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Experiment and simulation of the shrinkage of falling film upon direct contact with vapor

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HIGHLIGHTS

- Falling film direct contacting with saturated vapor was investigated.
- Experiments and a 3-D CFD model are proposed to study the phenomenon.
- Wetting area increases with increasing inlet temperature and flow rate.
- Detailed analysis explains the reason for the shrinkage.
- The *h* increases with increasing flow rate and inlet temperature.

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ABSTRACT

An experiment is conducted to study the shrinkage of falling film in countercurrent direct contact with saturated vapor. The experiment indicates that falling film shrinks along its width. The degree of shrinkage decreases with increasing liquid inlet temperature and flow rate. To study the details of the phenomenon, a three-dimensional multiphase computational fluid dynamics (CFD) model based on the method of volume of fluid (VOF) is developed. The model considers the variation of surface tension with temperature. The results of the simulation are consistent with the experimental data. Simulations reveal the temperature, velocity and tension surface profiles. The modified Marangoni number is compared to illustrate the influence of surface tension and demonstrates that the surface tension plays an important role in this phenomenon and the shrinkage of the film causes the heat transfer to decrease. This model is expected to be applied to the design of the industrial equipment with falling film.

1. Introduction

Falling film is a common flow pattern in industrial equipment such as distillation, absorption, evaporation and water desalination systems (Huppert, 1986; Oron et al., 1997; Craster, 2009). Because of falling film's high heat and mass transfer coefficients, high heating flux and low energy consumption, it is extensively used in industrial processes.

In a packing distillation column, the liquid forms falling film on the packing while the vapor, generated in the reboiler, flows upward countercurrently and directly contacts the liquid film. Vapor and liquid exchange heat and mass on the interface of falling film. Although the temperature difference between liquid and vapor is small in most of the column, it is larger in certain parts where reflux occurs, such as at the top of the column, bscause the temperature of the reflux is lower than the boiling point in practical production. In recent years, research has investigated the flow pattern of non-isothermal falling film. Published studies have demonstrated that the surface tension gradients caused by the non-isothermal interfacial temperature increase interfacial instabilities (Davis, 1987; Schatz and Neitzel, 2001). Correspondingly, these studies focused on the interfacial instabilities such as the surface wave and breaking of the film. Joo et al. (1996) presented a long-wave evolution equation that was used to describe the surface-wave and thermocapillary instabilities of a film on a heated plate. These researchers used this model to demonstrate a mechanism of rivulet formation through their model. Kim (1999) used the nonlinear evolution equations governing 2-D surface waves to study the film at a constant heat flux and a fixed temperature. This research showed that the film at a constant heat flux was a more stable system than that at a fixed temperature condition. Miladinova and Lebon (2005) studied the dynamics of a thin evaporating liquid film falling down an inclined plate in the cases of uniformly and nonuniformly heated plates.

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They found that the effect of the nonuniform heating was dominant prior to the film disappearance and that it enforced film rupture. Zhang et al. (2008a) provided a 2-D theoretical model to study the temperature distribution of falling film flowing over a vertical heated/cooled plate at a constant temperature. Zhang et al. (2008b) investigated the temperature field and flow patterns of falling film at different heating conditions.

Because falling film flow is influenced by many factors, it is difficult to analyze the heat and mass transfer process accurately through experimentations. During the recent the past, with the development of computer techniques and the theory of computational fluid dynamics (CFD), CFD has become an important method for researchers to simulate the flow phenomenon of falling film. By solving the continuity, momentum, energy and species equations, CFD can predict velocity, pressure, temperature and concentration profiles in complex systems (Haelssig et al., 2010). Cherif and Daif (1999) numerically studied the evaporation of the binary liquid film streaming on the internal face of one of the two parallel plates using mixing convection. The wetted plate underwent a constant uniform heat flux whereas the other was adiabatic. They showed the importance of the film thickness and mixture composition on the mass and thermal transfers. Agunaoun et al. (1998) presented a numerical analysis of the heat and mass transfer in a binary liquid film flowing on an inclined plate. The most interesting results were obtained in mixed convection, particularly in the case of an ethylene glycolewater mixture. In fact, the results obtained by Agunaoun et al. showed that it was possible to increase the accumulated evaporation rate of water when the inlet liquid concentration of ethylene glycol was less than 40%. Hoke and Chen (1992) presented a numerical study on the evaporation of a binary liquid film on a vertical plate. These authors presented the evolution of Sherwood and Nusselt numbers. Mhetar and Slattery (1997) studied the isothermal evaporation of a binary liquid film. The reserchers measured the diffusion coefficient during the evaporation of a binary liquid in a Stefan tube. With the development of computer techniques, some 3-D models were presented to simulate falling film. Chen et al. (2009) presented a 3-D two-phase model based on the VOF method to study the hydrodynamics and mass transfer behavior of packing material (Mellapak 350Y). Al-Rawashdeh et al. (2008, 2012) presented a pseudo 3-D CFD model, in which the 3-D Navier–Stokes equations, governing the three Cartesian velocity components, were reduced to a single 2-D Poisson equation for the cross sectional profile of the axial velocity component; this model is used to investigate the effects of channel fabrication precision and liquid flow distribution in a microreactor. Sebastia-Saez et al. (2013) presented a small-scale 3-D CFD model for the study of the hydrodynamics and physical mass transfer in structured packing elements. They found that surface textures have a strong influence on liquid misdistribution, which had a significant influence on the interfacial absorption rate. Qi et al. (2013) developed a 3-D model for predicting the wetting factor, film thickness and flow velocity of falling film. Sebastia-Saez et al. (2014) developed a VOF-based micro-scale 3D numerical model to study the influence of several operative parameters on absorption of gas into falling liquid films.

