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# Leak prediction through porous compressed packing rings: A comparison study

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ABSTRACT

The Prediction of leak rate is a significant challenge in the design of bolted flange joints and valves. With the increase of the strict regulations on fugitive emissions appropriate leakage-based standard design procedures are required. Fluid flow through porous media is a very attractive theory that can be used to predict leak rates through gaskets and compression packings. Valves that are the major source of fugitive emissions in the category of pressurized equipment use compression packings and seals the design of which is not covered by a standard design procedure.

In this study, three different models; capillary, concentric cylinders, and modified Darcy's models, are used to characterize the sealing behavior of graphite-based compression packing rings. Based on data from several experimental tests, the ability of each model to predict accurate leak rates is evaluated. The comparison between the predicted and the measured leak rates is conducted for different molecular size gasses and a wide range of gland stresses and gas pressures.

## 1. Introduction

Static sealing of micro and nanoporous materials used in packed stuffing-boxes for valve sealing are the general framework of this study. The performance of valve sealing has a major impact on operational safety in chemical, nuclear and fossil power plants. Excessive leaks can cause environmental damages, injuries, shutdowns and loss of revenues [1]. Fugitive emissions are estimated by ESA [2] to 10000 tons per year from European refineries and to 300000 tons per year from US power plants. About 50 to 60% of this amount is attributed to valves [3,4].

Improving the design and sealing performance of valves increases the safety and reduces fugitive emissions, maintenance, and revenue costs. Recent legislations and the strict regulations of fugitive emissions has forced industries to comply with new standards on valve fugitive emissions such as ANSI [5]; API-622 and 624 [6,7]; ISO-15848-1 and ISO-15848-2 [8].

There are two ways for a high pressure confined gas or fluid to escape from the inside of a valve. The first one is related to the leak that escapes to the cut-off circuit when the valve is closed and the second one is the leak through the stuffing-box packing. The latter is related to the flow through the porous compressed packing rings. This type of leak can be controlled by maintaining a minimum threshold gland stress applied to packing rings. Several studies have been investigated to evaluate the distribution of contact stress in a packed stuffing box [9–16] Very few of them establish a clear relationship between the stress and the leak and even less the prediction of leak rates for different gasses based on test conducted with a reference gass.

The literature shows that the prediction of fluid flow through porous packing materials is limited to few studies that have been conducted recently. Lasseux et al. [17] in their second paper that is a continuation work of a previous study [18] on the characterization of the permeability of a packing ring made of exfoliated graphite, used Darcy's law model with Klinkenberg's effect as the driving physical model to evaluate the porosity parameters experimentally with two leak detection test benches. Their study is limited to a single packing ring behavior while only the pressure decay method is used to measure gross leaks to characterize the permeability properties.

Other researchers conducted experimental work to correlate gaseous leaks in yarned packing rings. Cazauran et al. [19] applied TA Luft and VDI 2440 test data to correlate leakage of various types of gases they used Poiseuille and Knudsen laws to do the predictions. Schaaf and Schoeckle [20] measured leaks from compressed packing rings in order to test their capability to meet the requirements of the European and American standards such as TA-Luft and IPPC, ISO and API.

In general, the subject of micro- and nano-flow in porous media has attracted a lot of attention in the last decade because of several

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important engineering applications such as gas based fuel cells, gas extraction from shale reservoirs, micro-electro-mechanical-systems (MEMS) and so on. In all these applications, the characterization and prediction of gaseous or liquid fluid flow through their porous structures were a challenging task. The main difficulty to overcome in such studies is that the confined spaces are small, the operating conditions vary considerably, and the interactions between gas molecules and micro- and nano-scale pores are complex [21,22].

Gaskets and compressed packing rings are porous structures used for sealing purposes in bolted flanged connections and valves. Unlike packing rings, gaskets have been the subject of few studies related to the leakage prediction through their porous structures. Gu et al. [23] presented a gaseous leakage model which combines laminar flow and molecular flow regimes. Jolly and Marchand [24] studied the slip or near transitional flow in gaskets using Klinkenberg law of diffusion. They compared their model with the laminar molecular flow model and obtained almost the same results. Grine and Bouzid [25] conducted a leakage prediction study and were able to estimate leak rates in non-metallic gaskets with reasonable accuracy. They used capillary and parallel plate models with first-order boundary conditions. Furthermore, they included the effect of high temperature in their model and were able to obtain acceptable predictions of leak rates [26].

This study deals with the prediction of leak rates through porous yarned packing rings. Three different models; capillary model, concentric cylinders model, and a modified Darcy's law model are used to predict leakage based on the porosity parameters of the stuffing-box packing structure deduced experimentally using leak rate measurements of a reference gas. A well-equipped packed stuffing-box test bench is used to measure experimentally the leaks of a flexible graphite based compressed packing rings.

