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Experimental study of falling film evaporation in large scale rectangular channel

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ABSTRACT

The falling film evaporation in a large scale rectangular channel is experimentally studied in this paper for the design and improvement of passive containment cooling system. The evaporation mass transfer coefficient h_D is obtained by the evaporation rate and vapor partial pressure difference of film surface and air bulk. The experimental results indicate that increasing of air flow rate appears to enhance h_D, while the film temperature and film flow rate have little effect on h_D. Since the wave effect on evaporation is noticed in experiment, the evaporation mass transfer correlation including the wave effect is developed on the basis of heat and mass transfer analogy and experimental data.

1. Introduction

The research of the passive feather of nuclear safety attracts much attention after the Fukushima nuclear accident. The passive containment cooling system (PCCS) is applied in the advanced nuclear power plant AP1000. The falling film evaporation with nature convective air flow in the PCCS is the main heat removal manner. Therefore, the key point of the PCCS design and improvement is the evaluation of the falling film evaporation rate with counter-current air flow.

Some experimental and numerical studies have been carried out to study the characteristics of falling film evaporation. One of the early experiments for falling film evaporation in large scale rectangular channel was conducted by Ambrosini (Ambrosini et al., 1995). The air flow effect on evaporation mass transfer coefficient h_D was studied, and the heat and mass transfer analogy (HMTA) was evaluated with the non-dimensional number. This work indicates the direction and stress for subsequent similar studies. Then, Kang and Park expanded the experiment content (Kang and Park, 2001). Besides the air flow, they concentrated on the film temperature and film flow rate effect on the evaporation mass transfer coefficient, and a correlation was developed and applied in CONTEMPT4/MOD5 code. Additionally, momentum and mass transfer analogy was also used in their work (Kwon et al., 2008). Many researchers found that the water surface wave plays a great role in evaporation and condensation. By introducing oscillatory wave on the water surface, Hopfinger observed the drastically condensation rate increasing (Hopfinger and Das, 2009). The same phenomenon was also happened in Jodat's water evaporation experiment (Jodat et al., 2013). The numerical study of falling film evaporation can be divided into two groups. The first group assumed the "thin film and smooth surface", which means to neglect the wave effect on phase change (Fedorove et al., 1997 and Wangwises and Naphon, 2000). This assumption is only true for much smaller film Re. The second group emphasized the wave effect, and the wave correlated parameters are introduced in the governing equation (Patnaik and Perez-Blanco, 1996). However, these parameters are derived from experiment data. Thus, experimental study is not only helpful for the evaporation mechanism exploration, but also for the numerical tool development.

The objective of this paper is to study the falling film evaporation characteristics with counter-current air flow. The contents include the evaluating of important parameter, such as air Re and film temperature, effect on h_D. And the difference of h_D between HMTA and experiment is explained by the wave effect on the diffusion boundary layer. Finally, a correlation with the wave factor is developed on the basis of experimental results.

2. Experimental setup

The facility consists of test section, water supply system, air supply system, heating system and measurement system, and

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the schematic is shown in Fig. 1. The test section consists of a steel flat plate and air baffle made of stalinite. The steel plate is 5.0 m long, 1.2 m wide and 20 mm thick. The air baffle is located 30 cm away from the steel plate. The cross section size of the channel is 1.2 m wide and 0.3 m height. The motorized valves are applied in the water supply system to control the water flow, and electromagnetic flowmeter applied to measure the flow rate. The basic component of the air supply system is a centrifugal blower with a maximum air flow rate of 20000 m^3/h. The air flow generated in the blower part goes through the air duct and test section. The plate is heated by more than 200 copper tubes installed on the back of the plate, and high temperature heat transfer oils flow through the tubes. The hot wire anemometer is applied to obtain the air flow velocity. In the previous countercurrent flow experiment, air velocity is easily to be measured because of the small facility size. However, the air velocity distribution should be concerned in the 1.2 × 0.3 m size cross section. The 1.2 × 0.3 m size pore plate is used to adjust the air velocity distribution. Nearly 300 circular holes with 20.0 mm diameter uniformly located on the pore plate. By using of the pore plate, the verification test result shows a more uniform distribution of the air velocity. The temperature of air and film is measured by K-type thermocouples, and the calibration results shows that the error is within 0.5 °C. The evaporation rate is measured by the so called "weighting method". Specifically, the outlet water can be collected and weighted in the storage tank, then the outlet film flow rate is calculated. Since the inlet film rate is measured by flow meter, the evaporation rate could be obtained. Further description of the facility can be found in the previous work on WAFT (Huang et al., 2014).

3. Experimental results

The experiment test matrix is shown in Table 1. The purpose of this matrix is to study the air flow, film temperature and film flow effect on falling film evaporation.