Although many simulations and experiments have already been conducted on the flow pattern of non-isothermal falling film, the temperature difference was caused by the heated plate. These experiments and simulations differ from practical processes in a distillation column in which the temperature difference is caused by high temperature vapor.

In this paper, an experiment is conducted to study the flow pattern of falling film in direct contact with saturated vapor. To study the details of the phenomenon and simulate it experimentally, a 3-D CFD model is presented, in which the variation of the surface tension with temperature is considered. Through the model, the temperature and surface tension profiles are revealed to illustrate the shrinkage. The modified Marangoni number is estimated and compared to illustrate the influence of surface tension. Moreover, the variation of the heat transfer behavior caused by the shrinkage is investigated.

2. Experimental apparatus and procedure

To study the flow pattern of falling film, that countercurrently and directly contacts high-temperature vapor, an experiment with water and vapor was performed. The schematic diagram of the experimental setup is shown in Fig. 1.

The liquid stored in the feed storage tank was sent to the falling film contactor by the centrifugal pump. A temperature-controlling device controlled its temperature, and flow rate was measured by a rotameter. The liquid entered the falling contactor at the top through the liquid distributor forming falling film on a steel plate and exited at the bottom to the liquid recovery tank. The vapor was generated by a vapor generator, entered the falling film contactor through a vapor distributor at the bottom and exited at the top of the contactor. The liquid and vapor countercurrently and directly contacted and exchanged mass and heat in the contactor. The size of the steel plate was 400 mm × 100 mm × 6 mm (length × width × thickness). The flow pattern and distribution of the temperature were recorded by an infrared camera (Ti 200, Fluke, Inc). The temperature at the inlet and outlet were measured by thermoelectric thermometers.

Water and vapor were chosen as the experimental materials. The temperature of the water entering the contactor was chosen to be 30, 40, 50, 60, and 70 °C, and the flow rate was set at 60, 80, 100 and 120 L/h. The vapor flow was constant and set at a 20 m^3/h. This rate can maintain the temperature of the entire contactor at the saturation temperature. The effect of the vapor rate was not considered in the study, so the rate was constant.

3. Mathematical model

Falling film that countercurrently and directly contacts vapor at a high temperature is influenced by many factors. It is difficult to accurately analyze the heat and mass transfer process through experimentations. Therefore, a 3-D simulation model was presented

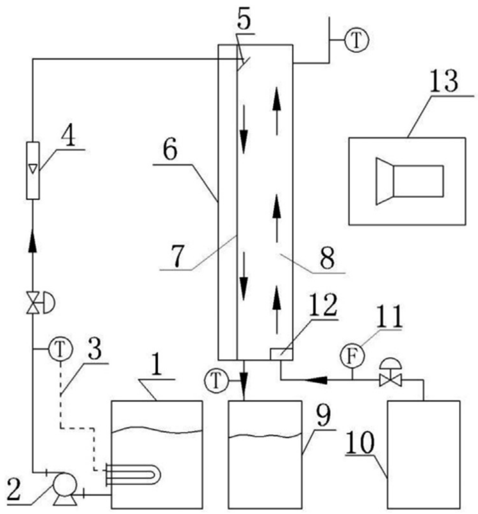

Fig. 1. Schematic diagram of the experimental setup, (1) Feed storage tank; (2) centrifugal pump; (3) temperature-controlling device; (4) rotameter; (5) liquid distributor; (6) insulating layer; (7) steel plate; (8) falling film contactor; (9) liquid recovery tank; (10) vapor generator; (11) vortex street flowmeter; (12) vapor distributor; (13) infrared camera.