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Imbibition dynamics including corner film flow in a spiral-grooved channel

C. Kankolongo^{a,b}, D. Lasseux^a, M. Prat^c, T. Zaouter^b, F. Ledrappier^d

^a Université de Bordeaux, CNRS, Bordeaux INP, I2M, UMR 5295, F-33400 Talence, France.

^b CEA, DES, ISEC, DPME, SEME, Laboratoire d'Étanchéité, Univ. Montpellier, Marcoule, France.

^c Université de Toulouse, INPT, UPS, IMFT, Avenue Camille Soula, 31400 Toulouse, France.

^d TECHNETICS Group France, Laboratoire d'Étanchéité Maestral F 26700 Pierrelatte, France.

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1. Introduction

In the field of sealing, mechanical assemblies commonly consist of two flanges made of hard metallic material and a seal made of soft metallic material as shown in figure 1a. These flanges have surface defects due to the manufacturing process, *e.g.*, face-turning, which produces a characteristic spiral-grooved profile as shown in figure 1b. The residual opening defects thus constitute leak paths for the fluid to be sealed and the modeling of fluid flow in the resulting connected aperture field between the high and low pressure zones is essential in order to predict seal efficiency. To help understand the flow

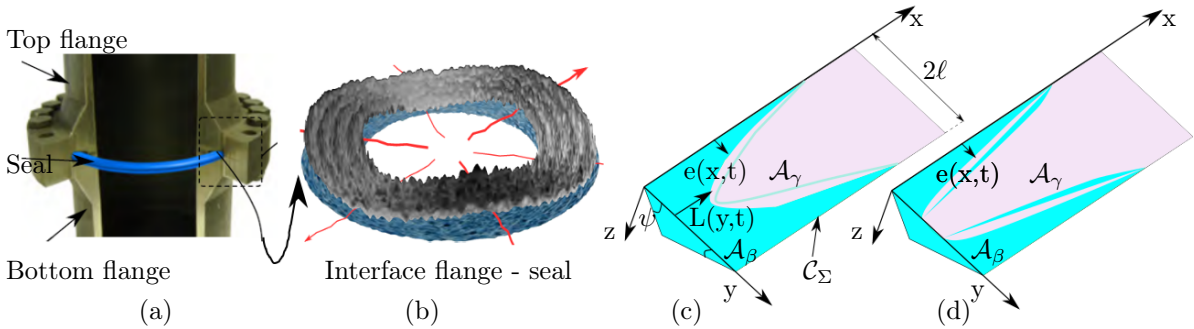


FIGURE 1: Flange - seal interface.

within the connected channels, in particular under two-phase flow conditions, (*i.e.*, when the fluid to be sealed invades the contact initially saturated by air), it is of interest to analyze the case of a rather simple situation made of single spiral-grooved channel, taking into account the presence of sharp corners as shown in figure 1c. In this context, liquid films can develop in the corners of the channel in the case of imbibition, as studied in [1, 2]. Indeed, the presence of the corner films may significantly modify the overall imbibition kinetic and can explain, for instance, capillary instabilities leading to gas trapping. For instance, Dong and Chatzis [1] studied the imbibition of a wetting liquid film in the corner without liquid invasion in the whole channel as shown in figure 1d. By making use of similarity solutions, they showed that the extension of the liquid film and the leak volume in the corner of a rectilinear channel of square cross-section are proportional to the square root of time when flow is triggered by the capillary pressure. Amyot [2] made a similar study in a rectilinear channel of triangular cross-section (figure 1d) with a flow rate imposed at the channel inlet. In accordance with experimental observations, it was shown that the dynamics of the central meniscus is disturbed by that of the liquid film in the corner. The present work reports on analytical solutions for the dynamics of the central meniscus, including that of the liquid film in the corners of a spiral-grooved channel, complementing the analysis reported in the latter reference.