3.1. Air flow affection on evaporation

The cases 1–5 in Table 1 is selected for the analysis of air flow affection on evaporation. The film flow rate is 600 L/h, and this flow rate ensures the flat plate completely covered with film. The inlet film temperature is 55 °C, and the outlet film temperature is controlled the same as the inlet by changing the heat flux across the plate. However, the inlet film temperature is 53–55 °C due to the fluctuation of temperature controlling. When the countercurrent air flow is larger than 7.0 m/s, the wave fragmentation is observed by high speed camera. The wave fragmentation causes the droplet entrainment in the rectangular channel, and the weighting method will overestimate the evaporation rate. Therefore, the air velocity in all the cases is below 7.0 m/s.

The film surface temperature is very important in the calculation of evaporation mass transfer coefficient h_D.However, film surface temperature is very difficult to be measured due to the non-rigid surface. The average temperature of inlet and outlet is applied in Kang and Ambrosini's work to represent the film surface temperature. And Ambrosini confirmed the accuracy of this approximation if the difference of inlet and outlet temperature is less than 5 °C (Ambrosini et al., 2006). Thus, average temperature is applied in this paper to represent the film surface temperature.

Fig 2 shows the inlet and outlet air temperature and the averaged film temperature. The inlet air temperature is 20 °C in the cases, while the air outlet temperature is nearly the same in cases 1–5. And the film temperature is controlled the same by adjusting the input heat flux.

The evaporation rate $\dot{m}$ is measured directly by weighting method, and h_D is defined as

$$h_D = \frac{\dot{m}}{\rho_{v,sat}(T_{\text{int}}) - \rho_{v,bulk}} \quad (1)$$

where $\rho_{v,sat}(T_{\text{int}})$ is the saturated vapor density at the interface, $\rho_{v,bulk}$ is the vapor density in the air bulk flow. Fig. 3 shows that increasing air flow rate enhances the evaporation rate and h_D significantly. In case 1, nature convection formed in the channel (air velocity is about 0.3 m/s) due to the temperature difference. In this situation, the evaporation rate is about 0.4 g/s/m^2, and h_D is 0.0056 m/s. When the air velocity is 6.0 m/s, the evaporation rate is 3.0 g/s/m^2, and h_D is 0.043 m/s. Thus, nearly liner relation exists between evaporation rate and h_D.

3.2. Film temperature affection on evaporation

The cases 1–16 in Table 1 are selected to study the film temperature affection on evaporation. The averaged film temperature is between 53 and 67 °C, while the air velocity is under 6.0 m/s. Fig. 4(a) shows the evaporation rate with different film temperature. The evaporation rate increases when the film temperature rises. According to the Dalton evaporation law, the evaporation rate is determined by h_D and vapor partial pressure difference

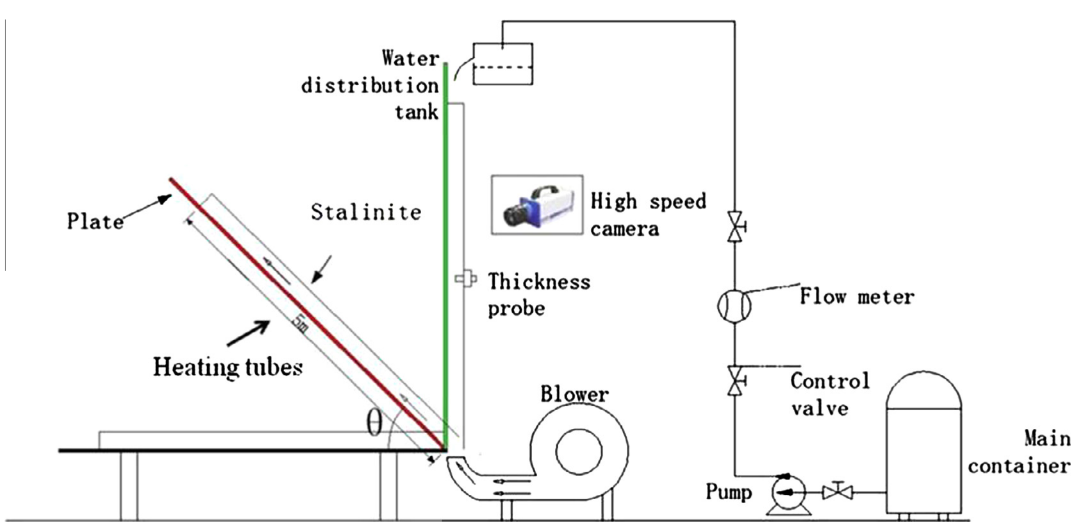

Fig. 1. Schematic of the experimental setup.