is under the supervision of an influential professor in the field of mechanical engineering.

I would also like to thank the jury members who accepted this thesis's review and devoted their valuable time to evaluate and attend the defense session.

I want to thank my colleague Dr. Ali Salah Omar AWEIMER, who improved the test rig during his Ph.D. studies. After graduation, and in spite of his job duties, he came to the university to help me conduct the experimental tests.

Special thanks to the ETS administration and dean office and the Department of Mechanical Engineering administrative staff and technicians who, in the background of the research process, provided the means and facilities to conduct this project.

Finally, I would like to thank my parents, who were always by my side, but this time, they supported me wholeheartedly from thousands of kilometers away. Special thanks to my wife, Somayeh Ghonchehzadeh, for her help and support during all time I was studying. Finally, I will always be indebted to my daughters (Dorsa and Elsa), who inspired me and give me happiness and joy during the difficult times.

La prédiction des taux de fuite liquide à travers les garnitures d'étanchéité

Seyed Amir Hossein BATHAEI

RESUMÉ

Les garnitures d’étanchéité sont les éléments les plus sensibles dans les assemblages mécaniques sous pression. Leur comportement sous l’effet du chargement et de la pression d’un fluide est très différent d’un matériau a un autre ; ce qui rend leur conception dans les presse-étoupe des vannes et les compresseurs très compliqués. Le mauvais choix de matériau et le nombre de bagues d'étanchéité dans la conception ou une installation incorrecte peuvent entraîner des fuites dans le système ; ce qui peut mener à des incidents graves pour les installations et les humains.

Les fuites de fluides (gaz ou liquide) provenant des conduites et réservoirs sous pression dans les installations nucléaire ou pétrochimique peuvent avoir des conséquences désastreuses pour les humains et l’environnement. Dans les rapports d’incidents survenus dans les installations industrielles, la plupart des fuites signalées sont liées aux vannes. Par conséquent, l'étanchéité des vannes et principalement les bagues d'étanchéité, est un sujet important qui nécessite une attention particulière. Le manque de normes appropriées dans ce domaine est criant. La nature poreuse des bagues de garniture peut être un chemin de fuites à moins que la taille des pores soit contrôlée et que la relation avec la nature du fluide soit établie. Malheureusement, le manque d’étude sur les garnitures de presse-étoupe des vannes est flagrant ; ce qui a suscité un intérêt en recherche dans ce domaine ces dernières années.

Jusqu’à présent, très peu de recherches ont été effectuées sur l’écoulement des fluides à travers les bagues de garniture, dont certaines ont été effectuées dans le cadre d’analyses numérique et analytique. Le besoin en recherche expérimentale dans ce domaine se fait sentir. En fait, les résultats des tests expérimentaux peuvent servir de validation et de confirmation des modèles analytiques et numériques. Dans le cadre de cette étude, un banc d'essai de fuite a été utilisé pour simuler les conditions réelles d'un assemblage presse-étoupe d'une vanne et nous conduire à des résultats proches de la réalité à température ambiante. Ce banc d'essai a été conçu pour mesurer la quantité de fuite de gaz ou de liquide à travers les bagues de garniture sous différentes charges de compression et pression de fluide. Différentes méthodes de mesure de fuite ont été utilisées en fonction de la quantité de fuite obtenue avec des garnitures en graphite expansée.

Ce travail vise à prédire le taux de fuite à travers les bagues d'étanchéité des presse-étoupes ; ce que les nombreux tests expérimentaux ont pu confirmer. En effet, ces tests ont été réalisés afin de valider le modèle d'écoulement et faire bénéficier les diverses industries des résultats obtenus en fonction des paramètres d'opération. En pratique, les nombreux paramètres affectant la fuite des bagues de garniture rendent les comparaisons difficiles. Cependant, la considération de certains paramètres simultanément peut produire des résultats proches de la réalité. Ce travail s'appuie explicitement sur la validation d'un modèle d'écoulement de liquide à l'aide de mesures expérimentales de petites fuites produites par un système de détection fait maison. L'étude des matériaux de l'anneau de garniture est concentrée sur la détermination de leurs paramètres de porosité lesquels sont utilisés dans des modèles analytiques d'écoulement de fluide développés pour prédire les taux de fuite. L'azote gazeux a été utilisé comme gaz de référence pour décrire la taille des pores et leur nombre existant dans le matériau poreux des garnitures d'étanchéité.

Enfin, selon les résultats de cette étude, les fuites à travers les bagues d'étanchéité peuvent être contrôlées et réduites, et leur prédiction est possible grâce au modèle analytique suggéré.

Mots clés: Anneaux de garniture, milieu poreux, fuite, expérimentation, modélisation analytique et numérique.

The Prediction of Liquid Leak Rates through Packing Seals

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ABSTRACT

Packing rings are the most sensitive member of packed stuffing boxes in pressurized mechanical assemblies such as valves and pumps. Their ability in dealing with pressure and temperature are not well established, making their long-term use in valves and compressors unpredictable. The wrong choice of the material, number of packing rings, incorrect installation and fluid incompatibility can lead to leakage failure and cause hazards to human and environment.

Leakage of fluids (gas or liquid) in the nuclear or petrochemical industries often occurs in carrier lines, valves, and compressors. Such a situation can cause high risk and have drastic consequences on human health and safety and the environment. In these industries, accident reports indicate that fluid leakage is often related to valves. The sealing of valves is insured by packed stuffing boxes that requires a special attention by researchers in this field. The porous nature of packing rings is an open path for leakage. Unfortunately, the lack of standard tests and design procedures of stuffing box packings of valves is alarming and has been the subject of recent studies.

In practice, a small amount of research has been conducted on fluid flow through packing rings, some of which cover numerical and analytical leakage predictions. There is definitely a need of experimental research in this field. In fact, the results of experimental tests can validate and confirm the accuracy of the predicted results and determine the robustness of the analytical and numerical models. In this research, a test rig was used to simulate the actual conditions of a valve packed stuffing box and lead us to simulate the leakage behavior at room temperature. This test rig was designed to measure gas or liquid leakage through packing rings under

different compressive loads and fluid pressure. Different leakage measurement methods were used depending on the amount of leakage obtained with flexible graphite-based packing.
This work aims at predicting leak rate through stuffing box packing rings; This is achieved by validation of the predictions with the experimental test results. In fact, the experimental tests have been performed to validate the analytical model and benefit the various industries with the results obtained under different operating conditions. Practically, the many parameters affecting leakage of packing rings have render the comparisons difficult to make. However, some parameters considered simultaneously have produced results close to reality. This work is based explicitly on the validation of a fluid flow analytical model based on several experimental leak measurements. The study on the packing ring materials starts with the determination their porosity parameters with a reference gas used in the developed fluid flow models to predict leak rates. Nitrogen gas was used as a reference gas to determine the pore size and their number in the packing ring porous structure.

Finally, according to the findings, leakage through packing rings can be controlled and reduced, and its prediction is possible using the validated analytical models.

Keywords: Packing rings, porous medium, leakage, experimentation, analytical and numerical modeling.

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LIST OF ABBREVIATIONS

ANSI	American National Standard Institute
API	American Petroleum Institute
CFX	High-Performance Computational Fluid Dynamics
CFD	Computational Fluid Dynamics
EPA	United States Environmental Protection Agency
FCI	Fluid Controls Institute
FEM	Finite Element Method
LVDT	Linear Variable Differential Transformer
PTFE	Polytetrafluoroethylene
VDI	The Association of German Engineers (In German)

LIST OF SYMBOLS

bars	Bars (0.1 MPa)
C	Centigrade
F	Fahrenheit
H	Hours
Inch	Inches
K	Kelvin
kg	Kilogram
MPa	Mega Pascal
m	Meter
mm	Millimeters
mg/s	Milligrams per second
ml/s	Milliliters per second
ppm	Parts per million
psi	pounds per square inches
s	Seconds

NOMENCLATURE

ε	Porosity
λ	Mean free path, m
μ	Dynamic viscosity, Pa/s
ρ	Density, kg/m3
σ	Tangential momentum accommodation coefficient = 1
c	Capillary second order model
D	Capillary diffusive model
D_p	Diameter of spherical particles, m
l	Length of packing, m
L	Leak rate, kg/s
N	Number of capillaries
NR^4	Porosity Parameters for capillary and diffusivity models, m4
P	Pressure, Pa
R	Radius of capillary, m
T	Temperature, K
u	Axial velocity, m/s
z	Capillary axial direction, m
K_n	Knudsen number; $\left(\frac{\lambda}{2R}\right)$
R_e	Reynolds number; $\left(\frac{D_p u \rho}{(1-\varepsilon)\mu}\right)$

INTRODUCTION

Valves are among the most widely used devices in the industry for controlling the flow of liquids or gases. Valves allow the control of the fluid in the piping system by mechanical, electrical, hydraulic, or pneumatic forces. The reliability of the piping system depends on fluid leak tightness in valve yarned stuffing boxes and bolted flange connections.

Valves are used to control liquid circulation in various process industries, including nuclear power plants, chemical plants, and petrochemical processes. In these industries, liquid leakage is always a nuisance, and even the smallest leak can cause irreparable damage to humans or the surrounding environment. Valve sealing can be divided into two parts: internal sealing, which means that fluid leakage inside the valve does not completely cut off fluid flow if needed, and external sealing, which prevents leakage to the surrounding environment. The sealing parts used to prevent these two types of leakage are schematically illustrated in figure 0.1-1.

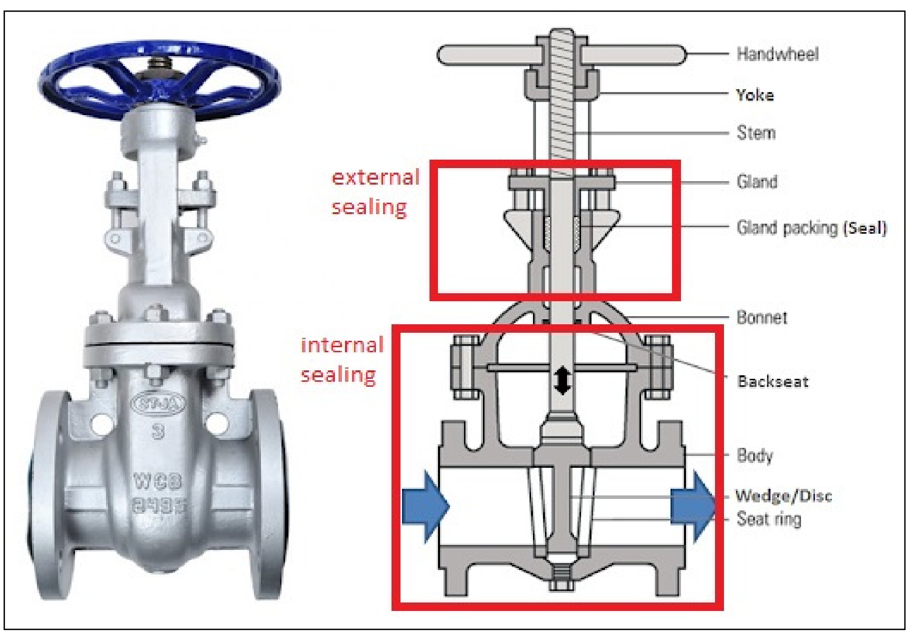


Figure 0.1-1 valve sealing sections

Any defect in the performance of a valve can have a remarkable impact. Accidents, loss of income, shutdowns, health and safety issues, and environmental damage are some consequences that have happened in the past few years. Even with the prolonged and widespread use of packed stuffing boxes to seal valves, there are no standard design method to follow to size them or standard test method to qualify packing seals for a particular application (Diany, Mohammed, et Abdel-Hakim Bouzid, 2009). Due to the current environmental protection laws and the strict requirements on fugitive emissions, consideration has been given to producing new packaging products that meet these regulations in the short and long terms.

These restrictions aim to reduce fugitive emissions of harmful gases and volatile compounds. Presently, climate change is one of the most critical environmental concerns. Scientific studies have shown that global warming is mainly caused by human activities that involves greenhouse gases and their release into the atmosphere. For instance, the amount of greenhouse gas emissions from oil and gas production, transmission, processing, refining, and distribution industries that uses a significant number of fittings and valves, was 163 megatons (Mt) in 2011 in Canada. These industries were the second-largest source of pollution (Canada Environment, 2013). A research study conducted by the U.S. Environmental Protection Agency (EPA) gives the percentage of fugitive emissions from the different equipment. The results presented in Figure 0.1-2 show that bolted joints and valves make up approximately 66% of the main components requiring sealing compliance in different plants. 90% of these components use packed stuffing boxes such as valves pumps and compressors. Nearly 60% of the total pollutant emissions are produced by valve leaks and packing failures (Hoyes, J.R., and Thorpe, L.C., 1995).

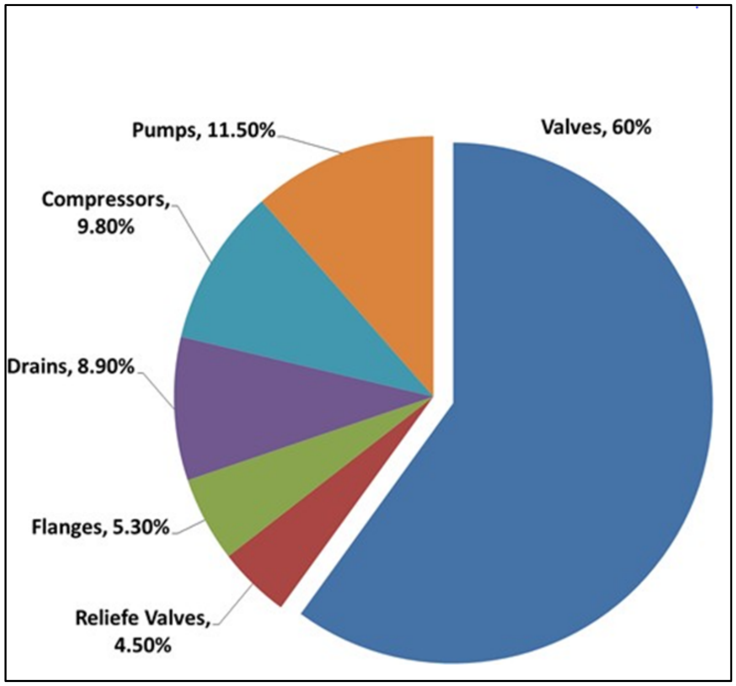


Figure 0.1-2 Percentage of gas equipment requiring sealing compliance by EPA

Following these worrying statistics, new environmental regulations and standards have been introduced to improve equipment leakage performance. The establishment of the Kyoto Protocol on the reduction of greenhouse gas emissions, in 2009, under the Copenhagen Accords, has forced some industrialized countries, such as Canada to commit to reduce greenhouse gas emissions to a safer level (UNFCCC, 2009).

Given the importance of external valve sealing, a proper research program on packed stuffing boxes should be launched to qualify packing according to the new regulations. The first step needed to achieve this goal is to advance the current understanding of the integrity of these devices and their impact on the sealing performance. This work aims to investigate the external sealing of packed stuffing boxes of valves and predict their leakage behavior based on the materials used and the operating conditions. These parameters include packing material, gland stress, fluid pressure, and type of fluid. This study will clarify two main points associated to leak tightness of packing seals: porous structure characterization and leak rate predictability.

The safety and reliability of piping systems of process plants depend on the proper functioning and leakage performance of bolted flanged gasket joints and packed stuffing boxes of valves (Klenk et al., 1999). The key parameters for the sealing performance of packed stuffing boxes are the porosity that is controlled by gland compression and the fluid pressure. The development of a suitable design method of packed stuffing boxes is very important to the engineer to ensure the correct functioning of this device during its lifespan. Understanding the different mechanical and leakage properties of packaging materials is vital in the development of a design procedure. For example, the coefficient of lateral pressure, creep, friction, and stiffness of the packing rings significantly affect the packing sealing performance. A realistic model that considers the above parameters will help develop a comprehensive design procedure for packed stuffing boxes.

A packed stuffing box consists of a certain number of packing rings that are placed in a circular space between the stem and the housing. The general principles of a packing seal can be explained with the help of Figure 0.1-1. The packing rings are compressed down by the gland through an axial compression force generated by the studs and nuts. The applied axial stress causes radial compression of the rings, creating a lateral contact pressure at the interface between the stuffing box and the stem. This lateral contact pressure at the stem and housing interfaces confines the pressurized fluid and prevents it from escaping to the outer boundary. It is essential to maintain the value of the contact pressure threshold throughout the service operation of the packed stuffing box. Valves are manipulated to control the circulation of liquids in nuclear, chemical, and petrochemical process plants. Many valve designs have been developed for different environments, fluid systems, and operating conditions to control generally a liquid or a gas to flow inside the piping system process. Not only do they play a significant role in the fluid process control but are also used to ensure industrial plant safety (Bartonicek et al., 2001).

To achieve the current study objectives, an accurate method to predict the liquid flow through packing seals working under a wide range of operating conditions of packed stuffing boxes is developed. The focus is on managing the widest range of shapes and materials for packed boxes. This work is aimed at providing of an in-depth model that can be implemented in a standard design method of packed stuffing boxes. The requirement of the adopted methodology in evaluating the proposed model relies on the need to illuminate the effect of selected parameters, including geometric, physical, and material, on the sealing performance and verified experimentally. Finally, this developed method must be reproducible with standard tools.