2. Model

The interest is focused on imbibition of a liquid (the β -phase) in a spiral-grooved channel of triangular cross-section as schematized in figure 1c, initially saturated by a gas (the γ -phase). It is assumed that

$\tan \psi \ll 1$ and the gas phase remains at constant pressure. Under these assumptions and on the basis of the lubrication theory, the Reynolds' equations describing mass and momentum conservation for the β -phase occupying the region \mathcal{A}_β , are given by

$$\frac{\partial q_{\beta i}}{\partial x_i} = 0, \quad q_{\beta i} = -\rho_\beta \frac{h(y)^3}{12\mu_\beta} \frac{\partial p_\beta}{\partial x_i}, \quad i = 1, 2, \quad (1)$$

In addition, assuming that the capillary number is small enough ($Ca = \mu_\beta u / \sigma < \tan \psi$, u being a characteristic velocity in the β -phase), the boundary condition at the fluid-fluid interface can be shown to reduce to the Young-Laplace relationship

$$p_\gamma - p_\beta = \sigma \kappa, \quad \text{at } x = L(y, t). \quad (2)$$

In these equations, q_β is the lineic mass flow-rate, p_β and p_γ are the liquid and gas pressure, respectively, ρ_β is the liquid density, μ_β is the liquid dynamic viscosity, $h(y)$ is the aperture, κ is the double mean curvature and σ is the surface tension. For completeness, the kinematic condition at the fluid-fluid interface parametrized by $y = e(x, t)$ must be considered, *i.e.* $\frac{\partial e}{\partial t} + \frac{q_{\beta x}(e)}{\rho_\beta h(e)} \frac{\partial e}{\partial x} - \frac{q_{\beta y}(e)}{\rho_\beta h(e)} = 0$.

By integration of the above equations, considering an imposed volume flow rate, Q_0 , at the channel inlet, the expression of the liquid film extension as a function of time, $L_f(t)$, can be obtained, as in [2], by making use of similarity solutions. It is given by

$$L_f(t) = \left(\frac{5}{24}\right)^{1/5} \tan(\psi)^{1/5} Q_0^{1/5} \left(\frac{\sigma \cos \theta_e}{\mu_\beta}\right)^{2/5} t^{3/5}. \quad (3)$$

A more detailed solution can be derived, that reads

$$L_f(t) = \left(\frac{5}{12}\right)^{1/5} \left(\frac{\cos^4(\theta_e + \psi/2) \cos^4(\psi/2)}{A}\right)^{1/5} Q_0^{1/5} \left(\frac{\sigma}{\mu_\beta}\right)^{2/5} t^{3/5}. \quad (4)$$

In equations (3) and (4), θ_e is the equilibrium contact angle and A is a constant which depends of ψ and θ_e .

The evolution of the liquid film extension, $L_f(t)$, is reported in Figure 2a according to the two solutions given in equations (3) (ST) and (4) (SA) using values of the different parameters given in [2]. Note that the two solutions are very close to each other. This is confirmed by the ratio, $R_{ST/SA}$, of the two expressions given in equations (3) and (4), represented in Figure 2, which remains close to unity for an angle of the corner, ψ such that $\tan \psi < 0.5$.

Coupling between the dynamics of the liquid film flow in the corner and that of the central meniscus ($L(y, t)$ in figure 1c) will be further discussed in our presentation.

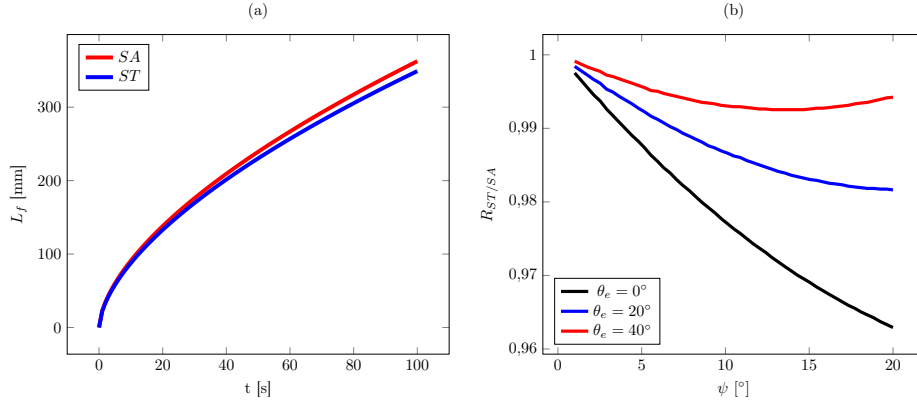


FIGURE 2: (a) Evolution of the film extension for an imposed volume flow rate; (b) Ratio of liquid film extensions as a function of ψ .

Références

- [1] Dong, M. and Chatzis, I., The Imbibition and flow of a wetting liquid along the corners of a square capillary tube, *Journal of Colloid and Interface Science*, 172, 278–288 (1995).
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