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An experimental analysis of the topology and dynamics of a falling liquid film over the wavy surface of a vertical pillow plate

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HIGHLIGHTS

- The film topology is characterized by two distinct zones.
- The film mainly flows down the rows of vertically aligned welding spots (zone 1).
- The wall region between adjacent zones 1 is covered by a thinner film (zone 2).
- The identified 2-zone film flow will facilitate pillow-plate heat exchanger design.

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ABSTRACT

The successful design of pillow-plate condensers requires specific knowledge of the falling liquid film characteristics. Due to the typical wavy, "pillow-like" surface of pillow plates, the film flow here differs from the flow over vertical smooth walls. In this work, we visualized the topology and free surface waviness of a falling liquid film over a vertical pillow plate by using a fluorescent dye and a high speed camera. First observations show that the liquid film preferably flows down the rows of vertically aligned welding spots (zone 1). As a result, the wall surface between these rows is covered by a thinner film (zone 2). In order to quantify this "2-zone" topology, we measured the local mass flow rate in zone 1 over the height of the pillow plate. The results confirmed that the liquid film is mainly "drained" in zone 1. The findings of this study will help to develop flow-pattern-oriented modeling methods and to design pillow-plate falling film equipment.

1. Introduction

Falling liquid films are encountered in a variety of industrial areas, including heating, ventilation and air conditioning, chemical and pharmaceutical industry and power plants. Among others, falling films are typical for condensation processes. Condensation is commonly carried out in shell-and-tube and plate condensers; on the other hand, pillow-plate condensers (PPC) represent a promising alternative to conventional equipment and offer a significant energy saving potential. The waviness of the pillow-plate channels promotes lateral mixing and turbulence, which results in a good thermohydraulic performance. Furthermore, PPC have several important structural advantages, including a fully welded and thus hermetically sealed design, high structural stability, light weight and easy and cheap manufacturing. The light weight and compactness make PPC ideal as top condensers in distillation columns, where they are implemented directly into the column head. The application area of pillow-plate heat exchangers (PPHE) is broad and expanding. In contrast to conventional equipment, however, no reliable design methods for PPHE are available in the open literature. Understanding the characteristics of the falling film over the pillow-plate surface is key to a successful design of PPC.

Literature on gravity driven film flow over plane walls is huge; in contrast, much less is to find for flow over periodic wavy surfaces. The studies of film flow over two-dimensional (e.g., Pozrikidis, 1988; Shetty and Cerro, 1993; Trifonov, 1999; Negny et al. 2001a,b; Wierschem et al., 2003; Trifonov, 2007) and inherently three-dimensional wavy surfaces (e.g., Wang, 2005; Luo and Pozrikidis, 2006, 2007) should be mentioned. In most of these studies, the length scales of the wavy substrate are comparable with the length scales of the falling liquid film (e.g., mean film thickness or wave amplitude). Trifonov (1999) theoretically investigated film flow over a two-dimensional wavy surface that had a similar cross-sectional profile as pillow plates. He found that a boundary layer separation occurred inside the film at the transition from a sinusoidal to a flat wall profile.

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Such a geometric transition is encountered in pillow plates in the vicinity of the welding spots.

Negny et al. (2001a) found, based on a numerical study, a vortex arising inside the film, slightly upstream of the crests of the wavy wall. Wierschem et al. (2003) experimentally studied gravity-driven film flow down inclined sinusoidal substrates of high waviness. They found that vortices arose in the valleys of the substrate which were generated beyond a critical film thickness only. Luo and Pozrikidis (2007) theoretically investigated gravity-driven film flow over three-dimensional doubly periodic corrugations of a small amplitude and found that the deformation of the free surface is reduced in comparison to film flow over a two-dimensional wavy wall. It is important to note that in the majority of the aforementioned theoretical studies, the film flow is limited to vanishing film Reynolds numbers, i.e. to the Stokes flow. Furthermore, the substrate corrugations in these studies are significantly stronger, i.e. they possess larger amplitudes and smaller wavelengths than the corrugations of the pillow plate surface.

Literature on pillow plates is scarce and currently comprises just few works by Mitrovic and Peterson (2007), Mitrovic and Maletic (2011), Piper et al. (2014a,b), Tran et al. (2014), Goedecke and Scholl (2014). From these, Mitrovic and Peterson (2007) and Tran et al. (2014) dealt with vapor condensation. However, in both these studies, the falling condensate film was not optically accessible, and thus the flow characteristics of the liquid film over the wavy substrate could not be studied.

In this paper, the flow characteristics of a falling liquid film over the three-dimensional periodic wavy surface of a vertical pillow plate are investigated experimentally. The results of this study will help to understand how the pillow-plate surface influences the flow of the falling film. This knowledge is important for the development of specific heat transfer models, which will help to improve the design of pillow-plate condensers and falling film evaporators.

