Measurement of Falling Film Thickness around a Horizontal Tube Using Laser-induced Fluorescence Technique

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Abstract. An optical method for the non-intrusive measurement of falling film thickness on the perimeter of the horizontal tube is described. This non-intrusive measurement method is based on the visualization of the falling film flowing around the horizontal tube and uses the laser induced fluorescence and image processing techniques. The falling film thickness around a Turbo-CII horizontal tube and a plain horizontal tube was measured when water flushed the tube vertically with a stable velocity. The results for the Turbo-CII tube are compared with those for the plain tube, and show that the film thickness around the Turbo-CII tube varies with the same trend as that around the plain tube, and the minimal values of the film thickness tend to locate at different angular position of 95º-120º under different conditions. The film thickness around the enhanced tube changes within a smaller range with time than that around the plain tube. The corresponding effects on flow uniformity have also been discussed.

1. INTRODUCTION
Falling-film horizontal-tube evaporator used in the refrigeration has many clear advantages over flooded tube bundles, such as high heat transfer coefficient, low refrigerant charge and so on. It represents the superiority in energy saving and environment protection. However, there are some difficulties in liquid distribution and tube alignment, which affect flow uniformity and dryout, especially in deep bundles, (Ribatski G., Jacobi A. M. 2005). So the falling-film horizontal-tube evaporator has not been widely used in refrigeration system and air-conditioning at present.

The process of falling film flowing around a horizontal tube is the main carrier of heat exchanging in the falling-film horizontal-tube evaporator and has a significant impact on heat transfer. Clearly, when the liquid flush the horizontal tube vertically, the flow uniformity is the key factor for the study of the heat transfer. The falling film thickness around a horizontal tube can be used to reflect the flow uniformity directly and predict dryout, so the research on the falling film thickness around a horizontal tube is an effective method to improve liquid distribution and tube alignment. Here it’s should be declared, for a fully developed laminar flow, the actual thickness of the film is also a sensitive factor for falling film heat transfer, which is inversely proportional to the local heat transfer coefficient. Thus, the film thickness is an important parameter for mechanism research and design of falling-film horizontal-tube evaporator.

The traditional expression of the falling film thickness was introduced by Nusselt, which was induced by assuming momentum effects on the falling film to be negligible and the intertube flowing mode to be a continuous sheet, as follows:
Where $\delta$ is the falling film thickness, $\beta$ is the angle around the perimeter from the top of a horizontal tube, $\Gamma$ is the flow rate on one side of the tube and $2\Gamma$ is the total flow rate on the tube, and the film Reynolds number is defined as follows (Nusselt, W. 1916):

$$Re = \frac{4\Gamma}{\eta_L}$$

The experimental research on the falling film thickness has also been developed and several different test techniques have been introduced, which are classified into intrusive and non-intrusive methods.

For the intrusive method, one popular technique is using parallel-wire conductance probes (Coney, M.W. E. 1973; Brown, R. C. et al., 1978; Koskie, J. E. et al., 1989). Another popular technique is by means of a micrometer to measure the falling film thickness. With this method, Thomson gave the values of the water film thickness at the angular position of $\beta=90^\circ$, which is in good agreement with Nusselt’s theory (Thomson, A. K. G. 1937). In literatures (Rogers, J. T. et al., 1989; Xu Li. et al., 2003), the water film thickness at $45^\circ$, $90^\circ$ and $135^\circ$ location were measured by means of a micrometer, the experimental results of Rogers were about 30% greater than theoretical values of Nusselt. As we know, the intrusive method may perturb the film flow and raise the surface at the insertion location due to surface tension effects.