It is worth noting that despite the widespread use of packed stuffing boxes to seal valves, there are no design method to size them, determining the required number of packing rings or predict their leakage during operation. Consequently, the selection of a valve compression packing to prevent leakage is made by trial and error. The packing rings must be adequately squeezed to avoid leakage of liquids to the outer border, and damage to the valve stem while allowing smooth rotational movement of the stem. If the packing rings are not tightened properly, the valve may leak, creating serious hazards. If the packing rings are too tight, they will impede movement and possibly increase the risk of stem damage. From an EPA fugitive emission perspective, it is essential to ensure tightness compliance while optimizing their use in valves. This includes a design methodology that optimizes their use in the range of allowable leakage rates while ensuring durability and the least maintenance requirement.

A hybrid experimental and analytical research methodology is suggested to meet the needs of a comprehensive study on the subject. The developed analytical model is based on the physical laws that govern fluid flow through porous media. Because the interactions between the different parameters may create certain complexities, experiments are used to adjust and calibrate the developed analytical model. An experimental validation will be conducted under different gland stresses and liquid pressures to cover a wide range of applications. The experimental testing will be performed on a fully instrumented packed stuffing box test bench of the Static and Dynamic Sealing Laboratory at the École de Technologie Supérieure. It should be mentioned that the test bench is designed to simulate a valve stuffing box and was modified to accommodate liquid leak measurement.

Experiments are performed under different working conditions to assess the actual conditions properly. Various factors, such as temperature, materials, fluid environments, pressures, and compression levels, can be investigated experimentally in this test rig. However, in this study, the focus is the prediction of liquid leakage from packing seals at room temperature.

This thesis is written in several chapters. The first chapter discusses common themes on the subject of packing seals that other researchers have examined. Sometimes, these are very closely related to the present work; nevertheless, few researchers are still conducting their investigation. In general, the study of the leakage behavior of packing seals is associated with leakage in valve stuffing boxes and, specifically, under the effect of gland stresses and liquid pressures.

As mentioned previously, the prime focus of this work is the prediction of liquid leakage in packing seals. An experimental study is conducted to confirm and validate the suggested analytical model. Therefore, a complete description of the experimental test conditions and their settings is given in the second chapter. This can be relevant for future studies in order to avoid designing an experimental test bench from scratch. The test bench is designed to measure the amount of liquid and gas leakage at room temperature but can also be adapted to measure mechanical properties such as load-compression, creep and relaxation at high temperature.

In the third chapter, the basic principles of gas and liquid flow through compressed packing rings is laid out through analytical modelling. Simulations and analyses conducted on flexible graphite packing provide detailed information on the model development used to predict gas and liquid leak rates. The results from the predictions are compared to the measurements for validation in chapter three of the thesis.

In the fourth chapter, the predictions of the flow through graphite packing rings using water are compared to the experimental data. The porosity parameters required for the analytical model are obtained from a combined experimental-analytical method that uses gas in order to predict the amount of liquid leakage through the packing rings.

At the end of this thesis, a general conclusion is presented. It summarizes the results obtained and the comparison with the experiments. The robustness of the model is then discussed and a recommendations are given with special focus on future research work and give guidance on the implementation of the developed model in a future design procedure of packed stuffing boxes.

CHAPITRE 1

LITERATURE REVIEW

1.1 Introduction

In this chapter, a review is conducted to cover the few conducted studies related to the prediction of leakage through packing seals and the mechanical properties of compression packing, which are generally given at room temperature. The previously conducted studies are divided into three types: numerical studies based on finite elements, analytical studies, and experimental studies.

1.2 Standards and codes on packed stuffing boxes

To date, there is no official standard that could be used by the design engineer to size packed stuffing boxes. Step-by-step instructions to install packing in stuffing boxes exist, but they are considered merely best practices in order to minimize leakage. Researchers and engineers have recently been working on different high-quality packing design standards for certain applications but have not been successful in implementing a leakage-based calculation procedure for packed stuffing boxes.

Nowadays, due to the advancement of technology and the recent studies on sealing technology, there are few ASTM-like standard methods on compression packing. This is the most important component of the valve packing box. Taking a closer look at the stuffing box of Figure 1-1, it shows that the packing seal component plays an indispensable role in preventing leakage to the valve outer boundary and the release of harmful gases to the environment around the valve.

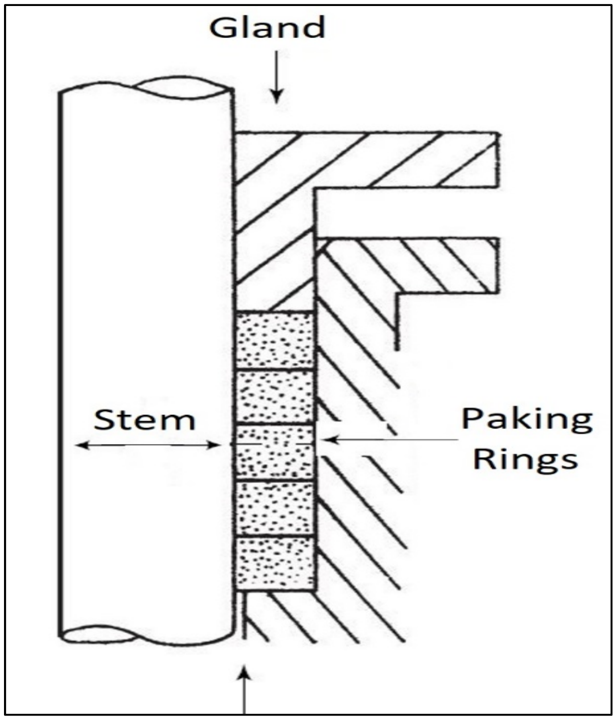


Figure 1-1 Stem packing valve assembly

New rules were enacted by the EPA for the petrochemical industry to mandate them to apply these requirements to prevent fugitive emissions and apply these new regulations in sealing equipment design. Jim Drago (June 2010) published a comprehensive study on valve stem packing tightness to reduce volatile emissions. His results show that a considerable amount of research is needed to develop a method of designing packed stuffing boxes.

Due to the importance of human health and safety and environmental protection, strict rules have been introduced to prevent the emission of harmful gases. Several standard tests on valve leakage have recently been adopted to be carefully considered in valve production. However, there is still no specific methods to guide designers to produce reliable and leak free valve stuffing boxes. Hence, developing new design method to promote environmental protection and health safety is essential.

In North America, the industry has to comply with the EPA's regulations. manufacturers must provide for all produced valves qualification and certification. Valve stem packing is recognized as the leading cause of equipment failure. With the new regulations and strict environment laws the development of test standards is required more than before. Standard organizations have recently developed few standards to certify valves and packing to comply with the low emission regulations. *ANSI/ISA- 93.00.01-1999, VDI 2440, Shell MESC SPE 77/312,* and *Environmental Protection Agency (EPA) Method 21*(TA-Luft, 2002) are among these criteria.

In 2017, a standard test for valves was set by the Manufacturers Standardization Society of the Valve and Fittings Industry with the code MSS SP-120, which is currently under the American National Standards Institute (ANSI). This standard is known as "Flexible graphite packing system for rising stem steel valve (design requirements)". Recently, few standard test procedures have been introduced to qualify packing seals and are being updated and revised regularly. API 622, API 624, and ISO 15848 (ver. 1 and 2) are four new available design standards. These standards seek to address fugitive emission and are adopted to reinforce environmental concerns. Although good progress has been made in leakage reduction, there is still a gap to fill in terms of provision of a standard design method to size valve stuffing boxes.

API 622 "The Measurement Test and Qualification Procedures for Packing" and API 624 "valve qualification test" have been developed and fine-tuned after a collection a wide range of data from different industries all over the world (Harrison, 2006). The international standards (ISO-15848-1 and 2) are the result of studies with a particular focus on quality control of industrial valves but involve measurement tests, fugitive emissions, and qualification. The first part, ISO-15848-1 (ISO 15848-1 (2006)), entitled "Classification system and qualification procedures for type test of valve assemblies," tests valves using vacuum while the fluid is helium or methane to evaluate the external leakage of stem packing rings. Both procedures use test rigs shown in Figures 1-2 and 1-3.

The EPA method 21 is a test procedure used to collect and measure leak in assemblies such as bolted joints or valves. This method is specifically adapted for field measurements and is used in the classification and identification of equipment requiring emission compliance. In general, the leak level limits are predetermined by standards or specified by the customer. For example, stem packing leakage is classified as A (lowest), B, C, and D (highest). The range of test temperatures is between -196 ºC and 400 ºC (Davis, 2012).

Figure 1-2 Test rig for ISO15848-1
Taken from Davis (2012)

ISO 15848 - Part 2 (2003-2015) "Production acceptance test of valve assemblies, on-off valves," is a roadmap for the certification of production and quality assurance for valves. This is a quality assurance test method that manufacturers can use during production to ensure the final quality of valves produced. The valve must also comply with the first part of the standard. Of course, every test is conducted under specific conditions, some of which are mentioned hereafter. The test is performed at room temperature, and the gas used in this standard must be helium. The pressure applied during the test should be six bars. Finally, the percentage of the total produced valves tested by this method should be recorded in the documents to be used in subsequent inspections (Davis, 2012).

American Petroleum Institute (API) issued four standards for valve fugitive emissions (Harrison, 2004). These standards are used in the testing of process valve packing for fugitive emissions. The first one is API-622 (API-622 (2011)), which is developed to test and qualify compression packing for valve stem sealing. The test bench for this standard is shown in Figure 1-3 and uses methane as the testing fluid. The test is run under certain conditions. Firstly, the temperature range is from ambient to 260 ºC (500 ºF) while five thermal cycles are applied.

Secondly, 1510 mechanical cycles related to the opening and closing of the valve should be conducted. This standard limit leakage failure to 500 particles per million (ppm) in compliance with the *U.S. Environmental Protection Agency*. However, a critical revision was made in leakage restriction in 2011 and there is a consent to reduce the limit to 100 (ppm).

Figure 1-3 Test rig for API-622
Taken from Davis (2012)

The second API standard related to valve fugitive emissions is API-624 (API-624 (2011)), devoted to rotating and rising-rotating stem valves. This standard is a comparative test of leak measured using methane as testing fluid. It refers to EPA method 21 for leak measurements and limits the leak to 100 ppm. The test bench shown in Figure 1-4 works in the range of temperatures between -29 to 538 ºC (-20 to 1000F). The test procedure involves three thermal cycles and 310 mechanical cycles. Like ISO-15848-1, the packing rings need to be photographed after disassembly to record any faults introduced during the test; reduction in packing thickness and changes in the surface finish are reported.

The third *API-623 (2013)* standard covers all kinds of valve sealing, and this standard is entitled: "Steel Globe Valves – Flanged and Butt – welding Ends, Bolted Bonnets". It is worth mentioning that the API-623 procedure can be followed after the API 624 is executed and covers valves exposed to corrosion and erosion or have large stem diameters and heavy wall sections.

Figure 1-4 Test rig for API-624
Taken from Davis (2012)

The last API standard, coded API-598, was published in 2016. This standard is entitled "Valve Inspection and Testing." It is used to inspect, examine, and implement pressure tests necessary for particular types of valves such as gate, globe, plug, ball, , and butterfly valves.

The American National Standard Institute (ANSI) has issued a standard test procedure with identification number ANSI/FCI 91-1-2010 in collaboration with the Fluid Control Institute (FCI) to qualify stem seals of control valves. The base version of this standard was released in 1991 by FCI. After some revisions, ANSI adopted a new version in 2010. The number of mechanical cycles defined for valve operation from fully open to fully closed and back to fully open is between 25k to 100k. Two allowable leak rate levels are specified: up to 100 ppmv and up to 500 ppmv. In some European countries, especially Germany, there is a famous standard for stem sealing entitled ISO 15848 / TA-Luft (2012). This standard reduces the fugitive emission and defines the permissible leakage limits for various systems such as stuffing boxes according to VDI4 2440 (Riedl, 2007). The leakage limit of sealing devices in TA-Luft/VDI 2440 also referred to as VDI 2440 is 10^{-4} mbar l/m/s, where the testing fluids are helium or methane at a specified testing temperature below 250 ºC.

Finally, all of the above standards are designed to address human health and environmental concerns to ensure that industrial valve is safe and reliable. All fugitive emission related standards have common goals but have different specification related to leak measurement, test fluid, temperatures, pressures, and mechanical cycles. Despite the existence of many standard test procedures, a comprehensive methodology to design valve stem sealing systems is yet to be developed.

1.3 Experimental studies

In stuffing-box packing, there are few packing properties that simultaneously affect the amount of gas or liquid leakage. However, the physical properties and their effect on the sealing performance at the short and long term are difficult to model. Nevertheless, some parameters can be taken into consideration during the numerical and analytical modeling. In a valve stuffing box assembly, all the structural members are interconnected and have an influence on the tightness performance which makes the prediction difficult and the experimental methods more challenging. The different structural members interact with each other to render the modelling of the porous structure of the packing material complex. The size and shape of voids, capillaries and leak paths are not straight forward to model. Experimental based methods are the preferred approach and have more success than other approaches to describe the performance of valve sealing under different conditions. They can also be used to a certain extent to validate the numerical and analytical model predictions. The experimental evaluation of the mechanical characteristics of stuffing box packing, such as load-compression, contact stress distribution and lateral pressure coefficient is essential to study valve stem sealing performance.

Preliminary studies in this field date back to the 1960s. Thomson (1961) showed that most leaks in valves are preventable, similar to other studies of those years, he declared that leaks could be controlled and reduced by applying adequate amount of initial tightening. In the late 1980s, studies began to analyze compression of packing seals and this has attracted the attention of many researchers. Ochonski (1988) built a test rig to validate an analytical model to evaluate the contact stresses based on the lateral pressure coefficient. The test rig measures packing axial deformation, the lateral pressure coefficient, and the friction coefficient. The test rig used to determine these properties is shown in Figure 1-5. As shown in the figure, the sensors were used on thin-walled sleeves at the inner and outer walls to indirectly measure packing lateral contact pressure. The displacement measurements were made by a dial indicator that picks up the axial movement between the gland and the frame. White asbestos plaited yarn impregnated with PTFE dispersion was used for the packing materials during the test and a pre-compression of up to 5 MPa was applied.

In his study, Thomson found that the lateral pressure coefficient at the outer radius of the packing is always less than that of the inner radius. However, except for the low tightening ranges of 1 to 12 MPa where air bubbles are trapped inside the pores of the packing material, it was observed that the lateral pressure coefficients at the internal and external radii are entirely independent of the gland pressure.

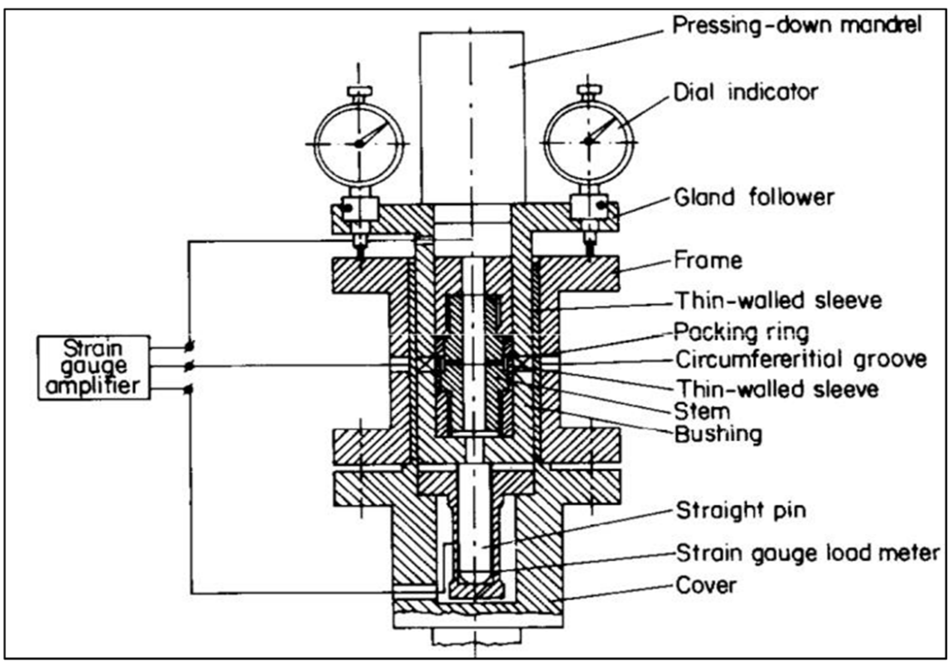


Figure 1-5 The test rig for the evaluation of the analytical model
Taken from Ochonski (1988, p. 33)

Hayashi and Hirasata (1989) matured the experimental testing to develop an experimental test method to determine the amount of axial gland load required to obtain sufficient lateral contact pressure to seal packing rings. They developed the test rig is shown in Figure 1-6.

As previous researchers have pointed out, it is crucial to investigate the suitability of packing ring materials for different applications. Aikin (1994) also focused on selecting suitable materials for packing rings to be used in the nuclear industry. He published useful test data on compression strength, chemical behavior, and corrosion to be used to select the suitable packing materials for a particular application.

