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Measurement on falling film thickness distribution around horizontal tube with laser-induced fluorescence technology

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ABSTRACT

The laser-induced fluorescence technology is used to measure the horizontal tube falling film thickness of pure water and natural seawater with 2.66% salinity. This experiment focuses on the film thickness distribution characteristics outside 19 mm and 25.4 mm outside diameter Al-brass tubes in column flow with the tube spacing ranging from 20 mm to 40 mm and the Reynolds number varying from 184 to 368. The fluorescent in liquid is induced by the laser. And the images of gas–liquid interface are captured by the digital camera. The quantitative descriptions of the liquid film thickness around the horizontal tube are obtained by the image processing technology. The results show that the film thickness increases with Reynolds number and decreases with tube spacing. In the axial direction, the thickness of the film increases with the distance from the section of liquid column center and maximized at the middle of two adjacent liquid columns. In the circumferential direction, the thickness of the film decreases until it reaches the minimal value near $\varphi = 90^\circ$ and then increases. The comparison of film thickness between water and seawater is also presented.

1. Introduction

The horizontal tube falling film evaporation is widely used in desalination, refrigeration, chemical engineering and food industry due to its obvious advantages [1]. In horizontal tube falling film evaporator, the distribution and fluctuation of film thickness around the horizontal tube reflect the flow state of the falling film and dominate the heat transfer. The significant effects of film thickness and fluctuation were mentioned in Mu et al. [2] and Xu et al. [3]. Hence the film thickness, as an important factor, is worth of concern and study.

Up to now, several previous studies on horizontal tube falling film thickness have been reported. A classical expression of the two-dimensional film thickness was presented by Nusselt [4] as follow:

$$\delta = \left[\frac{3\mu_L\Gamma}{\rho_L(\rho_L-\rho_G)g\sin\varphi}\right]^{1/3} \tag{1}$$

where φ is the circumferential angle from top of the tube; Γ is the spray density per side of the horizontal tube. The film Reynolds number is defined as follow:

$$\mathrm{Re} = \frac{4\Gamma}{\mu_L} \tag{2}$$

Slesarenko [5] pointed out that the falling film thickness of seawater around the horizontal tube with 32 mm diameter ranges from 0.35 mm to 0.5 mm when the spray density varies from 400 to 600 kg/(m·h).

Xu et al. [6] measured the thickness of water film at the circumferential angle of 45°, 90° and 135° along the perimeter of the horizontal tube with four different diameter tubes from 20 mm to 40 mm by using capacitance method. They found out that the thickness of liquid film increases with the spray density, but independent on the tube diameter although the reduction of tube diameter can enhance the fluctuation of liquid film.

A conductivity method was performed to measure the water film thickness of the 132 mm outside diameter aluminum tube at 45°, 90° and 135° circumferential angle by Rogers and Goindi [7]. A current circle can be formed while the probe touching the water film so that the film thickness can be detected. Their study indicated that the measured film thicknesses of laminar flow are 30% larger than theoretical values of Nusselt [4].

With similar conductivity method, Hou et al. [8] investigated the thickness distribution of water and seawater falling film around the horizontal tubes with 25.4 mm diameter, both smooth and scaled, by using a displacement micrometer. They found that the film thickness increases with Reynolds number but decreases

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Nomenclature

d	diameter, mm	φ	circumferential angle, °
g	acceleration of gravity, m/s^2	λ	laser wavelength
l	length, mm	w	distance between two certain lines of adjacent column, mm
l^*	dimensionless length	μ	dynamic viscosity, N s/m^2
s	tube spacing, mm	ρ	density, kg/m^2
Re	Reynolds number		
Greek symbols		*Subscripts*	
Γ	spray density per side, kg/m s	G	gas
δ	film thickness, mm	L	liquid
Δ	fluctuation intensity		

with the tube spacing. The film thickness distribution along the circumferential direction is asymmetric while the minimal values located in the range of 90–115°.

The bi-polar type conductivity probe embedded in horizontal tube surface was used to detect the water film thickness in Guo et al.'s research [9]. Guo et al. indicated that the film thickness increases with spray density and decreases with tube spacing. Besides, they found that the distribution of film thickness along the circumferential direction shows a symmetric arch. The variation along the axial direction is small.

