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Liquid flow transition and confined free film formation on a vertical plate with an open window

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ABSTRACT

A novel element for gas–liquid contact, a plate with rectangular windows was designed to enhance absorption process. This paper describes some experimental observations of free-surface flows arising when thin liquid film flows through the window. Dozens of windows with different geometries and six fluids with *Ka* varying from 52 to 3000 were used to investigate the flow mechanism. Various free-surface flow patterns composed of droplets, columns, sheets and their combinations were observed in the window region with increasing liquid flow rate. At a critical flow rate, liquid film was able to full fill the window and unique wavy trains were observed (named as twin-liquid films). To characterize the film formation conditions, an empirical equation based on experimental data was proposed. Hysteresis phenomenon was manifested by obviously different flow rate for the film formation and breaking. Multiple and dynamic flow structures shown here would broaden traditional knowledge of liquid flow in packed columns and clarify the mechanism of mass transfer intensification for the perforated packings.

1. Introduction

For many years, there has been a constant demand for low pressure drop column internals in rectification, absorption, stripping and liquid/liquid extraction. The prevailing trend in the chemical industry is to replace tray columns with those containing modern structured and random packings. It is therefore particularly important to use reliable methods for the prediction of mass transfer and hydrodynamic behavior of the two-phase flow. An exemplary demonstration of how to derive general considerations on the hydraulic behavior of random packings using the model of film flow in packed columns were done by Mersmann [1], which was then referred and modified by many other investigators. In 1995, Billet [2] proposed another film flow model, assuming the liquid film flows in simplified narrow channels, described by void fraction in the bed. However, in the last 30 years, more and more metal and plastic packings with an open structure are being produced, which own a very large void fraction up to 98%. It is reasonable to suspect how liquid film flows on packing surface with so little solid frame. Wilson's experimental results [3] showed that the wetted area of the random packing exceeded its dry area by as much as 90%, especially at high gas and liquid rates. As mentioned by Wagner [4], there is a different kind of surface generation in the newer packings. It is certainly different from the traditionally assumed liquid film flow and vapor channel flow approaches. For example, Bornhütter's experiments [5] with lattice type packings have confirmed the droplet formation (5–45% of the total liquid flow) in packed columns as a result of dripping from the edges and walls of the individual packing element. Later, Bornhütter [6] developed a cylinder model which takes into account both rivulets and drops (freely falling) in the mass transfer process. Recently, Mackowiak [7] proposed a totally new theoretical model, known as "Suspended Bed of Droplets". It has wider applicability and better precision for pressure drop than film model, especially for modern packings. However, the droplet formation process in packed column has not been detailed described and it is still doubtful whether so many droplets exist in packed column under normal operation conditions.

Therefore it is very necessary to recognize liquid flow patterns in packed columns from the perspective of fluid mechanics. Some works have been done on different liquid flow patterns over a solid plate. Schmuki and Laso [8] experimentally studied the existence of the different flow patterns exhibited by a liquid flowing down an inclined plate for a wide range of physical properties of the fluid. A perfect model that predicts the decay frequency of oscillating or pendulum rivulet flow was derived. Chang [9] summarized the complex wave dynamics of thin liquid film flow on a flat plate. The fundamental theories of periodic and solitary wave families were well analyzed with a mathematical approach. But those theories might not fit process in packed columns, where the flow conditions and the plate are much

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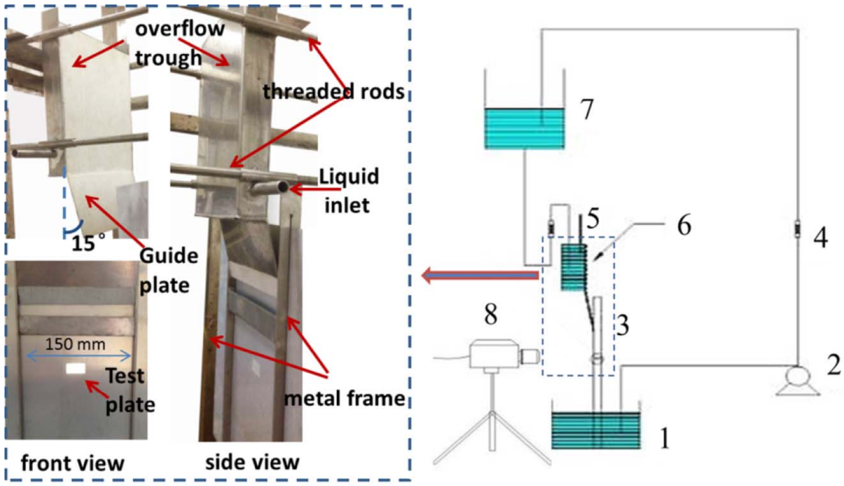