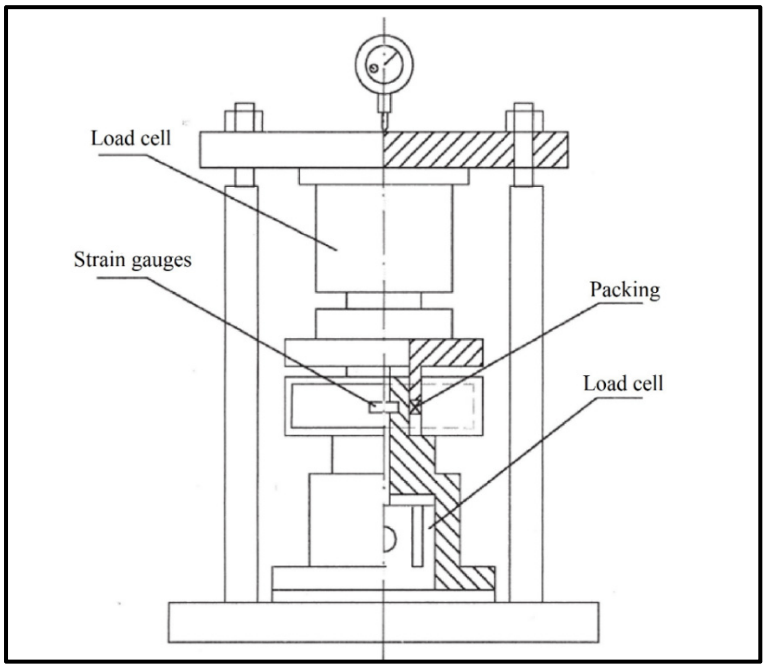


Figure 1-6 Test rig designed
Taken form Hayashi et Hirasata (1989)

During the last decade, Schaaf et al. (2005) tested new materials that could withstand high temperatures. They tested nonwoven packing material and exfoliated graphite rings as replacement of asbestos materials that was banned due to health issues. Roe and Torrance (2008) studied graphite packing rings experimentally, analytically and numerically and presented some results on the variation of the friction coefficient with time.

Veiga et al. (2008) investigated the sealing failure in high-pressure steam assemblies. They designed a test rig to examine the behavior of valve stem packing at high temperature. They focused their research on specific parameters to achieve good performance in valves. Vasse

(2009) also investigated the mechanical properties of compressed expanded graphite (CEG) using experimentation and finite element analysis. He compared both methods to generalize the methodology with other materials.

Ottens et al. (2010) reviewed an optimization scheme to achieve better performance of packed stuffing boxes. They kept the contact stress constant, minimize wear and apply surface treatment using AlTiN, Chromium-Nitride Multilayer, and Tungsten-Carbide. Friction tests were conducted using nitrogen at 160 bars and 400 ºC.

Lasseux et al. (2011) conducted an experimental investigation on the characterization of porous packing materials. They designed the two sand tests shown in Figure 1-7 to examine the permeability and Klinkenberg effect in both the axial and radial directions. In these experiments, the pressure decay method was used to measure leakage of graphite-based packing rings.

Diany, Mohammed, et Abdel-Hakim Bouzid (2011) developed a methodology to evaluate the axial contact stress distribution based on a hybrid experimental-numerical technique. This study focuses on the material mechanical properties to obtain the lateral pressure coefficients of Teflon and flexible graphite-based packings. The hybrid method is based on experimental data and finite element (FE) analysis. In addition to the prime focus of the lateral pressure coefficients, they examined leakage of these materials. The test rig is shown in Figure 1-8.

A year after that study, Diany and Bouzid (2012) presented an investigation on the creep and relaxation behavior of packing seals. A constitutive law for creep was developed for different types of braided packing materials. Comparisons of the creep-relaxation results obtained from experimental, analytical, and finite element methods showed good agreement. They studied three types of packing materials: Teflon (PTFE), flexible graphite, and carbon fiber. The designed test rig is equipped with a set of 20 strain gauges bounded over two inches to measure the strain deformation of the stuffing box housing. Using the experimental results, they were able to confirm the finite element contact stress distributions.

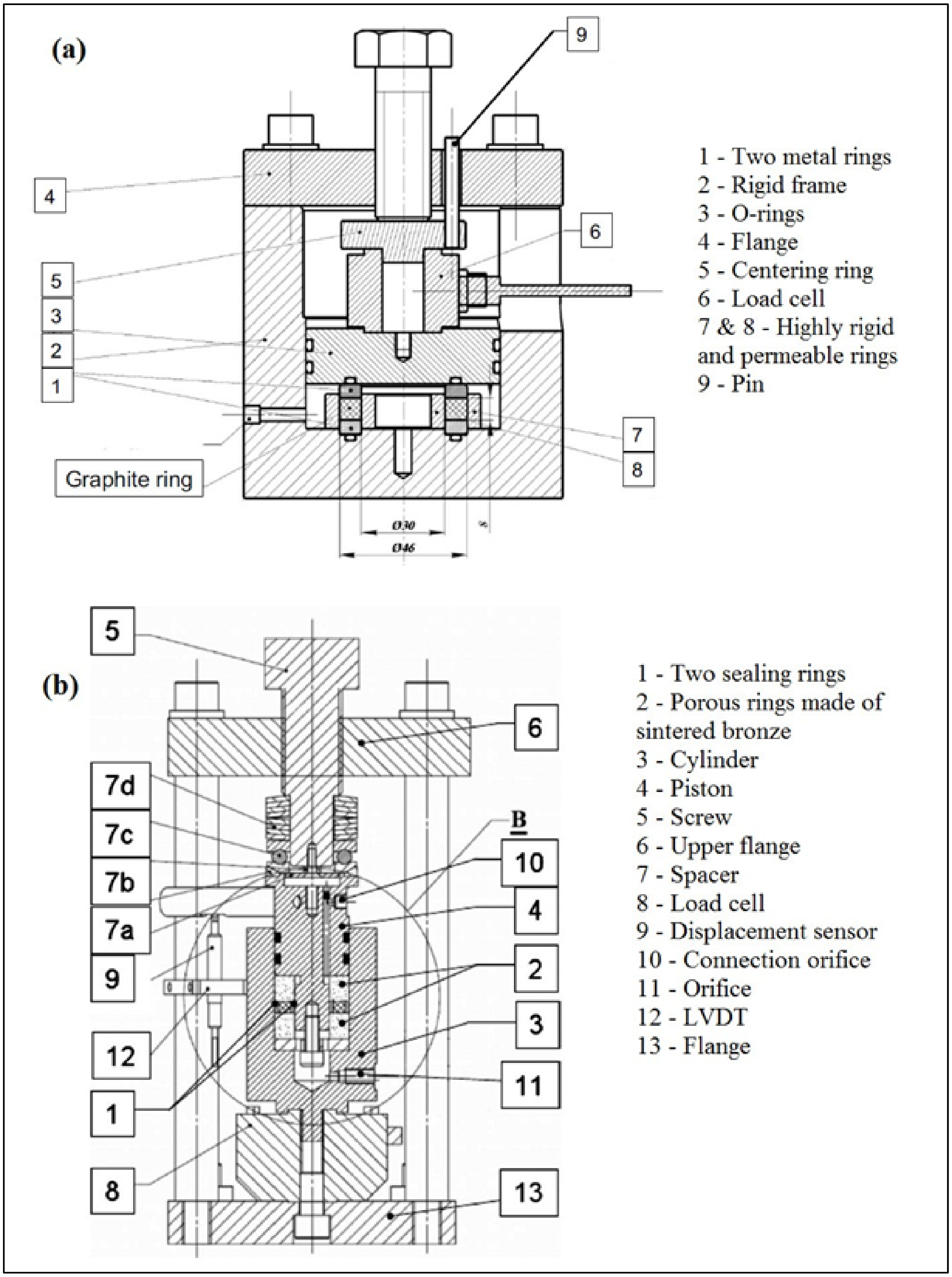


Figure 1-7 Test rigs used to determine the (a) radial and (b) axial permeability and Klinkenberg's effect (Lasseux et al., 2011)

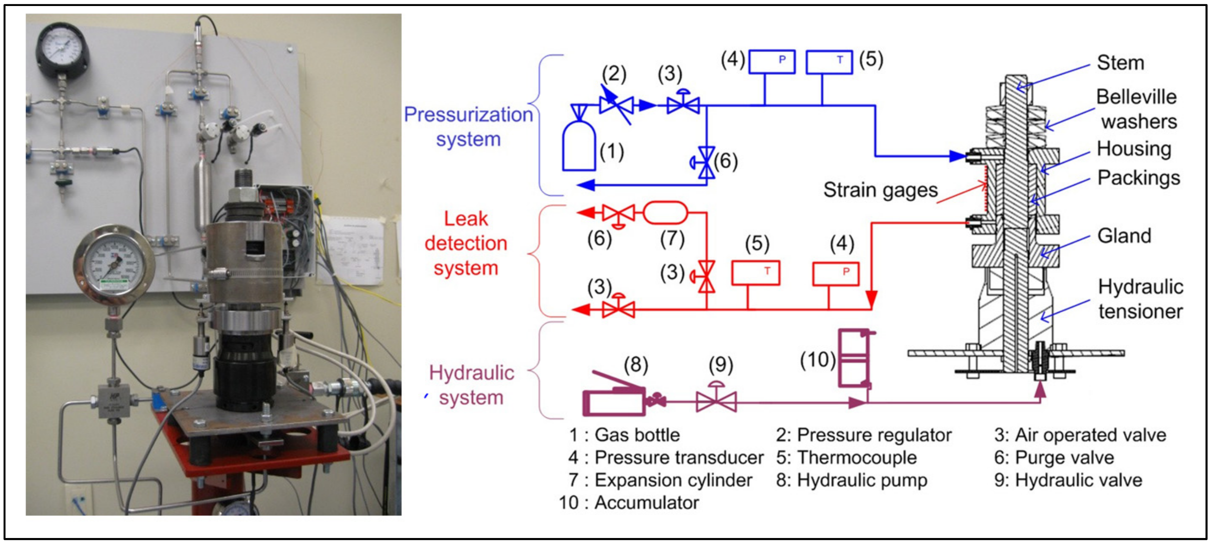


Figure 1-8 The stuffing box test bench
Taken from Diany and Bouzid (2011, p. 012201)

Kazeminia and Bouzid (2018) developed an experimental-based methodology to predict gaseous leaks through porous braided packing seals. To validate the simulation results, they conducted experiments on a stuffing box test rig that measures leak rates with different gases and at different pressures and gland stresses. They tested flexible graphite packing rings with three different gas types (helium, argon, and nitrogen) with helium as the reference gas to perform the predictions. They used different flow models namely modified Darcy and capillary models to predict leak rates. These predictions were compared to the experimental data and concluded that these analytical models can be reliable depending on the porosity and the level of leak involved.

Finally, an experimental study was conducted on a modified test rig of the Static and Dynamic Sealing Laboratory at the École de Technologie Supérieure by Aweimer et Bouzid (2019) to accommodate liquid leak rate measurement. The modified test rig focused on experimental leak measurements and its adaptation to characterize the porous structure of the packing material. In this study, they used gas and liquid as fluids and different materials of packing rings. Leaks through the porous packing materials were also simulated through numerical approaches using Ansys CFX.

1.4 Numerical studies

With the advent of the new generation of computers capable of rapidly processing information and computing, powerful software tools emerged in the field of engineering that allowed researchers to make their assumptions without incurring high costs. These software tools have become so powerful that they are now the most basic assistants to engineers and researchers. Like any other tool, the use of computers and software has its advantages and disadvantages.

One of the advantages of using computer numerical analysis is fast and easy simulation of laboratory conditions. Sometimes making test rigs takes a lot of time and imposes staggering costs on researchers. Instead of spending a lot of money to build laboratory equipment, one can easily simulate it in a software.

However, there are drawbacks to using powerful computer software. The capabilities of these software tools have limitations due to their programming, and it is practically impossible to simulate everything that researcher observes in their experiments. Sometimes, real behaviors are slightly different from their computer models. For this reason, researchers usually hesitate to publish their numerical findings without verifications in the laboratory.

A simulated packed stuffing box has advantages due to its round shape and symmetrical shape resulting from its axis of symmetry. However, simulating packing materials in software is generally very difficult and produces models far from reality. Although simulating the interaction between the packing ring and the side walls is challenging, researchers have presented several ways in recent years to simulate gland, stem, housing, and packing interactions numerically.

Gaft, Krivonogov and Petushkov (1989) used the finite element method (FEM) to obtain the actual contact pressure at the stem inner radius with the packing ring. They made comparisons between numerical and experimental results, and found that the contact pressure calculations used to analyze the leakage tightness of a packing ring were consistent with the experimental results. Perhaps the advancement of the numerical research today owes much to the early research conducted by these individuals.

Gauvin et al. (1996) examined the accuracy of the material permeability for several reinforcements and mold filling simulations. They compared the data obtained from numerical simulations with experimental results and confirmed that the numerical results were accurate. They stated that any change between the numerical and experimental results could be due to the nature of the fluid, pressure, and cavity stiffness.

Sawa et al. (2002) studied the effect of the nominal diameter of flanges on the gasket contact stress distribution. They used a nonlinear gasket model in their numerical study. They found that the variation of the gasket contact stress distribution is relatively small for smaller size diameters. They explained their finding by the difference in the number of bolts and the rotational flexibility of the flange. When the internal pressure is applied to the system, the actual sealing surface area decreases.

Diany and Bouzid (2006) performed their studies based on an axisymmetric configuration model with four-node element mesh of the packing, gland, housing and stem. Numerical analyses were performed to simulate the mechanical interaction of the packed stuffing box, and ANSYS software was used in the numerical study. They used 2D four-node hyper elastic elements to model the packing rings. Experimental data were used to obtain the nonlinear behavior of the used packing materials during the loading stage for the simulation. Although this study was highly reliable, the load loss due to pressure and temperature were not studied.

Diany and Bouzid (2009) used a numerical FE method to validate their proposed analytical model of packed stuffing boxes in valves. The model shown in Figure 1.9 is an axisymmetric finite element model used in their study. They compared the axial distribution of lateral contact pressure between packing-boxes and the sidewalls of the stem and housing for different number of packings, gland stresses and friction coefficients. The number of packing rings considered was from 2 to 8, the friction coefficient from 0.15 to 0.25, and the gland pressure from 10 to 50 MPa.

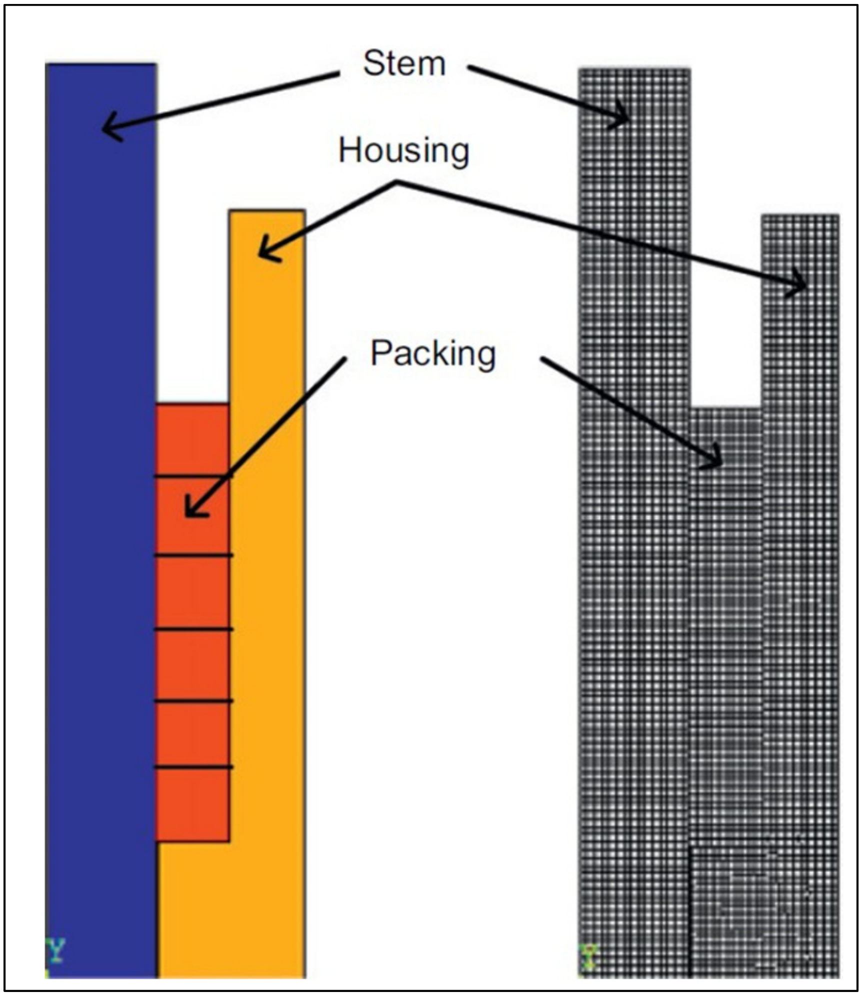


Figure 1-9 Finite element model of a stuffing box packing
Taken from Diany and Bouzid (2009, p. 032201)

Diany and Bouzid (2012) developed a hybrid numerical-experimental method to determine the lateral contact pressure. They used the finite element model shown in Figure 1.10 to evaluate the contact pressure by comparing the measured hoop strain on the external housing surface to the one produced by the FE model. This exercise was repeated with a gland stress that varies from 0 to 50 MPa.