For the non-intrusive method, the capacitance method is adopted to measure the liquid film thickness, which is a function of the electrical capacitance of an electrical condenser. For example, Dukler and Bergelin used this method to measure the liquid film thickness on a vertical plate (Dukler, A. E. et al. 1952). Recently, optical methods have become more and more widely used. Zhang et al. used the images from a camera to measure the average film thickness on a vertical tube, while a laser and a photo diode were used to measure the transient amplitude of waves (Zhang, J. T. et al., 2000). Desevaux et al. presented an interface measurement technique for a liquid film flowing inside small grooves by laser-induced fluorescence, which could provide a high resolution in the detection of the liquid-gas interface (Desevaux et al., 2002). D. Gstoehl et al. used the same technique as Desevaux to measure the falling film thickness around a plain horizontal copper tube in the sheet intertube flow mode. The test results showed relatively good agreement with Nusselt’s theory around the upper perimeter of the tube but much poorer agreement on the lower perimeter (D. Gstoehl et al., 2004).

Although there are so many methods which can be used to measure the falling film thickness outside a horizontal tube, none tested results of the film thickness around any kinds of enhanced surface tubes has been reported by now as far as we know. While for the falling-film horizontal-tube evaporator or other kinds of heat exchanger, the enhanced surface is widely used and may be more significant. So the film thickness distribution around the enhanced tube is the topic of our present interest. Furthermore, for enhanced surface, the simulation computation is more complex and hardly achieved, so it is more practical to measure the film thickness around some enhanced surface horizontal tube.

In this work, the film thickness of water flowing around the outside of horizontal enhanced tube was measured using laser-induced fluorescence, and compared with that of the plain tube. The variation trend of the thickness with time and tube perimeter position has been recorded by a high-speed digital camera with a high temporal and spatial resolution.

2. EXPERIMENTAL METHOD
2.1 Theory and Apparatus

The laser-induced fluorescence technique is adopted to investigate the film thickness outside the horizontal tube. When the fluorescent substance is illuminated by the laser, it will emit certain wavelength fluorescence. In aqueous solution, the gas-liquid interface could be identified by the fluorescence, which is captured by the high-speed digital camera. The key process in this experiment is to adjust the position of the sheet light and the camera to ensure the sheet light pass through the central axes of the horizontal tube and keep the camera at a position perpendicular to the sheet light, see fig.1. With the appropriate relative position of the sheet light and the camera, the film thickness obtained in the experiment could be just in the radial direction. The theory of the measurement can be described simply as follows. Firstly, capture the image of the test position on the tube surface without test fluid flowing around, which characterizes the geometry of the solid-gas interface, and then capture the image of the test position on the tube surface with test fluid flowing around, which characterizes the geometry of the liquid-gas interface. Finally, the falling film thickness can be obtained by comparing the interface of the liquid-gas with that of the solid-gas, as shown in fig. 2.

![Fig. 1 Relative location of the light sheet and the digital camera](image1)

![Fig. 2 The interface of the liquid-gas and that of the solid-gas](image2)

The mainly equipments used in this technique were introduced as follows.

- The light source: A continuous solid-state laser emitting in the green light of 532 nm wavelength with a power of 0.3 W, the beam diameter is 2.0 mm.
- The laser sheet generator: It can provide a sheet light beam which could vary in light density, light width and length with a limit range of 0.2×10 mm (minimum width × maximal length).
- The position adjustor: It could be used to move the sheet light around the central axis of the horizontal tube with a maximal range from 30° to 150° and at intervals of 6°. It also ensures the digital camera keep vertical to the incident direction of the sheet light.
- The fluorescent dye: The fluorescent substance used in the experiment is Rhodamine B, the concentration of the aqueous solution is 0.2g·L⁻¹, which has no significant modification of the physical properties of water.
- The image acquisition: The flow images are obtained by the high-speed digital camera which has a resolution of 1280×1024 pixels. A stop band filter (λ=532 nm) placed in front of the camera eliminates the spurious reflections and the incident light in order to perceive only the fluorescent light. So the interface can be easily detected because of the sharp contrast, resulting in an error of less than 25µm in the film thickness.
- The falling film fluid circuit subsystem (as shown in Fig. 3): It is used to supply different kinds of flowing condition to ensure a steady falling film around the horizontal tube. It consists of the liquid distributor, the tested tube, the liquid trap, the pump, several values, the filter and the flow meter. The liquid distributor provides a uniform flow distribution along the tube, it is 300×80×16 mm (inside Length × Height × Width), with the liquid entering at the top through two holes and leaving at the bottom through a flat plate with 3 mm diameter hole spaced 5 mm apart center-to-center. A grid with foam is added in the liquid distributor to
increase the homogenization effect. Three tubes are arranged vertically and the second one is chosen for the measurement. The distance between the first tube and the liquid distributor is 3mm and the intertube spacing is defined as $s$ which is variable according to the different experimental condition. The tested tubes are plain tubes and enhanced tubes. The plain tube is 19.05 mm-diameter copper tube whose surface is carefully cleaned. The enhanced tube is 19.05 mm-diameter Turbo-CII copper tube with the fin height of 0.559 mm and the fin density of 43 fpi. Fig. 4 depicts the photograph of the Turbo-CII tube. The changes of the flow rate could read directly from the flow meter by varying the valve opening.