1—Collecting tank; 2 —Pump; 3—Test plate; 4—Liquid rotameter; 5—Mercury thermometer; 6—Liquid distributor; 7—Head constant tank; 8—High speed digital camera;

Fig. 1. Experimental setup.

more complex. Therefore, investigations of complex liquid flow on packing surface are carried out. Zhao and Cerro [10] measured the film thickness profiles, streamline patterns and free-surface velocities for a variety of surface shapes and fluids. The position of the liquid film interface was found, in general, to have the same period as the wavy solid surface but amplitude and phase-shift vary with flow parameters. Pavlenko et al. [11] investigated experimentally the dynamics of film flow over corrugated packing sheet with holes. Their results indicated that the flow through the holes in corrugated plates with a texture has a significant influence on spreading and sizes of wetted zones over the packing height. Hoffmann et al. [12] analyzed the complex flow behavior of homogeneous and heterogeneous liquids on inclined plates in detail with experiments as well as numerical methods. Intricate flow behaviors like film break-up, rivulet and droplet flow are represented by the calculations correctly. Those works are very helpful to know liquid flow behaviors in packed columns and optimize the packing geometry. But as Santos et al. [13] pointed out, there is still more information needed on droplet formation, flow transition of streams and curtains (free falling) in void fraction of packed bed. Moreover, most previous investigators neglected the synergistic effect between solid wall and void fraction. Influence of open windows (large size perforation on the packing surface) on solid packing surface and influence of solid frame on liquid in the void fraction have not been clarified.

With a retrospect on the development of modern packings, the discrepancy between random and structured packings in terms of their hydraulic and mass transfer behavior has been decreasing, characterized by a high loading capacity, good separation efficiency in large columns as well as a low pressure drop [7]. And most importantly, both are highly perforated, with a lattice type or pass-through structure. Recently, Hu [14] mentioned that, in such perforated structure, there exists another type of film flow that is rarely reported in the existing literature: confined free film (now named as twin-liquid film), in which both wall-bounded film [15] and free film coexist and interact each other. The important feature that distinguishes confined free film from typical liquid films is that it not only presents two free surfaces, but it is also enclosed in a solid boundary and is in contact with the surrounding solid frames. Compared with wall-bounded films on a non-perforated plate, a larger mean velocity, thinner film thickness, intensive capillary waves and strong vorticity on the free surfaces were observed in the window, and disturbances from the window could propagate over the whole plate. By solving a species transport equation, simulation results [16] showed that the average mass transfer coefficient K_L value increased 26.9% for the open window region and 17.4% for the wall region below the window, respectively, in comparison to the wall region up the window, and the average K_L value of confined free film along the flow direction is about 19.2% higher than the value of wall-bounded film. To prove the mass transfer intensification of the plate with windows, Hu et al. [17,18] developed a novel structured packing with vertical packing sheets perforated by large size windows for viscous absorbents. Experimental results indicated that by adopting such a packing geometry, better mass transfer efficiency can be obtained when compared with currently used commercial structural packings. Interestingly, Nikolai Kolev et al. [19] have also proven the high performance of a new packing with stamped horizontal lamellae, which is actually a plate full of rectangular windows. Experimental data at extremely low liquid loads showed a high ratio of effective to total surface area of the packing, higher than 1, which was observed only in cases with formation of drops and jets in the packing free volume.

Most of the previous researches focus on the mass transfer performance of perforated packings, but little has been done on the film formation and flow transition. This paper aims at presenting a rich variety of flow phenomena in the window region (which is similar to flow in the void fraction of packed columns) and analyzing systematically the influence of fluid properties and window geometric features on the confined free film formation. A description of the experimental setup and procedures is presented in Section 2. Results and discussion of the detailed experimental observation will be given in Section 3. Visual observations of flow patterns under different flow rates and various window geometries are reported first in Section 3.1. Detailed discussions on the influence of liquid properties, geometric features of the window and the hysteresis phenomenon on the liquid film formation are presented in Section 3.2.

2. Experimental setup and procedures

Fig. 1 depicts a schematic diagram of the experimental setup. The liquid is released from a cylindrical tank over the test plate, and then flows through a liquid distributor composed of a multistage overflow trough and a guide plate, before being introduced to the top of the test plate. Inside the overflow trough, a distributor pipe with holes is connected to the liquid inlet to improve the initial liquid distribution. The test plate is fixed vertically with an external metal frame. To promise a uniform liquid film flow above the window region, four threaded rods are used to adjust the relative location of the guide plate with respect to the plate. The liquid drained from the bottom of the plate is collected in a storage tank for recirculation. The liquid flow rate is controlled by a calibrated rotameter covering the range of this study. Experiments are carried out at ambient pressure and room temperature. The