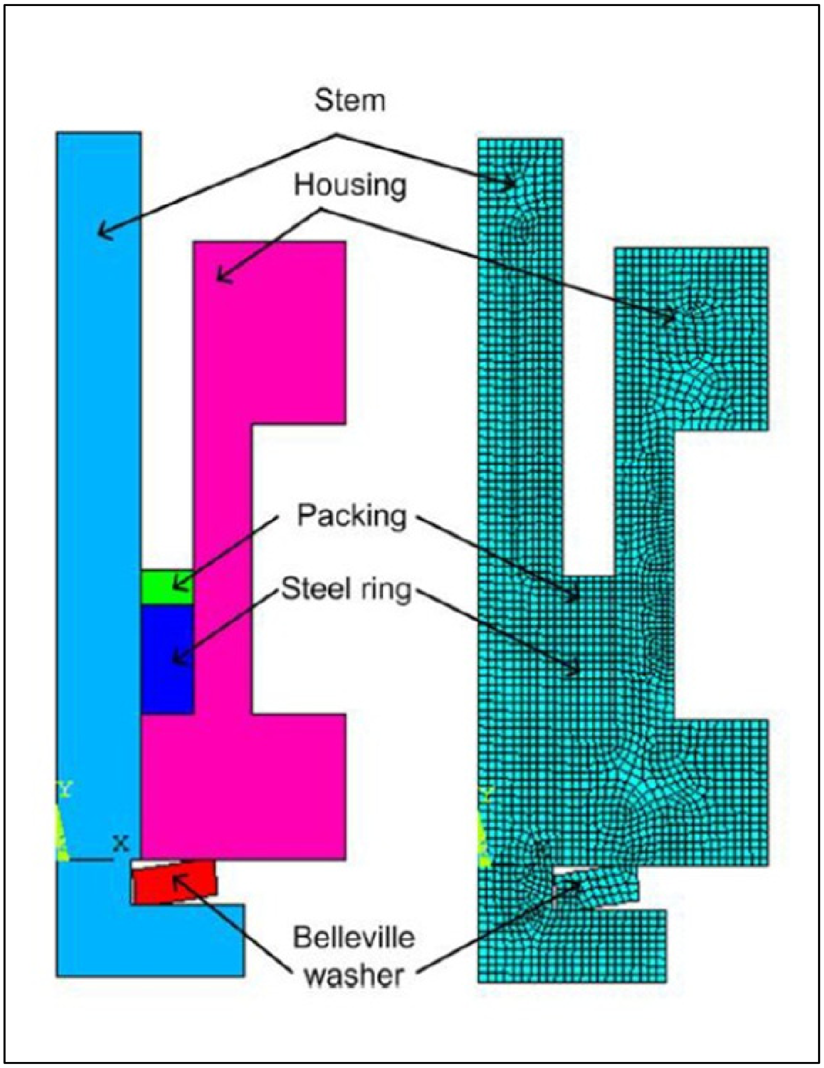


Figure 1-10 Finite element models to study the creep characterization of the packing element
Taken from Diany and Bouzid (2009, p.032201)

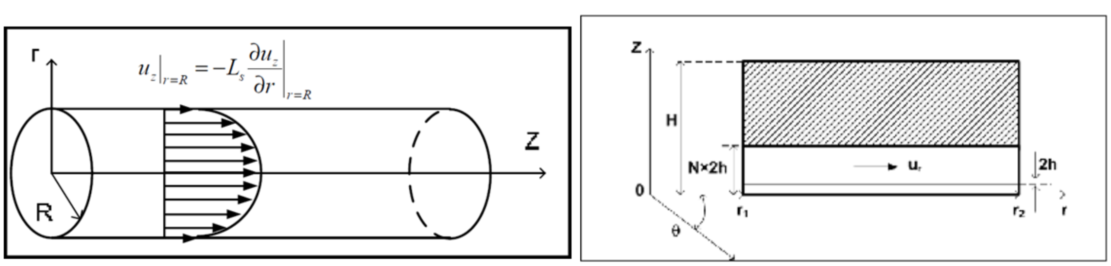
Tahir, Hallström and Åkermo (2014) determined the effect of various parameters of a two-dimensional dual scale fibrous structure on the overall permeability of packing rings using Computational Fluid Dynamics (CFD). A good agreement was observed when the permeability difference between the solid and porous states is about 5% to 6%.

1.5 Analytical studies

There are two types of leaks in valves. The first one is referred to as surface leak and takes place at the interface between the packing rings and the sidewalls formed by the housing and the stem. The second one is porous leak and takes place though the porous structure of the packing material. Arghavani et al., (2002) showed that leaks through pores can be greater than surface leaks in soft materials. The proportion of these leaks depends not only on the gland stress and pressure but on the structural complexity and the size and number of pores inside the packing material.

Ewart et al. (2006) found that the flow in cylindrical micro tubes can be modelled to estimate the mass flow rate under steady isothermal conditions. They measured the rate of gaseous flow under slip regime using a sophisticated experimental test rig. Their studies concluded that higher Knudsen numbers would deepen the understanding of the reflection process at the wall and extend the awareness of rarefied flow behaviors.

Grine and Bouzid (2010) considered the flow of liquids through the micro- and Nano-channels of graphite-based gaskets. They proposed radial capillary straight tubes to model water and kerosene flow through the gasket material and compared the analytical results to test data obtained on a well instrumented experimental test rig shown in Fig. 1.11. However, some differences were observed due to interfacial flow present at low contact pressures.



(a) (b)

Figure 1-11 Macroscopic models for studying the characteristics of porous media: (a) the Capillary Model, and (b) the Annular Model

Grine and Bouzid (2011) developed an experimental method to characterize the gasket porosity parameters required in the modelling. The leak predictions were based on Navier-Stokes equations. They concluded that the higher the gaskets stress, the lower the leak path diameter, number of micro paths and number of voids. In the experiment, helium gas was used as a reference gas to characterize the pores and use this information in the analytical model to predict leak rates for other gazes. Air, Argon, and Nitrogen were the gases that were used during the experiment to compare with the prediction.

Dongari and Agrawal (2012) presented a fluid flow model based on Navier–Stokes equations to predict leakage in packing rings. They used the second-order slip boundary condition based on Knudsen number. They incorporate the Knudsen diffusion phenomenon in rarefied gases to estimate the flow. In this paper, an attempt was made to compare the analytical results with the experimental ones. Their analytical model was based on fixed values of slip coefficients for circular and rectangular capillaries subjected to pressure and thermally driven rarefied gas flows.

Based on their previous paper, Grine and Bouzid (2013) modelled the flow through gasket joints at high temperature using the viscous properties of the fluid media and the pore characteristics of the packing material. Their study showed a decrease in the leak rate with a temperature increase. Also, Singh, Dongari and Agrawal (2014) exploited the augmented Burnett equations to accurately model the flow in capillaries. They concluded that there is a good agreement between the experimental results and the analytical solutions obtained for a Knudsen number below 2.2.

1.6 Conclusion

Although the numerous articles and studies mentioned in this chapter about packed stuffing boxes, neither a unified design method or a standard design procedure to be used to size these components were ever released. This fact has lead researchers to pursue extensive studies in this field to understand packing behavior and the different parameters affecting their performance. The ETS Static and Dynamic Sealing laboratory has been working on this field to realistically examine the behavior of packed stuffing boxes analytically, numerically and experimentally under different service conditions. This triangularization method to validate the research findings is the core methodology adopted in this laboratory.

Due to the new regulations on fugitive emission and the new environmental protection laws, a lot of work remains to be done to improve the tightness of pressure equipment and in particular those requiring leakage compliance. Although many years of research, there is still no clear path that can lead to the implementation of unified design procedure based on leak criteria in stem sealing. Further studies in this field are required to solve leakage failures and reduce emissions.

As mentioned, very few numerical and analytical studies have been conducted in this area. In addition, experimental research is representative of the reality and give support to other theoretically-based methods. It should be given a big priority in any research work when possible and can be used as a confirmation and validation tool in any analytical or numerical predictive method. In the present work, we will start by examining the previous predictive models developed by researchers, especially those from the Static and Dynamic Sealing Laboratory at ETS University in order to evaluate their accuracy.

Several parameters affect the leakage of packed stuffing boxes. The assembled valve performance is mainly influenced by pressure, temperature and gland stress. The packing mechanical properties such as load compression, lateral pressure coefficient, friction and creep are other influencing factors. In the experiments performed in this research, we have tried to reproduce the real behavior and working condition in a laboratory test bench to achieve realistic results. Different gland stresses are applied through a hydraulic pump to a simulated packed stuffing box liquid leak with water under pressure. The results are compared to an analytical liquid flow model used as a predictive tool. The work concludes by summarizing the findings and providing recommendations for future work on packing seal properties under different working conditions.

1.7 Objectives and subjective

The experimental validation of developed theories is essential for advancing research and put into practice the acquired knowledge. In particular, investigating the theoretical prediction of the rate of fluid leakage through packing materials can be supported by experimental data. An appropriate laboratory test rig is necessary to check the accuracy of the selected mathematical model and its validation. According to the existing numerical and analytical fluid flow models, gas and liquid experiments were not combined together to characterize porous materials and make prediction.

The main objective of this work is to develop a methodology to analytically predict liquid flow by accurate quantification of the rate of leakage through packed stuffing boxes under specific working conditions of gland stress, pressure and fluid media.

The predictive model is based on the characterization of the porous structure namely the number and pore size present in the packing material using Nitrogen as a reference gas. The methodology is based on pseudo analytical-experimental approach that can be followed to extract the pore characteristics.

The developed model is validated experimentally on a test rig with a homemade liquid leak detection system capable of reaching 10^{-5} ml/s. This value is enough to measure tiny leaks from packed stuffing boxes that would not be reached by commercially available flow meters. The selected test fluid is water because this liquid does not interact with the selected graphite based yarned packing material.

CHAPITRE 2

EXPERIMENTAL SETUP

2.1 Introduction

Limiting the external or internal leakage rate is a critical issue in designing the valves. And this problem has been addressed by many researchers worldwide. Years ago, researchers used stuffing boxes in valve design to reduce system leakage. The number of parameters that are important in the efficiency and effectiveness of stuffing boxes is very large, including: stress distribution, porous structure, time-dependent behavior (creep and relaxation), deformation of components, fluid pressure, number of packing rings, temperature exposure, gland stress, and corrosion. In fact, due to the breadth of parameters affecting stuffing boxes performance, only experimental studies can validate the prediction of analytical approach.

If an approved experimental test is available, it can be used to validate numerical or analytical predictions. By designing a reliable system, we can perform the following: determining the behavioral characteristics of stuffing packing boxes, determining the optimal parameters for design and production, and validating the numerical or analytical predictions.

A test bench was designed for this purpose. A system with all the necessary standards (TA-Luft, ISO, or API) was considered in the design. at the Static and Dynamic Sealing Laboratory of the university ÉTS, Diany and Bouzid (2012), in which the maximum number of parameters could be examined. The test bench was equipped with mechanical and electronic devices to investigate the effect of changing the experimental parameters on the amount of leakage. The test bench instrumentation is precise enough to measure all influenced parameters. Modifications were made to the test bench for this study, which could meet new research needs by maintaining its originality and overall structure.

2.2 Packed stuffing box test rig

The test rig setup used in this study, the operating parameters, and extensive mechanical, electronic, and computer components to obtain reliable results are shown in Figure 2-1. This test rig can be divided into six general sub-sections and the tasks of each section are described below.

Section A is the mechanical section. This section involves the mechanical simulation of real conditions. In the test rig, a well-instrumented stuffing box is installed, which can hold six packing rings. It should be noted that the default thickness of these packing rings is 3/8 inches as originally specified in the design specifications.

Section B consists of a control panel. There are three different circuits installed on this control panel, each with its own tasks. One of the circuits responsible for applying high-pressure fluid is called the pressurizing system. The second circuit is equipped with different devices for measuring and techniques to measure system leakage. These different methods vary depending on the amount of leakage. Finally, an electrical board is responsible for powering the equipment, connecting it to the data collection device, and transmitting data to a data acquisition system.

Section C is composed of some pressure gas bottles containing helium, argon, and nitrogen to be used according to the experimental study and pressure conditions. An electro-pneumatic pressure reduction regulator is attached to the tanks to reduce the pressure for use in the test rig. The pressure reduction regulator device is equipped with a feedback control system and selected pressure gas supplies to the system by a pressure transducer.

Section D is responsible for supplying electricity and controlling the electrical circuits. This part of the system acts as the brain to execute the appropriate commands in the rig so that the test proceeds properly.

A hydraulic system is installed in section E to apply the gland required load during the test through the hydraulic tensioner. In the associated hydraulic circuit, an accumulator is installed to maintain hydraulic pressure and therefore ensure a constant load on the packing rings. The hydraulic pressure can be reduced due to creep and the presence of accumulator compensate this drop to make it stable.

In section F, there is a computer system connected to the data acquisition system. The two are jointly responsible for controlling and modifying the test rig condition and for recording data received from the measuring equipment. A program was written on LabVIEW platform to perform this task.

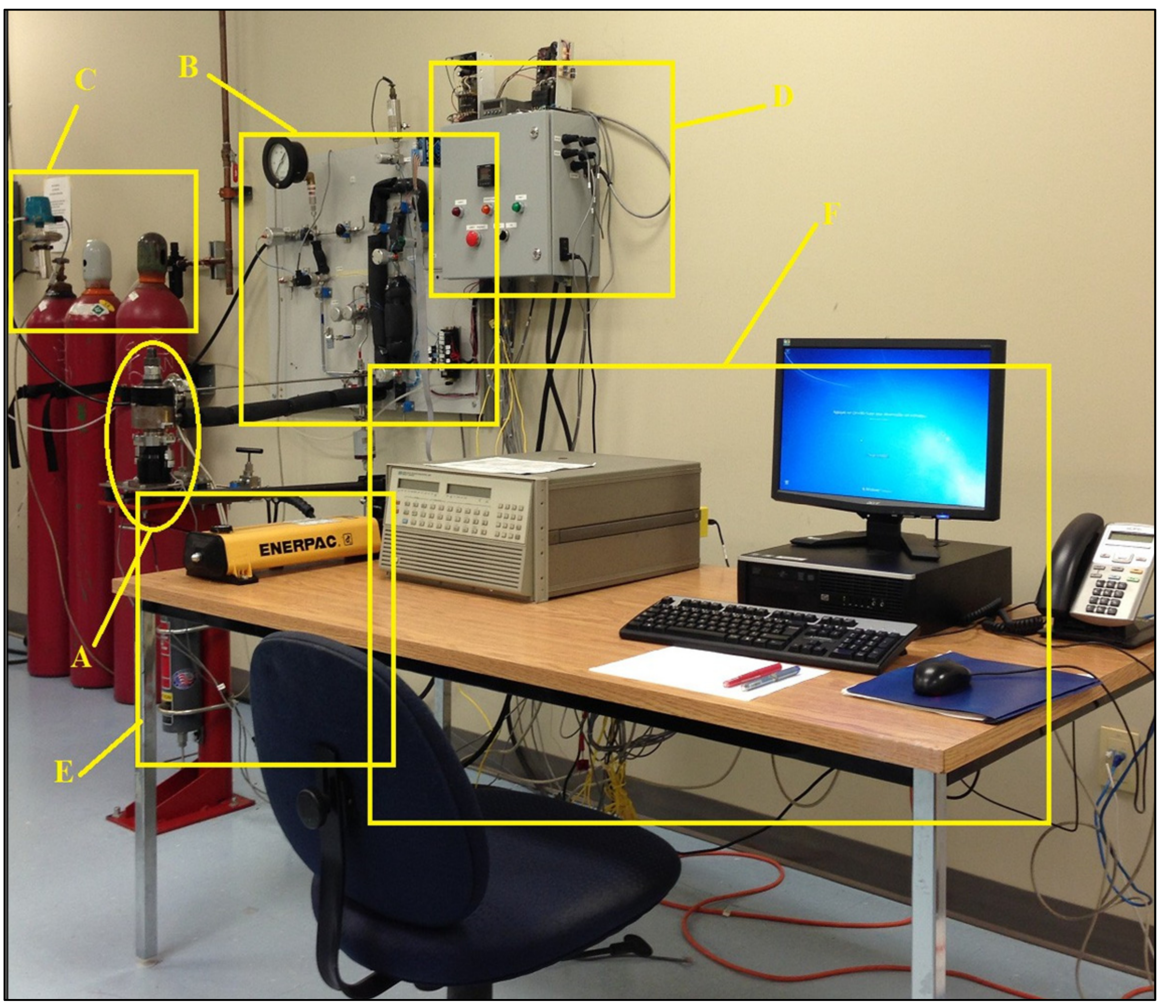


Figure 2-1 Test rig setup for experimental investigations

2.3 The packed stuffing box assembly

Figure 2-2 is a detailed schematic of Part A in section 2.2: the mechanical assembly of a stuffing box that is at room temperature. The critical parts of the packed stuffing box assembly are shown in a section view below.