2.2 Experimental Procedure

Before starting a test, the liquid distributor would be leveled carefully. Tubes were aligned in the test section at a stated tube spacing. Since a tube inclination would cause a nonuniform distribution of the flow, the tubes also were leveled before a test, and leveling was checked again after the liquid started circulating in the system. The liquid flow rate was adjusted to obtain a column mode, if the column fell at fixed sites without drifting towards either end of the test tube, the tubes were level and its horizontal axes were considered in the middle of the hole center in the liquid distributor. The position of the sheet light and the camera was adjusted carefully for the test and the solid-gas interface were recorded by the digital camera. After that, the test liquid was circulated through the system for several hours to ensure that the tubes were carefully wetted, at last the liquid-gas interface was captured and the flow rate was read.

An image processing program written in MATLAB was developed specifically for extracting the interface of liquid-gas and solid-gas. In this program, the original image was digitized. An appropriate threshold of the gray levels permitted the removal of the background noise to obtain a clear image. The edge detection was then achieved by identifying sequence number of the pixel in which the gray levels have a step change, and the film thickness is obtained by comparing the numbers of the solid-gas pixels with that of the liquid-gas pixels and multiplying pixel size. It should point out that, for the enhanced tube, because the enhanced surface is accidented, the solid-gas interface for the measurement of the film thickness is not the real one captured by the camera, but a reconstructed plane which was fixed according to the adjacent fins. Therefore, the experimental film thickness around the root section of the enhanced tube was thinner than its real value. Although, it would not affect the study result of the flow uniformity and the distribution trend of the film thickness around the tube.

Several tests were performed to estimate the reliability of the measurement technique. The average observed difference between two measurements under the same condition for the plain tubes was ±7% while for the Turbo-CII tube was ±5%.

3. EXPERIMENTAL RESULT AND DISCUSSION

The experimental liquid was pure water with a very minor amount of Rhodamine B under the normal temperature (about 27℃) and pressure (about 98 kPa) conditions. The intertube spacing of the measurements was 3 mm, 6 mm, 9mm, 12mm, and 19mm. All test conditions were below the Reynolds number for transition to turbulent flow (typically cited to
be 1600-1800), so the wave influence on film thickness could be neglected.

Fig. 5 shows the variation trend of the film thickness around the plain tube with the angle at $Re=574$ and the intertube spacing was $s=6.4\,\text{mm}$. Compared with Gstoehl’s experimental results attained under the same condition, the maximal film thickness is about 9% smaller and the minimal film thickness is much closed to Gstoehl’s values (D. Gstoehl et al., 2004). From the figure, the experimental results at $\beta<84^\circ$ approach to Nusselt’s theory value, while the experimental results at $\beta>96^\circ$ are smaller. This variation trend validates that Nusselt’s theory gives a reasonable prediction of film thickness on the upper perimeter of the tube and tends to significantly overestimate values on the lower perimeter. This variation trend is also in accord with the results of the previous numerical simulation on the film thickness reported by our group (X. F. Wang et al., 2008).

The temporal change of the film thickness is recorded in fig. 6. The time interval is 0.05s. The flow is under the condition of $Re=225$ with tube spacing of 12mm at the angular position of $\beta=48^\circ$. The film thickness around the plain tube and the Turbo-CII tube all change randomly and the film thickness around the Turbo-CII tube vary with a more narrow range than that around the plain tube. The differences between the maximum film thickness and the minimum film thickness are 0.070 mm for the plain tube and 0.020 mm for the Turbo-CII tube, which are respectively about a rate of 15% and 6% to the average film thickness.