Gstoehl et al. [10] utilized a non-intrusive optical method to measure the film thickness outside the 19.05 mm-diameter tube, taking water, ethylene glycol and water–glycol mixture (50–50% by mass) as the experimental fluids. The images of interface were captured when the fluorescent Rhodamine in liquid was induced by the laser. Gstoehl et al. focused on the sheet flow and regarded film thickness distribution as two-dimension. They found that the film fluctuation increase with Reynolds number, but the film thickness decreases with Reynolds number.

A similar measurement method was applied by Wang et al. [11] for surveying the falling film thickness around plain tube and Turbo-CII tube both with 19.05 mm diameters. It reported that the film thickness around the plain tube increases at first, decreases afterwards with the increasing of flow rate. Besides, it decreases with the increment of tube spacing.

The conductivity probe method belongs to intrusive measurement. The probe influences on the film flow to some extent and the liquid climbs along the probe when the probe touches the liquid film due to the surface tension. Both the aspects above affect the accuracy of the measurement. The capacitance method is a non-intrusive measurement, approximately considering the tube wall and the probe head surface as the parallel plate capacitor. The accuracy of capacitance method is easily affected by several factors such as splash droplets due to the short distance between probe head and liquid film. The sensor area of bi-polar type conductivity probe which is embedded in tube wall is relatively large, hence the film thickness measured by bi-polar type conductivity probe is an average value on sensor area and the probe location is limited. The laser-induced fluorescence method is a non-intrusive optical method, and the accuracy largely depends on image pixels. Hence, for obtaining higher precision, the spatial resolution is emphasized in this paper.

Besides, although several scholars experimentally measured the film thickness around the horizontal tube, most of them focused on the film thickness distribution under sheet flow or treated the flow mode as sheet flow and neglected the variation of film thickness along the axial direction. Therefore, the film thickness distribution characteristics of column flow, which is the main flow mode in horizontal tube falling film evaporator, should be studied in detail.

2. Experimental apparatus

The experimental apparatus includes two parts: falling film water circulation system and image sampling system.

Fig. 1 shows the schematic diagram of experimental setup for falling film water circulation. The size of the upper tank is 500 mm × 400 mm × 200 mm (inside height × width × depth), with an overflow plate of 450 mm high and a baffle of 300 mm high. This structure of upper tank is designed for keeping the water level and preventing the impact of return water. Four Al-brass tubes with length of 500 mm are fixed in the adjustable bracket horizontally: the upper one is the spray tube with 3 mm-diameter holes drilled at an interval of 8 mm along the bottom line, the tube diameter is 25.4 mm and the effective spray length is 300 mm. The second one is the distribution tube, which is located 2 mm lower than the upper tube. The narrow gap can help the distribution tube to get wet completely for the purpose of generating uniform falling film. The bottom two tubes are the test tubes with 19 mm or 25.4 mm-diameter. The surfaces of all tubes are cleaned carefully before the experiment. The Re range in this experiment is controlled in 184–368 which insures that the falling film is under the column flow.

The image sampling system mainly includes the parts of follows:

- The laser source with lens system for sheet light. A continuous solid-state laser of $\lambda = 532$ nm (green) is used in this experiment. The width and length of the laser sheet are 0.2 mm and 60 mm respectively while the laser source is located 500 mm away from test tube.

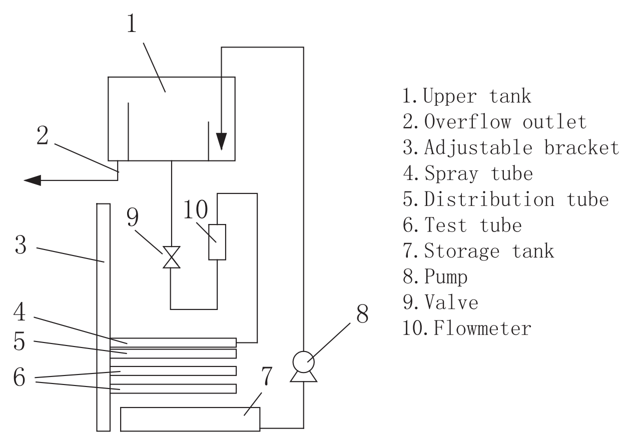

Fig. 1. Schematic diagram of experimental setup.