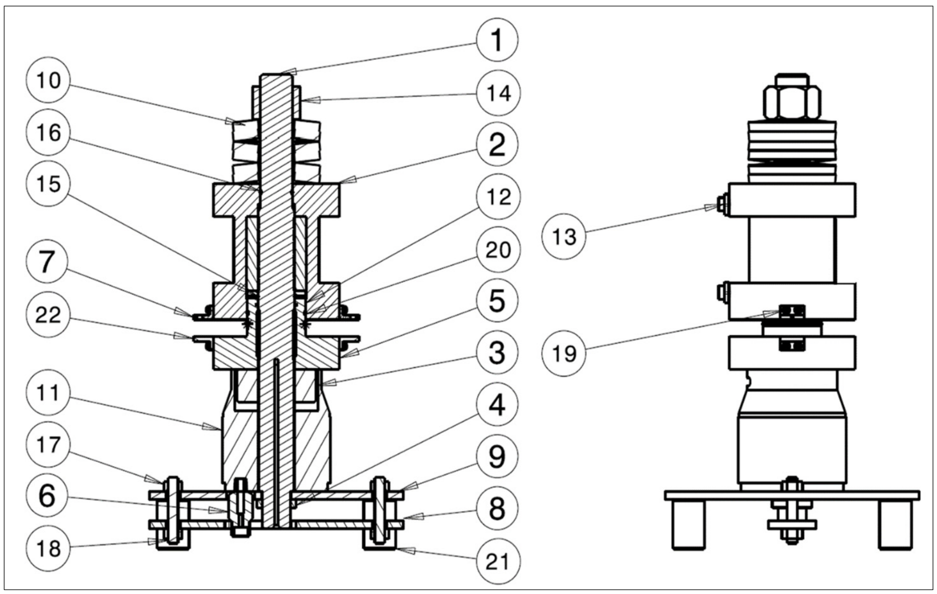


Figure 2-2 Packed stuffing-box experimental setup

In the section view of the rig shown in Figure 2-2, the stem is labeled 1. It is used to open and shut the flow. In this study, 3/8-inch diameter packing rings with a stem made of a 1-1/8-inch diameter were adopted for all experimental tests. The stem is threaded on both sides for connection to the hydraulic tensioner and a nut on the other side. This design makes it possible to apply the load to the packing ring through the stem without any additional bolts.

The next part is the housing, numbered 2. The packing encloses the rings and the stem to simulate the assembled valve housing body. Belleville washers (No. 10) are used for live loads and can be changed to simulate the real stuffing box rigidity. The testing gas or liquid enters the chamber from inlet number 13 and exits from the outlet in case of leaks. Special O-rings are placed on top of the packing room to prevent leakage (No. 16). Any leakage from number 16 does not affect the results of the test.

A hydraulic tensioner (No. 11) and a tensioner nut (No. 3) are responsible for applying the gland compression load. The magnitude of the axial displacements, is measured by two LVDTs diametraly opposed one of which is shown in Figure 2-3. These LVDTs measure the amount of compression of the packing rings as a result of the hydraulic pressure applied to the tensioner.

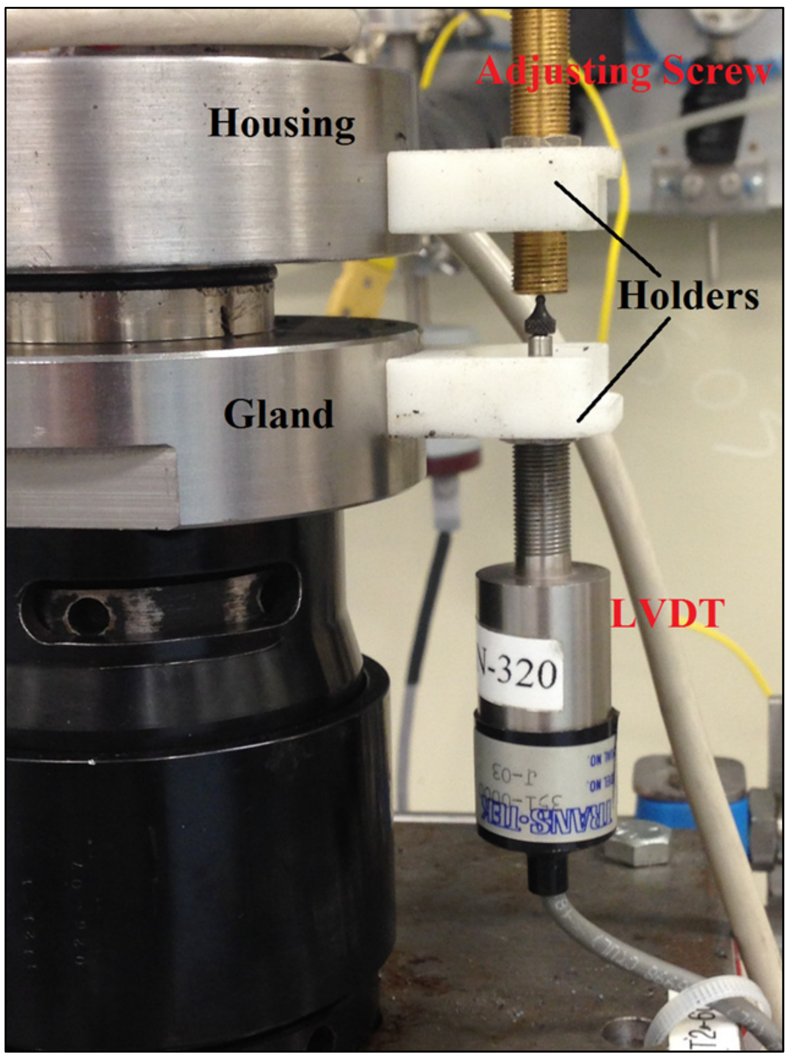


Figure 2-3 Displacement measurement mechanism with LVDTs

2.4 The fluid pressurization system

The gas pressurization system in the test bench is shown in Figure 2-4. Helium (He), air, argon (Ar), and nitrogen (N2) gases can be connected to the test rig in pressurized tanks.

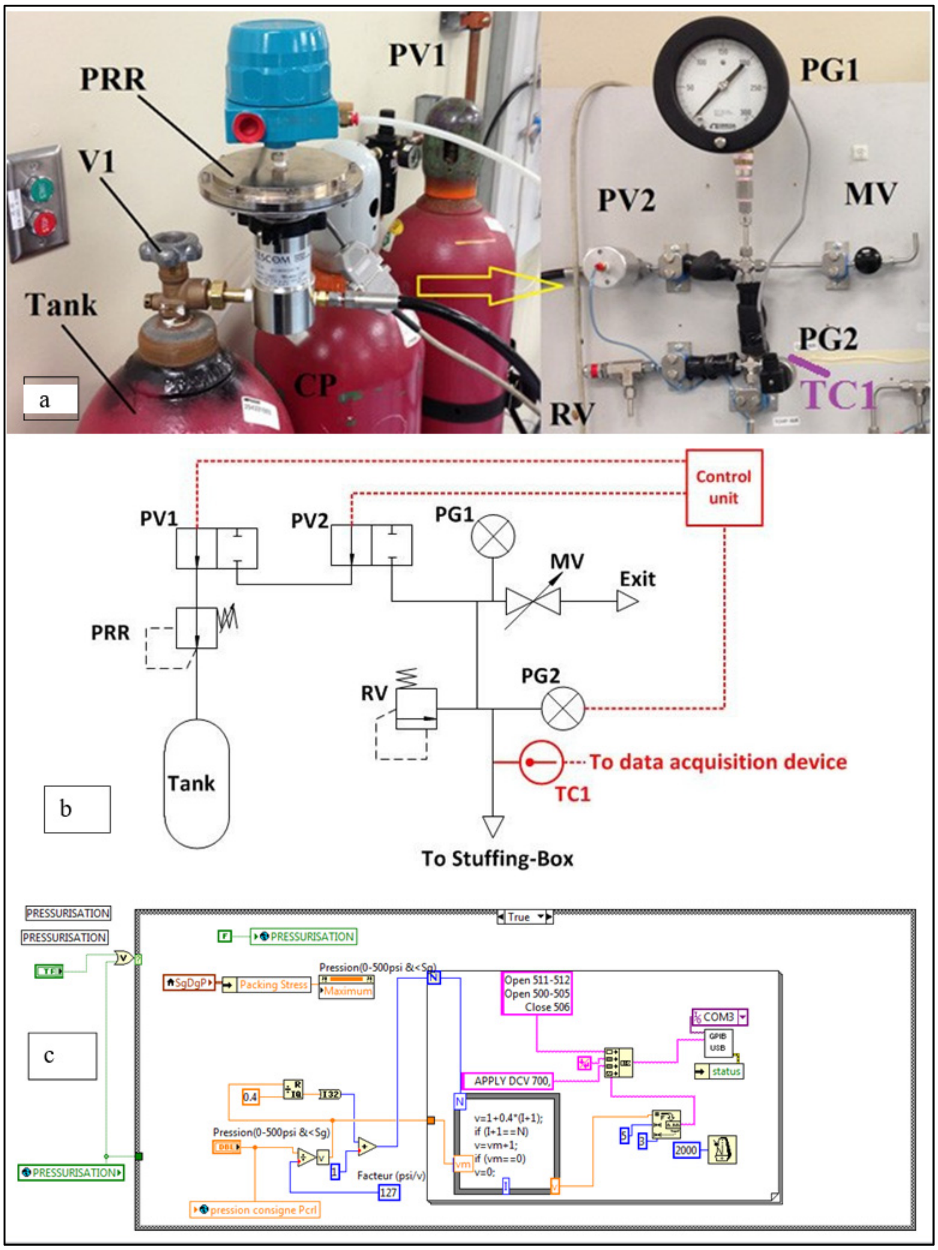


Figure 2-4 Pressurization circuit (a) the test bench assembly, (b) the details of the pressurization system, and (c) LabVIEW program

A valve fitted with an electronic air-operated pressure regulator (PR) controls the gas pressure and a pressure transducer (PG2) to ensure that a constant gas pressure is supplied to the test rig. To ensure safety during the test, a pressure gauge is placed on the control board. A relief valve (RV) and manual valve (MV) are installed in the pressurization circuit to reduce the applied pressure when needed. All these components are also programmed to be controlled and recorded using the LabVIEW platform. Figure 2-4 (C) shows this section of the software.

In this study, nitrogen was used to measure the leakage. The molecular weight and the mean free path of the nitrogen gas used in this study compared to air are presented in Table 2-1.

Table 2-1 The molecular weight and mean free path of N_2 and air

Gas	Molecular weight (g/mol)	Mean free path ($*10^{-10}$)
Nitrogen	28.01	6.044
Air	28.97	6.111

2.5 The hydraulic system

The bolt tensioner connected to the hydraulic system is used to apply the compressive load to the gland. A hand-operated hydraulic pump can provide a maximum of 10,000 psi to the hydraulic circuit. The load is uniformly applied to the first packing rings and transferred to the rest. A hydraulic accumulator is installed to maintain the hydraulic oil pressure constant and therefore the compressive load on the packing rings during testing. Different instruments display the beneficial load on the gland to give the operator an insight over the test condition. In addition to the pressure gage and pressure transducer, a Wheatstone bridge strain gauge measured the load applied to the stem and transmitted to the gland and finally to the packing rings. Figure 2-5 shows the hydraulic circuit, including a manual hydraulic pump, a hydraulic accumulator, a hydraulic distributor, a shut-up valve, a pressure gage, a pressure transducer and a hydraulic tensioner.

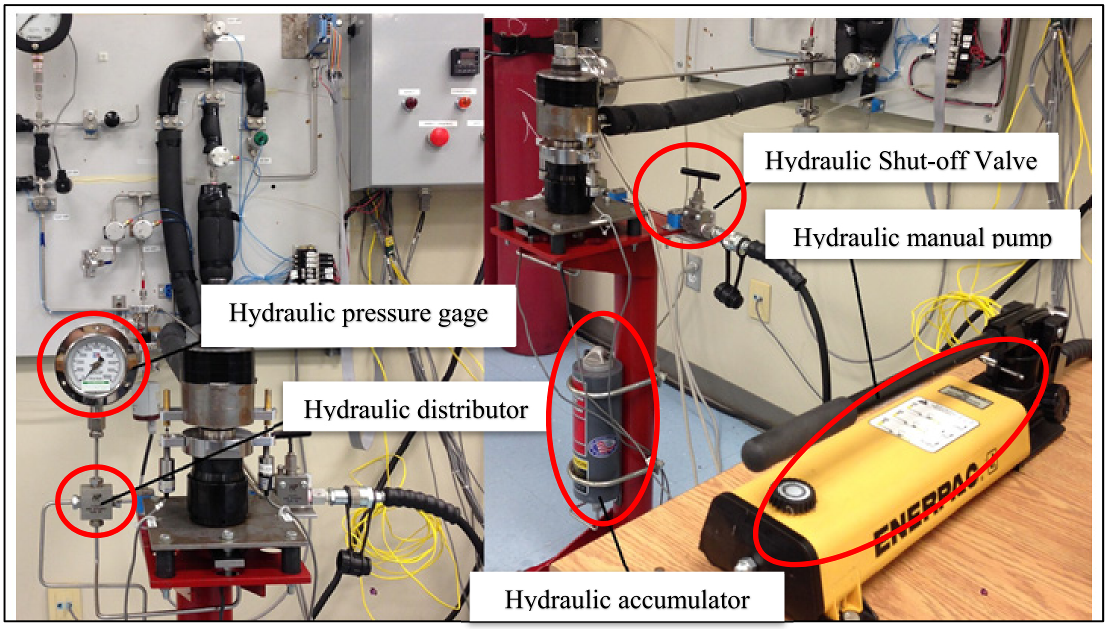


Figure 2-5 The hydraulic circuit

2.6 Leak detection methods

This test bench is equipped to measure five leak detection methods. The choice of the effective method from this method is based on the amount of leakage and the duration of leakage measurement. Although this test rig is designed to measure leakage with several methods, they can be divided into two main categories: the gas leak measurements and liquid leak measurement.

2.6.1 Gaseous leak measurement techniques

For the gaseous leaks, the flow meter, the pressure decay method, the pressure rise method and the mass spectrometry are used.

2.6.1.1 Pressure decay method

The pressure decay method is a technique that measures leaks using the pressure drop of the high-pressure line. The pressure decay fills the system with gas until the gages reach the specific amount of gas pressure. Then a supply valve called PV1 closes stopping the gas filling. The monitoring of the decrease of pressure with time confirm the presence of leak through stuffing box packing rings and the associated leak rate can therefore be deduced. The pressure transducer PG2 monitor the pressure variation over time. LabVIEW evaluate the leak L depending on the parameters used in Equation 2-1 (Bazergui, 2003). Figure 2-6 shows the pressure decay leak measurement system.

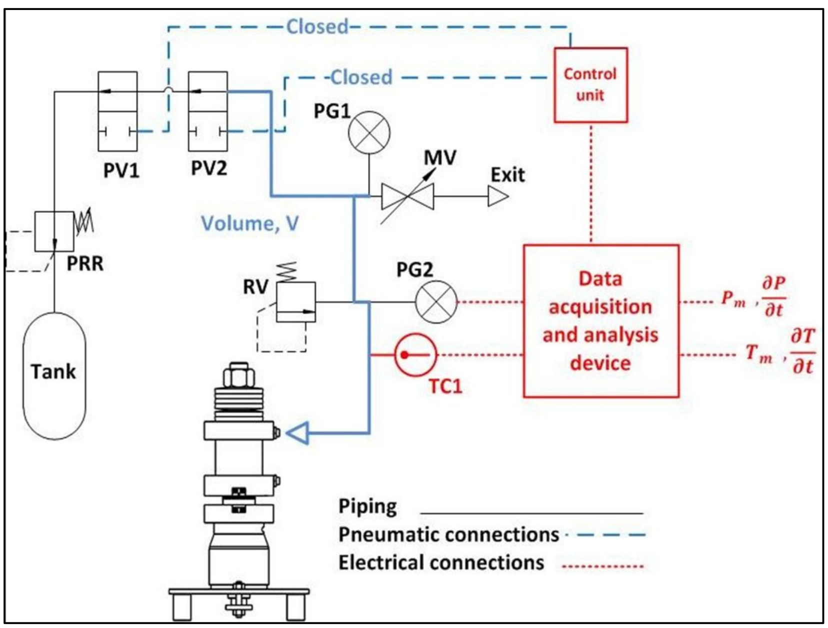


Figure 2-6 Pressure decay leak measurement system

In equation 2-1 of the leak rate L, T_{st} and P_{st} are the standard room temperature and pressure, V is the volume of the high-pressure circuit from the cut-out valve to the gasket internal volume, P_v is the average gas pressure, and T_v is the average temperature.

$$L = \frac{T_{st}}{P_{st}} \frac{P_v V}{T_v} \left(\frac{1}{P_v} \frac{\partial P}{\partial t} - \frac{1}{T_v} \frac{\partial T}{\partial t} \right) \tag{2-1}$$

2.6.1.2 Pressure rise method

The second leak detection technique is the pressure rise method. The pressure rise method consists of measuring the pressure increase in the leak collection chamber located at the gasket outer periphery to measure the leak rate. Figure 2-7 shows the pressure rise circuit that was used in this study. The pressure rise technique is used for two different leak detection levels: fine leaks and gross leaks.