## 2. Physical models

Several methods have been proposed to characterize fluid flow through porous media. These methods can be classified based on the interactions between the gas molecules and the pore walls. This phenomenon quantified by Knudsen number that is a dimensionless parameter that expresses the mean free path to the relative size of the pore. For Knudsen numbers greater than ten the number of interaction between gas molecules and pores wall is more important than between gas molecules themselves and hence the flow regime can be considered as a molecular flow while for Knudsen numbers smaller than 100 a continuous regime is present. Two further classifications of the flow regimes that are neither absolutely continuous nor molecular exist. When Knudsen number is $0.001 < Kn < 0.1$ the flow regime is known as slip flow and when Knudsen number is $0.1 < Kn < 10$ the flow regime is known as transition flow [27].

The porous packing seal used in the experiment is constructed by a set of four packing rings made of expanded graphite-based braided construction. A general configuration of a packed stuffing-box in its axisymmetric sectional view is shown in Fig. 1. The compression force is applied by the gland located at the top of the packing rings that are confined in the radial direction in the stuffing-box between the housing internal wall and stem outside surface. Fig. 2 shows a sectional view of three different porous material models that are considered in the prediction of leak rates through packing rings; the capillary model, the concentric cylinders model, and the modified Darcy's law model.

### 2.1. Capillary model

This model is adopted by many researchers in different applications [28-30]. With this approach, the porous structure is assumed to be made of a set of uniform diameter capillaries that are parallel to the stuffing-box axial direction as shown in Fig. 2 (a). For a capillary tube, starting from the equation of momentum conservation in the cylindrical coordinate, the velocity-pressure relationship is given by

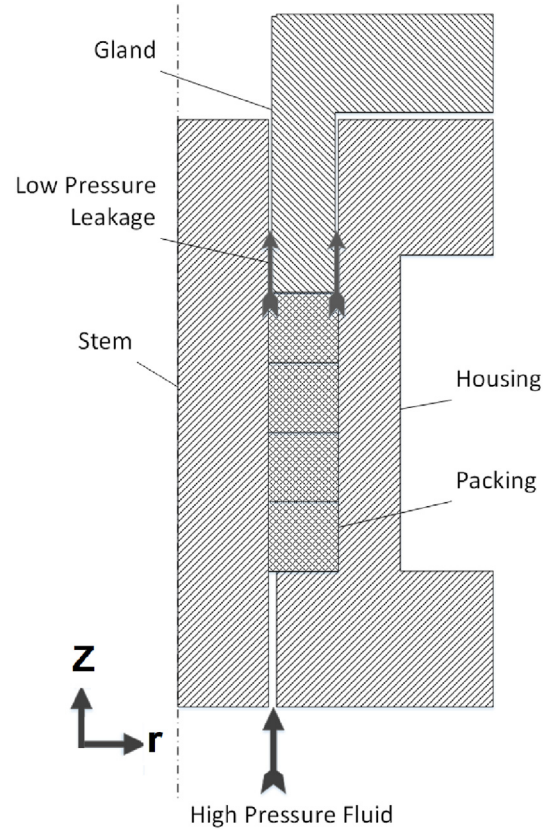


**Fig. 1.** Simplified packed stuffing-box with the main components.

$$\frac{1}{r}\frac{d}{dr}\frac{rdu}{dr} = \frac{1}{\mu}\frac{dP}{dz} \tag{1}$$

Assuming an isothermal flow and considering the first order boundary conditions the velocity at the wall and the variation of velocity at the center are given by

$$u_{z,c} = -\frac{2-\sigma}{\sigma}\lambda\frac{\partial u_z}{\partial r}\ r = R_c \tag{2a}$$

$$\frac{du_z}{dr} = 0\ r = 0 \tag{2b}$$

In which $\sigma$ is the slip or tangential accommodation coefficient which according to Albertoni [31] has the value of 1.1466 and according to Kogan and et al. [32]. is 1.012. Equation (1) is solved with the boundary conditions of Eq. (2) and that derivitive of the velocity at the center is equal to zero to give the velocity as a function of the radial and axial directions of the capillaries as

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

The leak rate for $N_c$ capillary channels is obtained by integration of velocity through the area as

$$L_c = 2\pi\rho N_c\int_0^{R_c} u_{z,c}(r)rdr \tag{4}$$

Substituting Eq. (3) into Eq. (4) gives

$$L_c = \frac{N_c\pi R_c^4 P_0^2(\Pi^2-1)}{16\mu\Re T\ell}\left[1 + 16\frac{Kn(2-\sigma)}{\sigma(\Pi+1)}\right] \tag{5}$$

Using the capilary radius Knudsen number can be defined as

$$Kn_c = \frac{\lambda}{2R_c} \tag{6}$$

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