2. Experimental setup

The experimental set-up used in this work is shown in Fig. 1. It comprises a pillow plate (PP), a collecting tank (T), a Haake P2-CT50W thermostat (TS) with integrated pump, a needle valve (V), a film distribution device (D), an ultraviolet light source (LS) and a camera (C). The LS consists of ultraviolet neon tubes of 1 m in length, of which one is placed on the left-hand side and the other on the right-hand side of the test section (in Fig. 1 only one is shown). FI denotes here an offline volumetric flow measurement. The characteristic dimensions of the pillow plate are the longitudinal ($2s_L = 95$ mm) and transversal ($s_T = 55$ mm) welding spot pitch, the diameter of the welding spots ($d_{SP} = 10$ mm), the maximum inner inflation height ($h_i = 8$ mm) and the thickness of the plates($\delta_w = 3$ mm). The length H of the pillow plate is equal to 1500 mm and the width B is equal to 405 mm, both representing dimensions encountered in industry. The irrigation width is equal to B and is assumed to be large enough for the influence of edges on the structural flow characteristics of the falling film to be neglected.

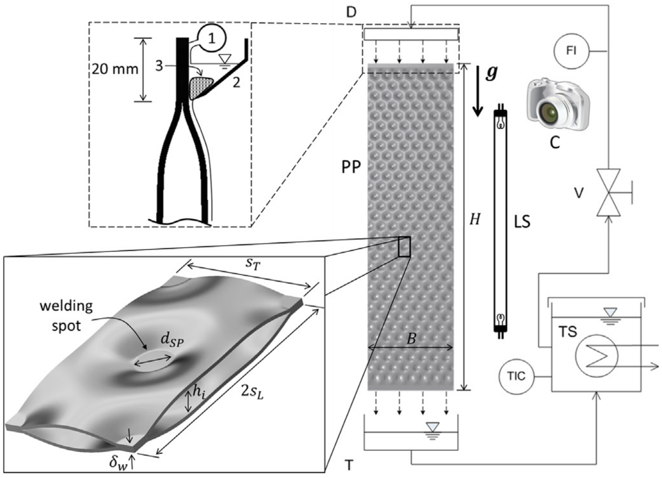

Fig. 1. Process flow diagram of the experimental setup.

In operation, a thin liquid film of demineralized water is distributed evenly across the inlet edge of the vertical pillow plate. The film flows down the wavy pillow-plate surface under the influence of gravity and is collected in a tank located at the outlet edge of the pillow plate. The collected fluid is then recirculated to the thermostat, where it is kept at a constant temperature of 25 °C. The volumetric flow rate of the recirculated fluid is adjusted via the needle valve. It is important to note that in all experiments care was taken that the pillow-plate surface was fully wetted.

The film distributor is shown schematically in Fig. 1. It consists of a one-side perforated tube (1), a guiding plate (2) and a microfiber wedge (3). The perforated tube evenly distributes the working fluid over the inlet edge of the pillow plate. The fluid is then directed to a gap with a fixed height of 0.5 mm. The distribution was optimized by placing a microfiber wedge in the gap. The fabric dissipates all disturbances in the gap, thus producing a laminar and smooth film over the irrigation width.

3. Visualization of the falling liquid film

In this study, the film topology was visualized by adding a fluorescent dye (fluorescein) to the demineralized water, which was then excited by UV light. The color of the emitted light is green in the case of fluorescein. At a fixed dye concentration, the fluorescence intensity increases with an increase in liquid film thickness. Hence, variations in the local film thickness can be observed. With this method, characteristic flow patterns and preferred flow paths of the falling film are qualitatively investigated.

Wave dynamics and wave motion were observed using a Weinberger SpeedCam-Pro high-speed camera with a resolution of 512 × 512 pixel at a frame rate of 1000 fps. Additionally, a Canon EOS 300D photo-camera was used to analyze the free surface at a higher image resolution.

4. Results and discussion

4.1. Film topology

In Fig. 2, the results of the film topology study are presented for four different mean film Reynolds numbers $Re_{f,m}$. The latter was determined by the following expression:

$$Re_{f,m} = \frac{\dot{m}_{tot}}{\eta_f B} \tag{1}$$

The photos were taken with a Canon EOS 300D Digital camera, and the exposure time was set to 10 s. The larger exposure helps to better visualize the main streams. At all investigated mean film Reynolds numbers, an interesting zonal effect was observed. This effect is seen in the photos as the regular intensity variation (light–dark–light–dark) of the emitted green light. In the regions where the intensity appears higher (lighter green), i.e. along the rows of vertically aligned welding spots, the film is thicker (zone 1) than in the adjacent regions. This means that the film preferably flows down in zone 1 rather than to be distributed evenly across the pillow-plate surface. Consequently, the