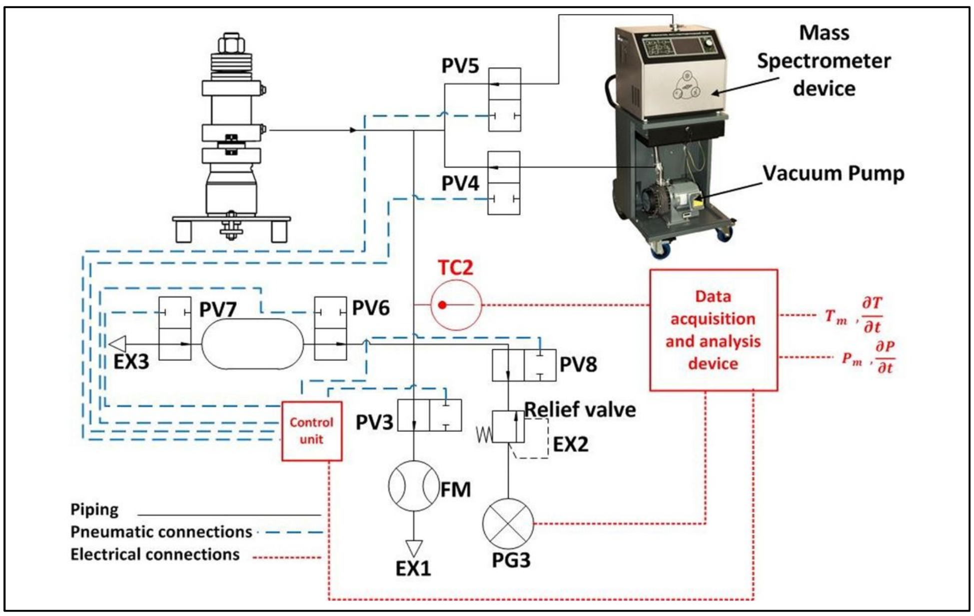


Figure 2-7 The pressure rise and mass spectrometer leak measurement system

2.6.1.2.1 Fine leaks

When the amount of leak is in the range between 0.001 and 0.1 ml/s, fine leak detection can be used to measure the leak rate, where a very low range pressure transducer is installed to measure the small increases of pressure with high precision. The pressure transducer measures the pressure of the gas accumulated in the leak collection chamber. The leak collection chamber must have a known volume prior to testing. Figure 2-7 shows the valve to activates to use the appropriate method.

2.6.1.2.2 Gross leaks

The approach to calculate leak rate is the same with fine leaks, but in this method, the level of leak rate is high (big leak), between 0.1 and 1 ml/s. Equation (2.1) is used by Labview to measure leak rates. A cylinder with a volumetric capacity of 1000 ml is used to the circuit as shown to reduce the rate of pressure increase and avoid damaging the pressure transducers.

2.6.1.3 Flow meter technique

For the high leak rates (greater than 1 ml/s), measurement by a flowmeter is a direct and effective method. Figure 2-8 shows all possible techniques for leak detection used in this study to measure leak rates in different situations.

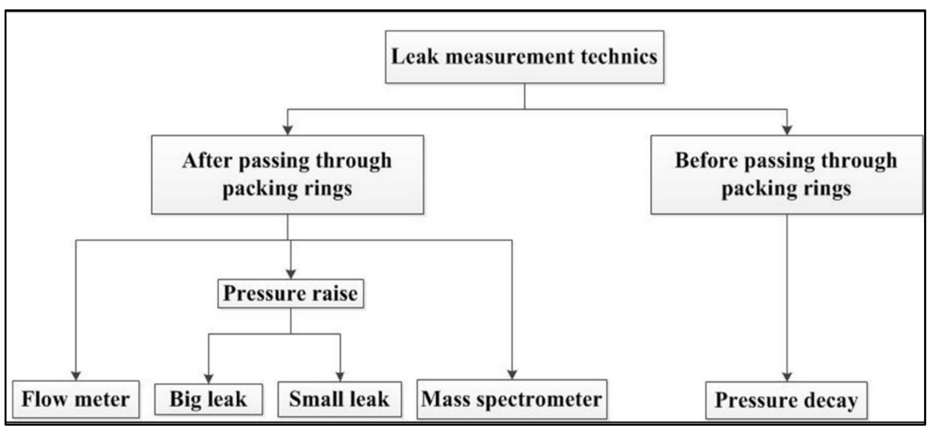


Figure 2-8 Chart of leak detection techniques

2.6.1.4 Spectrometry

An analytical technique that is used to measure the mass-to-charge ratio of ions is Mass spectrometry (MS). Mass spectrometry is done to identify unknown compounds in a given sample. It can also be used for the quantification of known materials. The method ionizes the molecules of the chemical species and sorts them based on the charge-to-mass ratio and relative sufficiency.

2.6.2 Liquid leak measurement technique

for the liquid leak rates, there is only one method used based on the pressure rise method. The special liquid leak measuring device shown in Fig. is used successfully in [15] and can measure leaks down to 10-5 mg/s of water. The outside leak collection chamber is also filled with the same inside liquid to seal allowing only a 2 ml volume of air to be compressed during leak measurements. Any leak into the collecting chamber compresses the small air volume and increase its pressure. The liquid leak measuring device is composed of a liquid supply and purge system to operate safely and protect the 2 psi pressure transducer.

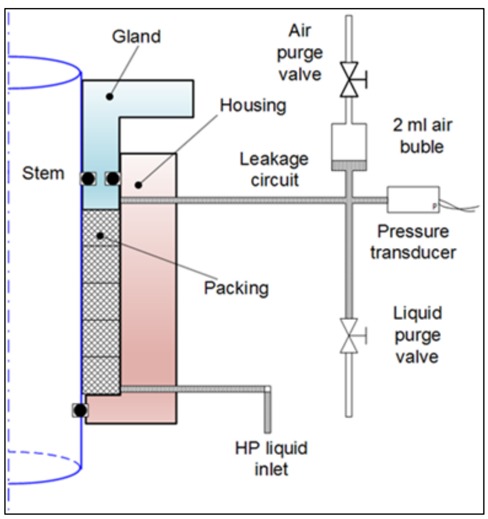


Figure 2-9 Liquid leak measurement technique

2.7 Monitoring test parameters

The test bench is equipped with some instruments to measure and control the system. In general, they contain two main categories: the control devices and the measuring instruments. There are five types of measurement devices: strain gauges, thermocouples, pressure transducers, LVDTs, and a flowmeter. The time and the room temperature are also recorded.

Twenty strain gauges are bounded to the packed stuffing box external wall to measure the axial deformation. Two LVDTs are installed diametrically opposed to measure the packing ring axial displacement due to compression. The thermocouples are installed on the test rig tubing to measure the temperature required for leak rate evaluation for pressure rise and pressure decay methods. The pressure transducers monitor the pressures in the different circuits. The flowmeter measures the gas leak rates above 1 ml/s.

2.8 Data acquisition and control system

All the sensor signals are aggregated and processed by an HP data acquisition and control system. Section F in Figure 1-2 shows this part in the test rig. Figure 2-9 shows the computer graphical interface in LabView used by the test rig operator.

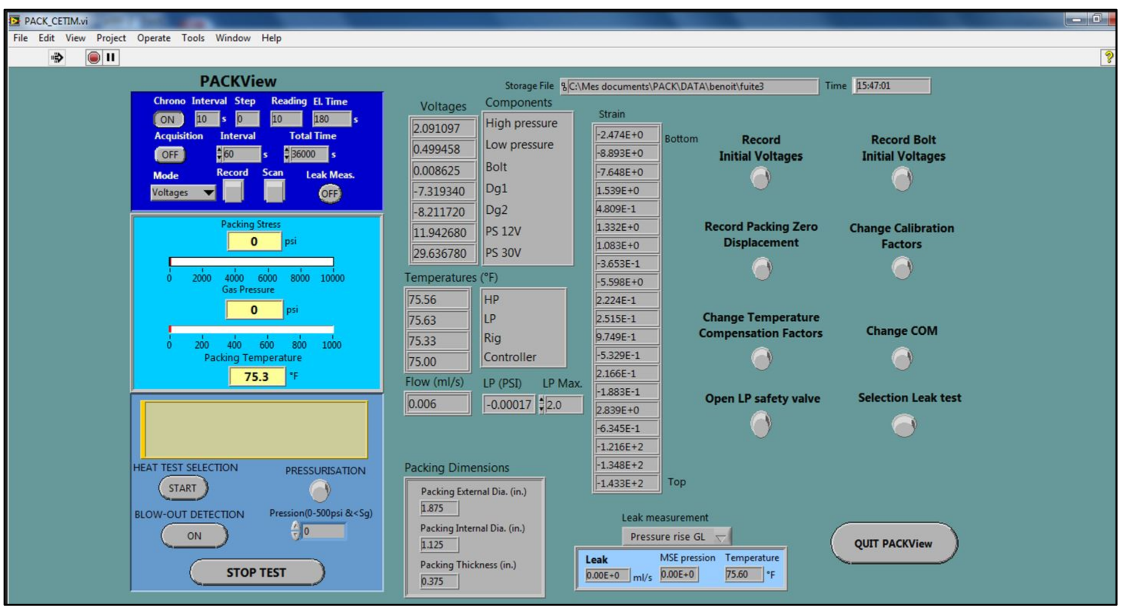


Figure 2-10 The LabVIEW platform

2.9 Test procedure

The test procedure starts with the insertion of the packing rings inside the housing in immaculate condition. The assembly is then mounted on the stem and the gland is then inserted.

The LVDTs are then placed on both sides of the gland. O-rings for high and low pressure sides are placed on the stem and the gland. Depending on the test goals, up to six packing rings can be placed inside the stuffing box. However, five packing rings were loaded in this study. The packing rings are in direct contact with the gland.

After assembling the packed stuffing box, the operator needs to power on the electric panel, switch on the data acquisition system, and finally run the packing test vi under the LabVIEW platform. First the operator needs to apply the desired compression to the packing set with the hand pump and the tensioner and then apply the gas pressure to the system through the regulator valve in this order to avoid excessive leak. Based on the amount of leak rate obtained, the operator will decide on the appropriate leak detection method to use. The flowmeter is the reference for indication of the leak rate level. After testing, the operator should release the fluid pressure first and then release the load from the hydraulic system. The test procedure carried out is summarized in Table 2-2.

Table 2-2 Test procedures for leak detection through packing rings

Leak detection test
The procedure to start the leak tests 1. Assemble the packed stuffing box with the five rings. 2. Inspection of the O-rings' conditions. 3. Turn on the power supply. 4. Start the data acquisition system and the LabVIEW program. 5. Adjust the LVDTs and set the instruments to zero. 6. Apply the load through the hydraulic tensioner. 7. Apply the desired gas pressure. 8. Select best leak detection method after measurement by the flowmeter. 9. Wait for leakage stabilization. 10. Record the temperature, pressure, strain, displacement leakage, and time.
The procedure to finish the test 1. Release the gas pressure and then the load in the packing ring 2. disassemble the packed stuffing box. 3. Close the data acquisition system and the power supply.

CHAPITRE 3

ANALYTICAL APPROACH: GAS AND LIQUID FLOW MODELS

3.1 Introduction

Considering the explanations in the chapter one and the necessity of the experimental data obtained from the test rig, it was concluded that experiments are required to validate the numerical or analytical methods. The test conditions and the experimental preparation were explained in the chapter 2 and the reached flow models are described in this chapter. In the following models, the flow is assumed constant, isothermal, and locally incompressible. The body forces are negligible, and the speed profile is considered to be locally fully developed.

3.2 Gas flow models

The leak paths that fluid particles follow through the porous gasket material such as fiber, graphite, and polytetrafluoroethylene (PTFE) are modeled as circular channels oriented in the axial z direction. The theoretical approach used is one that is adopted in other materials such as gaskets [8]. A porous domain such as packing rings is represented by a set of parallel capillaries of uniform radius R with the first order slip condition shown in Fig. 3-1. The equation of conservation of momentum in cylindrical coordinates for an ideal gas, without taking into account the effect of inertia at low Reynolds number with a large ‘=2R, reduces to

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{du(r)}{dr}\right)=\frac{1}{\mu}\frac{dP}{dz} \tag{3-1}$$

In the case of isothermal flow without displacement of the wall of a micro tube of circular section, the first and second boundary conditions are

$$\left.\frac{du(r)}{dr}\right|_{r=0} = 0 \tag{3-2}$$

$$u\Big|_{r=R} = -\frac{2-\sigma}{\sigma}\lambda\left.\frac{du}{dr}\right|_{r=R} \tag{3-3}$$

Also:

$$\frac{d}{dr}\left(r\frac{du_z}{dr}\right) = \frac{r}{\mu}\frac{dp}{dz} \tag{3-4}$$

$$r\frac{du_z}{dr} = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{r^2}{2} + c_1\right) \tag{3-5}$$

$$\frac{du_z}{dr} = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{r}{2} + \frac{c_1}{r}\right) \tag{3-6}$$

Therefore, the general solution for Equation (3-6) is as follows:

$$u_z = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{r^2}{4} + c_1 lnr + c_2\right) \tag{3-7}$$

where $c_1 = 0$ as the speed has a finite value at $r = 0$. Using the conditions at the boundary, the following is obtained:

$$-\frac{2-\sigma}{\sigma}\lambda\left.\frac{du_z}{dr}\right|_{r=R} = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{R^2}{4} + c_2\right)$$

$$\left.\frac{du_z}{dr}\right|_{r=R} = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{R}{2}\right) \tag{3-8}$$

We can find:

$$c_2 = -\frac{2-\sigma}{\sigma}\lambda\frac{R}{2} - \frac{R^2}{4} \tag{3-9}$$

The following formula gives the velocity distribution in the micro tube:

$$u_z = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{r^2}{4} - \frac{R^2}{4} - \frac{2-\sigma}{\sigma}\lambda\frac{R}{2}\right) \tag{3-10}$$

When the effect of rarefaction is not considered ($K_n \approx 0$), the velocity at the center of the micro tube is as follows:

$$u_{z_0} = -\frac{R^2}{4\mu}\left(\frac{dp}{dz}\right) \tag{3-11}$$

since:

$$u_z|_{r=0} = \frac{1}{\mu}\frac{dp}{dz}\left(-\frac{R^2}{4} - \frac{2-\sigma}{\sigma}\lambda\frac{R}{2}\right) \tag{3-12}$$

$$= -\frac{1}{\mu}\frac{dp}{dz}\frac{R^2}{4}\left(1 + \frac{2-\sigma}{\sigma}4\frac{\lambda}{2R}\right)$$

$$= -\frac{1}{\mu}\frac{dp}{dz}\frac{R^2}{4}\left(1 + \frac{2-\sigma}{\sigma}4K_n\right)$$

$$\Rightarrow \frac{u_z}{u_{z_0}} = u_z^* = 1 - r^{*2} + 4\frac{2-\sigma}{\sigma}K_n \tag{3-13}$$

and:

$$r^* = \frac{r}{R} \tag{3-14}$$

$$u_z^* = \frac{u_z}{u_{z_0}} \tag{3-15}$$

$$K_n = \frac{\lambda}{2R} \tag{3-16}$$

According to Equation (3-13), due to the sliding at the wall, we can see the Hagen-poiseuille velocity profile. The dimensionless average speed is as follows:

$$\bar{u}_z^* = \frac{1}{\pi}\int_0^1 u_z^*\, 2\pi r^*\, dr^* = \frac{1}{\pi}\int_0^1 \left(1 - r^{*2} + 4\frac{2-\sigma}{\sigma}K_n\right) 2\pi r^* dr^* \tag{3-17}$$

$$\bar{u}_z^* = \frac{1}{2} + 4\frac{2-\sigma}{\sigma}K_n \tag{3-18}$$

$$\bar{u}_z = u_{z_0}\left(\frac{1}{2} + 4\frac{2-\sigma}{\sigma}K_n\right) = \frac{-R^2}{4\mu}\left(\frac{dp}{dz}\right)\left(\frac{1}{2} + 4\frac{2-\sigma}{\sigma}K_n\right) \tag{3-19}$$

Considering the slip flow model, the mass flow of a gas through micro tubes of circular section is expressed by the following equation:

$$L_G = \rho \bar{u}_z A = \rho \bar{u}_z A / R_e T \tag{3-20}$$

$$L_G = \rho \bar{u}_z A = \frac{\pi R^2 p}{R_e T}\left[-\frac{R^2}{4\mu}\left(\frac{dp}{dz}\right)\left(\frac{1}{2} + 4\frac{2-\sigma}{\sigma}K_n\right)\right] \tag{3-21}$$

$$L_G = -\frac{\pi R^4}{4\mu R_e T}\left[\frac{1}{2}p\frac{dp}{dz} + 4\frac{2-\sigma}{\sigma}pK_n\frac{dp}{dz}\right] \tag{3-22}$$

The mass flow rate can be calculated using the equation (3-22) where this rate is independent of z:

$$L_G = \frac{-\pi R^4}{4\mu R_e T l}\left[\frac{1}{2}\int_{p_i}^{p_0} p.\,dp + 4\frac{2-\sigma}{\sigma}p_0 K_{n_0}\int_{p_i}^{p_0} dp\right] \tag{3-23}$$

$$L_G = \frac{-\pi R^4}{4\mu R_e T l}\left[\frac{1}{2}\left(\frac{1}{2}p^2\right)_{p_i}^{p_0} + 4\frac{2-\sigma}{\sigma}p_0 K_{n_0}(p)_{p_i}^{p_0}\right] \tag{3-24}$$

$$L_G = \frac{-\pi R^4}{4\mu R_e T l}\left[\frac{1}{4}(p_0^2 - p_i^2) + 4\frac{2-\sigma}{\sigma}p_0 K_{n_0}(p_0 - p_i)\right] \tag{3-25}$$

$$L_G = \frac{-\pi R^4 p_0^2}{16\mu R_e T l}\left[(1-\Pi^2) + 16\frac{2-\sigma}{\sigma}K_{n_0}(1-\Pi)\right] \quad where\ \Pi = \frac{p_i}{p_0} \tag{3-26}$$

$$L_G = \frac{\pi R^4 p_0^2(\Pi^2 - 1)}{16\mu R_e T l}\left[1 + 16\frac{2-\sigma}{\sigma}\frac{K_{n_0}}{\Pi + 1}\right] \tag{3-27}$$

Hence, since the joint is saturated with N pores, Equation (3-27) changes to the following form:

$$L_G = \frac{N\pi R^4 p_0^2(\Pi^2 - 1)}{16\mu R_e T l}\left[1 + 16\frac{2-\sigma}{\sigma}\frac{K_{n_0}}{\Pi + 1}\right] \tag{3-28}$$

3.3 Liquid flow models

It is assumed that the liquid flow in the packing rings is in the axial direction. Packings, which are our sealing elements, are made of porous materials.

The flow of liquid through the porous materials of the packing rings using a straight, circular capillary model is simulated. There are other flow simulation models based on Darcy's law (Kazeminia and Bouzid, 2018) but this are not considered here as the flow is considered relatively small in case of leaks. As shown in Figure 3-1 the packing rings are considered to be composed of many straight capillaries oriented in the axial direction. A straight circular capillary model is used given the one-dimensional flow due to the axisymmetric flow assumption.

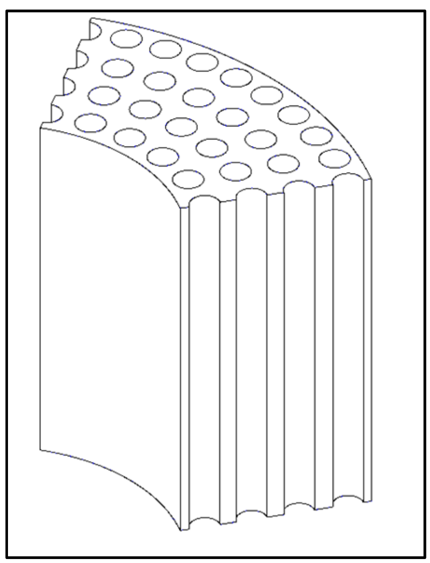


Figure 3-1 Packing ring models (capillary model)

In the model, which has been used for simulating the flow inside the packings, it is assumed that the packing rings are composed of N capillaries with radius R. The velocity in the radial direction inside the capillary is neglected due to the simple flow profile assumption, which is broken down by introducing the momentum correction factor. Therefore, the only apparent variation of the velocity is in the axial or z-direction of the capillary axis. The relationship between velocity and pressure for a fully developed and isothermal flow in the capillary is obtained by the following equation of motion:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{du(r)}{dr}\right) = \frac{1}{\mu}\frac{dP}{dz} \qquad (3\text{-}29)$$

At the middle of the tube, there is the boundary condition that is represented by Equation 3-30. Based on the first-order slip model of liquid. The boundary condition at the wall is represented by Equation 3-31:

$$\left.\frac{du(r)}{dr}\right|_{r=0} = 0 \qquad (3\text{-}30)$$

$$u(r,z) = -l_s\left.\frac{du}{dr}\right|_{r=R_g} = -l_s\left(\frac{du}{dr}\right)_w \qquad (3\text{-}31)$$

Where the slip length in a liquid condition of a circular capillary is denoted by l_s and is given by the following:

$$l_s = 0.059|\gamma^{0.485} \;\; where\; \gamma = \frac{\Delta PR}{2\mu l} \qquad (3\text{-}32)$$

And therefore:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{du_z}{dr}\right) = \frac{1}{\mu}\frac{dp}{dz} \qquad (3\text{-}33)$$

In the simple case of an isothermal flow and without wall displacement established in a micro tube of circular section, rearranging Eq. 3-33 and integrating gives:

$$\frac{du_z}{dr} = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{r}{2} + \frac{c_1}{r}\right) \qquad (3\text{-}34)$$

Therefore, after integrating Eq. 3-34 the general solution for Equation (3-33) is obtained as follows:

$$u_z = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{r^2}{4} + c_1 lnr + c_2\right) \tag{3-35}$$

where $c_1 = 0$ as the speed has a finite value at r = 0. Using the conditions at the boundary (3-30), the following is obtained:

$$-l_s\left(\frac{du}{dr}\right)_w = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{R^2}{4} + c_2\right) \tag{3-36}$$

We can find:

$$c_2 = -\frac{R^2}{4} - l_s\frac{R}{2} \tag{3-37}$$

For the solution of the velocity in the z-direction, Equation (3-30) is merged twice and the above boundary conditions are applied to give direction as a function of the radial direction:

$$u(r,z) = \frac{1}{\mu}\frac{dp}{dz}\left(\frac{r^2}{4} - \frac{R^2}{4} - l_s\frac{R}{2}\right) \tag{3-38}$$

The leakage rate of N capillaries can be obtained by combining velocity in the capillary area as:

$$L_L = N\int_0^R \rho\, 2\pi \mathrm{r}.\, \mathrm{u}(r,z)dr \tag{3-39}$$

Finally, the total leak rate through all capillaries is given by the following equation:

$$L = \frac{N\pi R\rho(P_i - P_0)}{8\mu l}\left[1 + \frac{4l_s}{R}\right] \tag{3-40}$$

3.4 Procedure to determine porosity parameters N and R

Packaging porosity parameters N and R are determined from the curved fitting of the data obtained with Nitrogen used as the reference gas and using the gas flow Equation derived using a similar theoretical approach (Aweimer et al.,2017). The total gas leakage rate is:

$$L_G = \frac{N\pi R^4 p_0^2(\Pi^2-1)}{16\mu R_e T l}\left[1+16\frac{2-\sigma}{\sigma}\frac{K_{n_0}}{\Pi+1}\right] \tag{3-41}$$

where K_n is the e Knudsen number:

$$K_n = \frac{\lambda}{2R} \tag{3-42}$$

and ∏ is the pressure ratio defined as follows:

$$\Pi = \frac{P_i}{P_o} \tag{3-43}$$

where λ is the mean free path given by the equation below:

$$\lambda = \frac{16\mu}{5P_0}\sqrt{\frac{RT}{2\pi}} \tag{3-44}$$

The mass flow equation can be linearized in terms of the reciprocal pressure 1/∏+1 and is expressed by Equation 3-45, where A and B are determined using Equations 3-46 and 3-47:

$$A = NR^4\left[1+B\frac{1}{\Pi+1}\right] \tag{3-45}$$

$$A = \frac{16\mu lRTL}{\pi P_0^2(\Pi^2-1)} \tag{3-46}$$

$$B = 16\frac{2-\sigma}{\sigma}K_n \tag{3-47}$$

The porosity parameters N and R can be obtained from the slope A and the intercept B from the experimental curve obtained by using nitrogen as a reference gas in Eq. (3-44) which expresses A as a function are the pressure ratio of 1/∏+1.

CHAPITRE 4

RESULTS AND ANALYSIS

4.1 Introduction

The experiments were performed according to the steps described in chapter 3. A comparison between the leak rates obtained experimentally and those predicted analytically was conducted for the purpose of validating the proposed analytical model. The agreement between the results obtained will be discussed in this chapter. The experimental measurement is conducted at room temperature for both the gas and liquid tests which represents a first step to valid the leak predictions in packed stuffing boxes of valves. It is worth to mention that although the prediction of leak rates at high temperature is equally important, it is not the objective of this work.

4.2 N2 Gas leak tests

Fluids are classified into two categories; liquids and gases. Gases such as nitrogen and helium are usually used as reference gazes for testing and forecasts due to their constant properties. The measurement of gas leakage in packing rings is used hereafter to determine the porosity parameters. Nevertheless, there are extensive research work on gas flow that use the same technique to predict leakage with gases. in current research work, nitrogen is used as a reference to size the flexible packing material pores.

4.2.1 Porosity Parameters

Nitrogen gas was used as the test gas in the gas leak tests. With a density of 1.251 mg/ml, this gas was tested at six levels of gland stresses and they are 3.45, 6.89, 10.34, 13.79, 17.24, and 20.68 MPa.

Different gas pressure values were also examined at each gland stress to determine the packing rings gas leakage rate. The gas pressure was controlled by the air operated high pressure gas regulator via the LabVIEW program. Six levels of gas pressure were applied to the packed stuffing box; 0.34, 0.69, 1.03, 1.38, 1.72, and 2.07 MPa the gas leakage rate was recorded for every pressure and gland stress combination.

4.2.2 Effect of gland stress and pressure on Gas leaks

As illustrated in Figure 4-1, the results clearly show that as the amount of gland stress increases, the amount of gas leakage decreases. Increasing the gland stress causes the packing ring pores to decrease. Tightening the space between the packing rings and the walls results in a reduction of the amount of leakage.

It is also observed that the increase of gas pressure applied to the packing ring increases the amount of leakage (Figure 4-1). The higher the gas pressure, the more the gas flows through the packing rings pores and side walls. The results obtained by the experiments, show how the gland stress and inlet gas pressure affect the leakage rate. The relatively linear relationships between the results are evident.

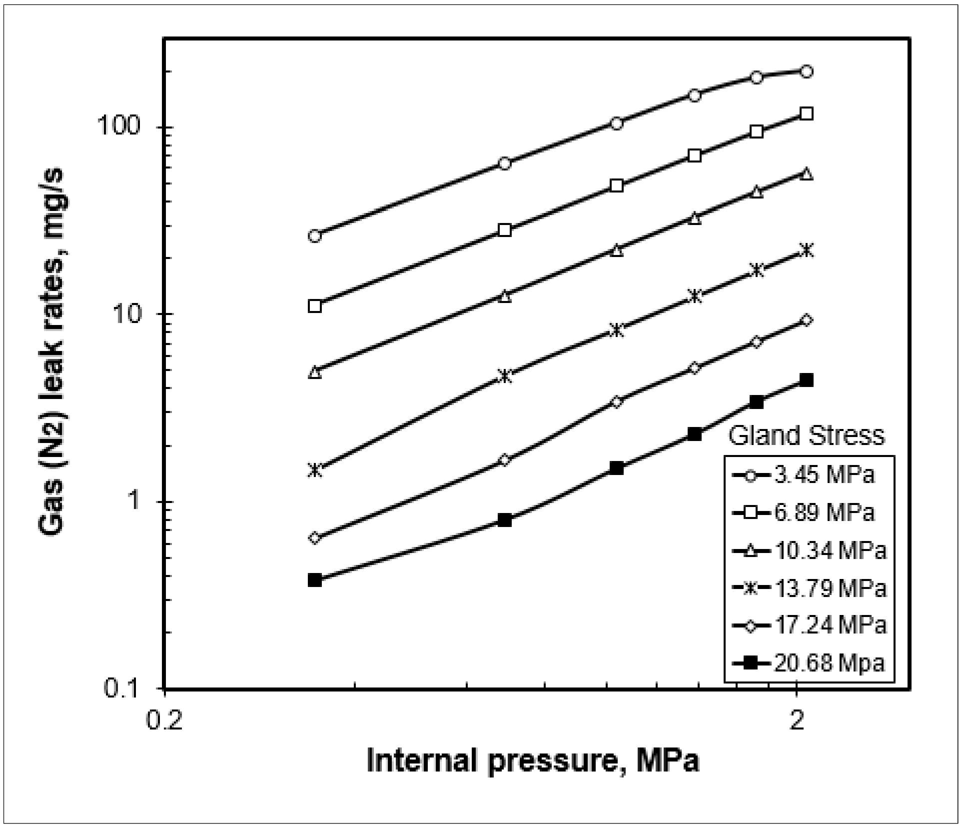


Figure 4-1 Leak rate experimental results for gas (N2) in flexible graphite packing

4.2.3 Determination of porosity parameters

Figures 4-2 illustrate the relationship between the porosity parameter "A" as a function of the reciprocal pressure 2/∏+1 given by Equation (3-18). The relationship for flexible graphite packing rings is linear for the different gland stress levels. The two porosity parameters, the number (N) and the radius (R) of capillaries, can be determined by the slope and the intercept using Equations (3-19) and (3-20). According to the Equation (3-18) the intersection and slope of line A represent NR^4 and BNR^4 respectively. Therefore, B can be obtained. The Knudsen number is then obtained from Equation (3-20) for σ equal to 1. The hydraulic diameter D=2R can be inferred for the gas used for the pore characterization test. Finally, the number N of the capillaries is obtained.

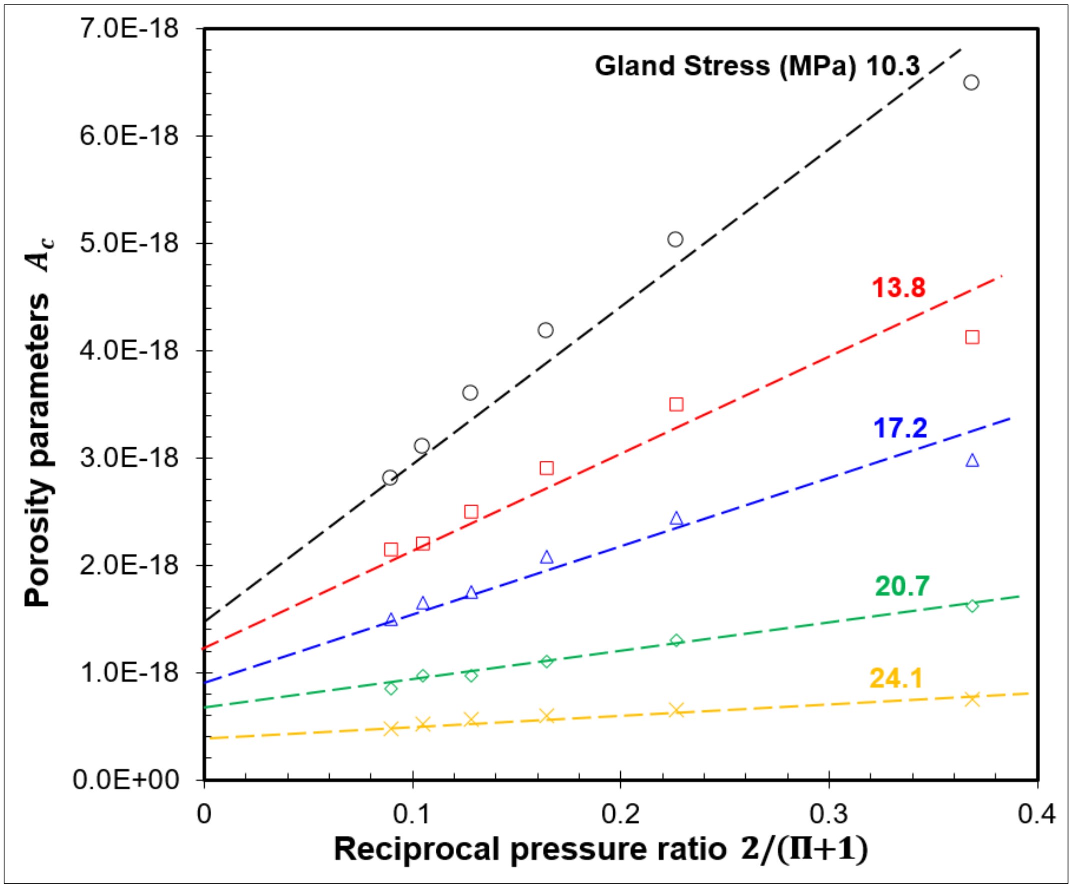


Figure 4-2 Graphs to obtain the porosity parameters in flexible graphite packing

Figures 4-3 and 4-4 show the change in radius and number of capillaries as a function of gland stress. Using these curves, the size and number of capillaries under each specific packing stress can be obtained to predict the amount of leakage of the studied liquid using Equation (3-14). The relationship between NR^4 and gland stress is exponential, however, when the two parameters N and R are considered separately, the trend becomes linear. The linear relationships are given in Figure 4-3 for flexible graphite packing. It should be noted that increasing the gland stress causes both parameters to decrease. Obviously, the below relationships are for the for the tested flexible-graphite packing rings and every material should have its own relationship:

$$R = -5.05 \times Sg + 161$$
$$N = -7.61 \times 10^{8} Sg + 1.92 \times 10^{10} \tag{4-1}$$

According to the equation (4-1), initially under no stress the capillaries have a radius of 161 nm while the number of them exceeds 1.92×10^{10}. The characteristics of the pore size given by Equation (4-1) along with the properties of water and Equation (3-18) were used to predict the liquid leakage rate.

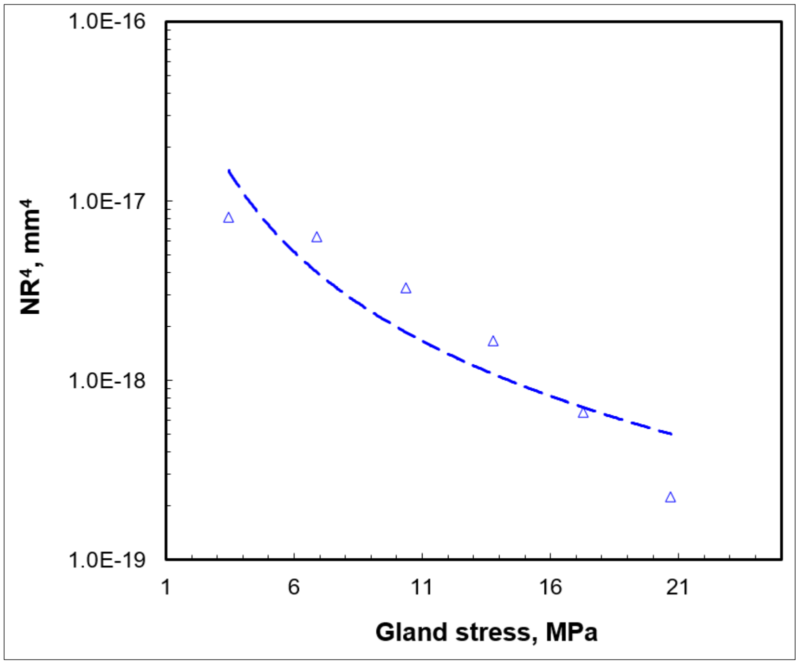


Figure 4-3 Porosity variation (NR^4) of packings

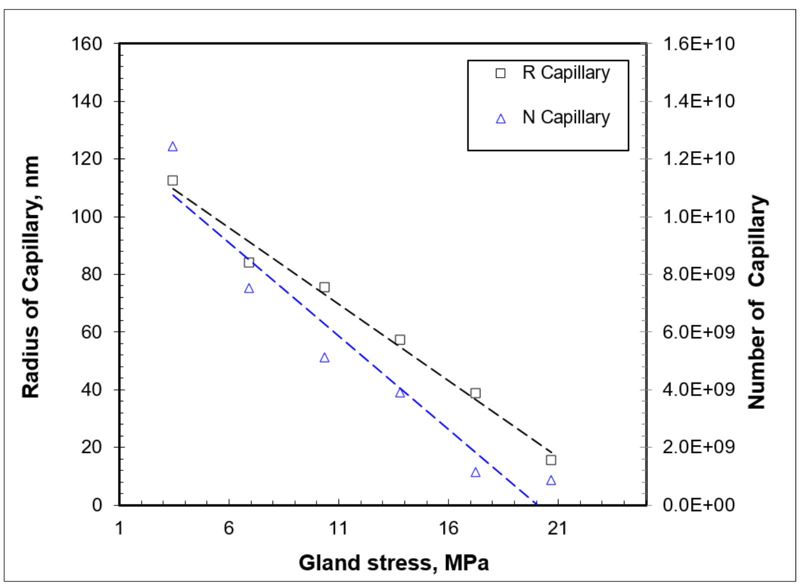


Figure 4-4 Porosity variation (Radius of the capillary) of packings

4.3 Water leak tests

After the experimental gas leak tests to characterize the porous structure of the packing material, the liquid leak test is conducted and compared to the prediction using the data presented in section 4.2. The predictions were examined experimentally in this thesis to evaluate their accuracy. The agreement of the two proves that the methodology used is a practical approach to predict liquid leakage. Accordingly, the leakage rate through the packing rings can be predicted for any liquid that do not react with the packing material.

4.3.1 Test parameters for water leakage

Water was used as the test fluid in the liquid leak analysis. With a density of 1 mg/ml, this liquid was tested with initially six levels of gland stress to validate the analytical model. These are 3.45, 6.89, 10.34, 13.79, 17.24, and 20.68 MPa. Additional test was pursued to verify the relation between the gland stresses and leakage at higher stresses. Therefore, the tests continued with gland stresses equal to 24.13, 27.58, 31.03, and 34.47 MPa. The curve of leak rates vs pressure confirms the existence of a proportional relationship between leakage rates even at higher gland stress levels.

Different gas pressure values were examined with each gland stress to determine the packing rings water leakage rate effect with pressure. Different pressure values controlled by the air piloted gas regulator and the LabVIEW program were applied to the stuffing box system. Six levels of gas pressure were applied and these are 0.34, 0.69, 1.03, 1.38, 1.72, and 2.07 MPa.

4.3.2 Water leakage results

As illustrated in Figure 4-5, the results obtained in the experiments show that as the amount of gland stress increases, the amount of gas leakage decreases. Increasing the gland stress causes the packing rings to be compressed resulting in a reduction of the pore size and the leak paths between the packing rings and walls and consequently the amount of leakage decreases.

However, increasing the amount of liquid pressure in the packed stuffing box increases the leak rate. The higher the liquid pressure, the more the water flows through the packing ring material. The experimental results show how the increase in gland stress and inlet gas pressure affect the leakage rate. The quasi linear trend in a semi-log plot between the leakage rate and liquid pressure is confirmed as suggested by the analytical model (Figure 4-5).

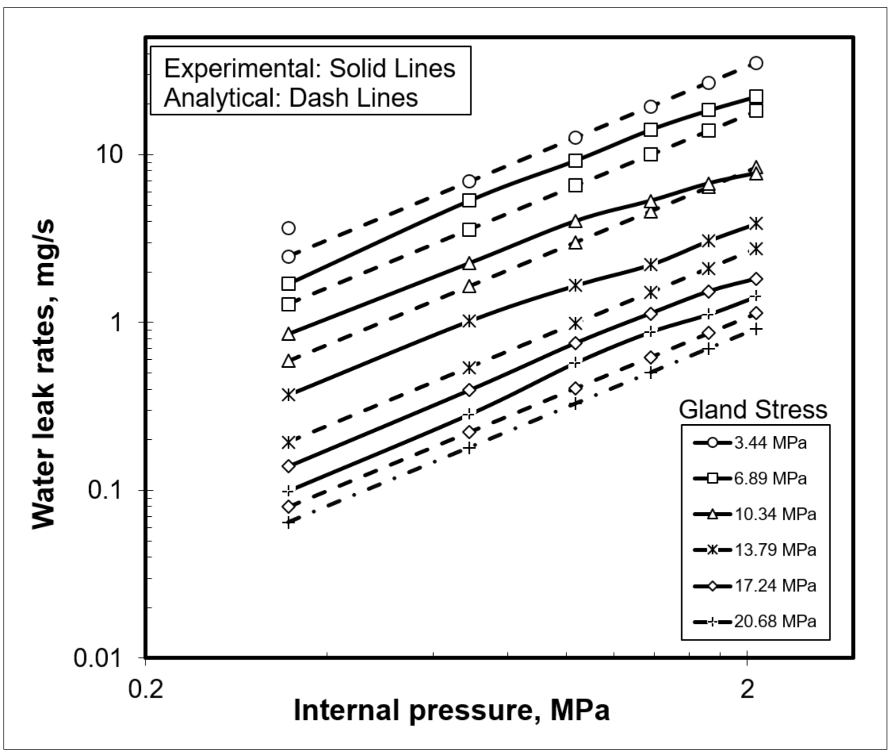


Figure 4-5 Leak rate predictions and experimental results in flexible graphite

Figure 4-6 shows how the water leakage rate variation with pressure at different values of the gland stress. The results of both the liquid leak measurements and the predictions indicate that increasing the gland stress reduces the amount of leakage. And as the fluid pressure at the entry of the packing rings increases, the amount of leakage increases.

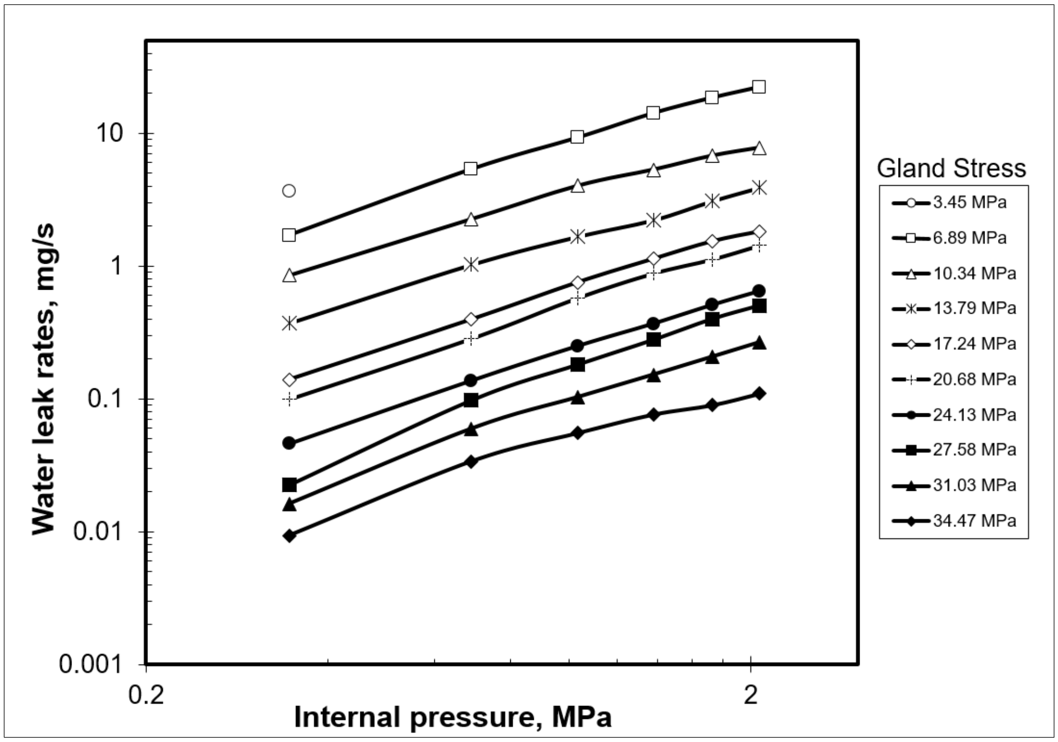


Figure 4-6 Additional experimental results for leak rates of water
at different gland stresses from 3.45 to 34.47 MPa

4.3.3 Displacement measurement in the water leakage test

As mentioned in the chapter 2 two LVDTs were installed on the test rig to record the gland displacement with respect to the housing and the amount of packing ring compression. The amount of compression of the packing rings recorded by the LVDTs indicates that as the stress on the gland increases, the packing rings become more compact, and the porosity of the packing material decreases. The reduction of the pores and leak paths inside the packing rings and at the walls leaves less and less space for water to pass through and reduces leakage. The relationship between displacement and glans stress and water leak rate are illustrated in Figures 4-7 and 4-8, respectively. The displacement leak relationship is perhaps a better relation that can represent the link to the leak than the stress because the size of the pores is directly related. In addition the displacement is an important parameter and in particular, when the thermal expansion and relaxation takes place and is more indicative of the leakage behavior.

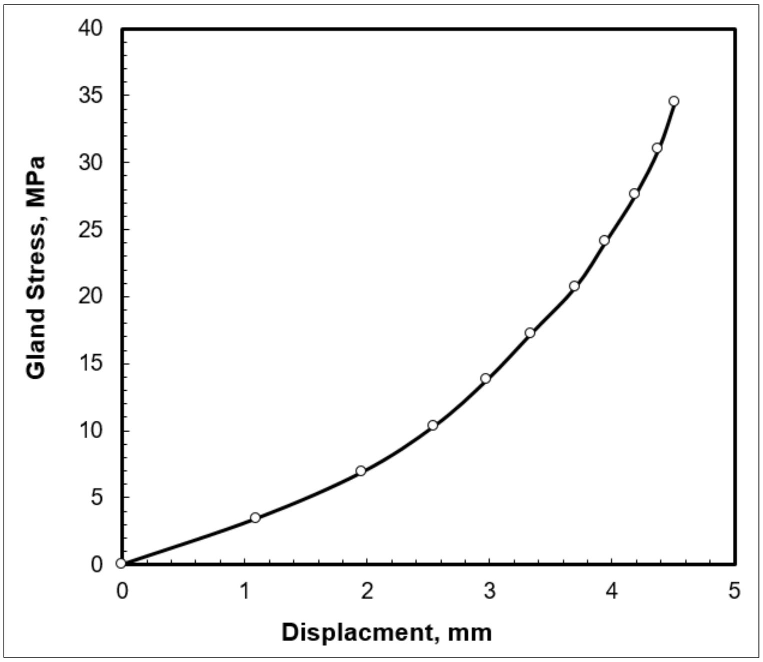


Figure 4-7 The amount of displacement in the gland axis at different stresses on the test rig

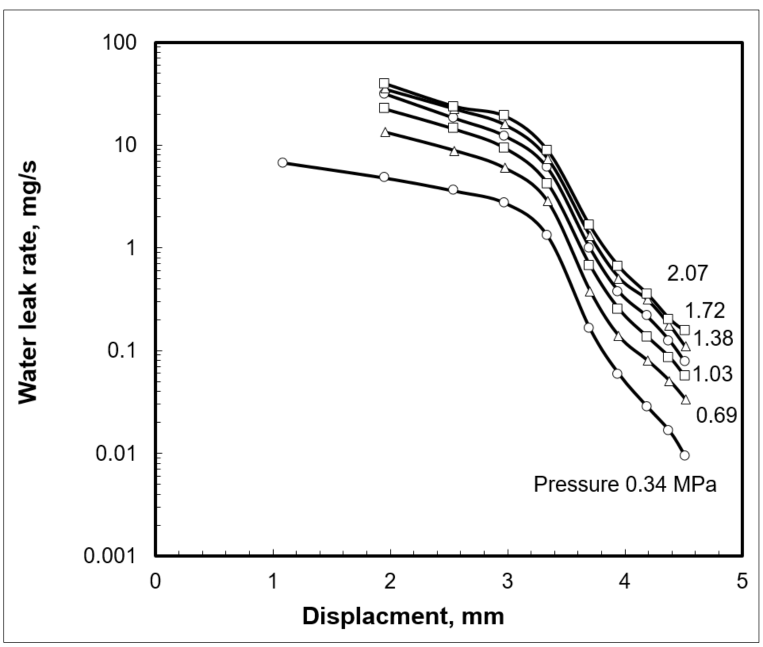


Figure 4-8 The leak rates vs displacement

CONCLUSION

This research project deals with fluid flow through porous media. The work is aimed at predicting liquid leak rates in packed stuffing boxes in order to help the various industries improve seal ability compliance and reduce leakage in their systems. The nuclear and petrochemical industries can benefit most from this study to comply with the fugitive emissions by selecting appropriate packing materials to control fluid leakage.

Packing seals are integral components of valves used to prevent leakage. The mechanical properties and parameters that affect the leakage rate are numerous and complex. The experimental work confirmed that the proposed analytical model can be used to predict liquid leak rates with reasonable accuracy. The results obtained provide a clear signal to engineers and researchers to continue the work to implement a valve stuffing box design procedure like the bolted flange joint design procedure that already exists since the 50's. Even though the best stuffing box design cannot produce zero leakage, a minimum leakage criterion can be incorporated since the suggested model can be used to predict leakage. Such a design procedure can help comply with the new regulations on fugitive emission.

This thesis was aimed to achieve the following goals:

- Prediction of liquid leak rates through packing seals under different working conditions
- Experimental characterization of the porous structure of packing ring materials
- Experimental validation of the suggested analytical liquid prediction model with water as a liquid media using a home-made liquid leak detector device capable of measuring down to 10^{-5} ml/s.

The methodology used to characterize the pore size for use to validate the suggested analytical model has proven to be efficient and precise. The tests using nitrogen as a reference gas were proved to be adequate to size the porous structure of the packing material under different gland compression. The analytical predictions of liquid leak rate compare well with the experimental data obtained under different gland stresses and liquid pressure.

Axial compressive stresses between 3.45 and 34.47 MPa were applied to the packing rings made of flexible graphite through the gland and pressures between 0.34 and 2.07 MPa were supplied with water to measure leak rates. Although the tests are conducted at room temperature, the results obtained are promising and are representative of industrial applications. Tests using Nitrogen gas as a reference has proved to be an excellent mean to characterize the pore size of the graphite packing rings and should be pursued for other packing materials. The experimental test results proved to be I acceptable agreement with the predictions. It was also observed that the higher the fluid pressure, the higher the amount of leakage. The methodology is promising and should be used for other materials and under other working conditions including high temperature, creep and cyclic loading. It is hoped that the work would be pursued further in order to generalize the methodology and reach an implement phase in a design procedure of packed stuffing boxes.

Finally, it is necessary to develop sealing technology by improving leakage predictive tools in order to improve the sealing performance of packed stuffing boxes and bolted flange gasketed joints under different conditions to reduce the release of volatile gases and increase the safety of humans and the environment.

RECOMMENDATIONS

This study focuses primarily on predicting liquid leakage through packing rings using analytical models and comparing the results experimentally with tests conducted under different controlled working conditions. To generalize the study, the work may include other materials, operating conditions, and applications.

The recommendations of this thesis are outlined as:

- Perform leak tests with other types of packing ring materials that have distinct porosity properties.
- Use the same methodology to characterize the pore sized of the selected materials.
- Test the suggested model with other liquids
- Consider the effect of high temperatures, including the changes of liquid properties, porous structure, thermal expansion, creep-relaxation, aging, and corrosion.
- Considering the effects of lubrication, friction, and wear on the leakage performance of packing rings.
- Two-phase flow conditions when using special liquids that experience phase change, such as steam and water.

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