Fig. 7 and fig. 8 show the film thickness versus flow rate of the Turbo-CII tube and the plain tube with $s=3\,\text{mm}, 6\,\text{mm}, 9\,\text{mm}, 12\,\text{mm}, \text{and} 19\,\text{mm}$ at $\beta=48^\circ$, respectively. The flow is in steady column flow mode at the Reynolds number from 180 to 340, which is also within the $Re$ range for column flow mode of Roques (J. F. Roques., 2002). In these two figures, the film thickness change slowly with an inflection point. The increasing flow rate may induce the liquid accumulated between the adjacent coming liquid column and result in the increasing of the film thickness, and the liquid will be accumulated to a limit as the flow rate increasing.
then it will be outspread along the tube. The location where the liquid is accumulated varies with different flow rate. And the change trend of film thickness is different due to the relative location of the tested area and the film accumulated area. For the plain tube, the inflection point is more obvious, which may be due to block effect of the fin of the enhanced surface on the liquid accumulation.

The film thickness decrease with the increase of the tube spacing because of the flow accelerated, while the film thickness of the plain tube at $s=3$ mm is smaller than others, as shown in fig.8. The same phenomenon for $s=3.2$ mm is also observed by D.Gstoehl. The reason may be the effect of the surface tension on the film flow. For a small tube spacing (smaller than a certain limit) where the liquid could not spread between the adjacent tubes completely, a large amount of the flowing liquid are accumulated on the bottom of the upper tube on the function of the surface tension. Little liquid flowing down around the tested tube results in a smaller film thickness.

Fig.9 and fig.10 show the film thickness of the Turbo-CII tube versus angles at $Re=180$ and $Re=260$, respectively. Values of the film thickness on the upper tube are larger than that on the lower tube, which is similar to that of the plain tube. In these two figures, the minimal values of the film thickness are not just at angle of 90°. According to all our test results, the minimal values of the film thickness tend to locate at different angular position of 95°-120° under different conditions.

Generally, if the film thickness gets thinner or the flow become unstable under some flow conditions, the local dryout on the surface of the tube would occur. The area where the local dryout probably occurs could be found from all these tested results. With regard to falling film evaporation with nucleate boiling in the film, the thinner film at the angle from 95° to 120° on the low perimeter of the tube tend to suppress nucleation and facilitate the formation of dry patches. And by the observation, the most unsteadily flowing may occur with the liquid accumulating which accompanied by the local film getting thicker, so it is significant to study the area and condition of the liquid accumulating. Compared with the plain tube, the fin of the Turbo-CII tube may store a little liquid and steady the film flowing, thus, the Turbo-CII tube provides a good performance for the flow uniformity.

CONCLUSIONS

An optical method based on laser-induced fluorescence and image processing of high-speed digital camera has been developed to measure the falling film thickness on the outside of a horizontal tube. The film thickness was measured for the plain tube also for the Turbo-CII tube under different flow rate condition with different intertube spacing, respectively. The measurement provides the variation of the thickness with time, angular position from image processing of the image sequences.

The present measurements show that the film thicknesses around the Turbo-CII tube vary with the same trend as that around the plain tube, which validates Nusselt’s theory giving a
reasonable prediction of film thickness on the upper perimeter of the tube and significantly
overestimate values on the lower perimeter. The minimal values of the film thickness tend to
locate at different angular position of 95°-120° under different conditions, and the angular
position of the thinner film may be the main position for dryout detection. For the enhanced
tubes, the falling film thickness change within a smaller range with time than that around the
plain tube.

NOMENCLATURE

\( g \)  acceleration due to gravity (9.81), [m·s\(^{-2}\)]

\( Re \)  film Reynolds number, \( 4\Gamma/\eta \)

\( s \)  intertube spacing, [mm]

\( t \)  test time, [s]

Creek symbols

\( \beta \)  angular position on a horizontal tube measured from the top, [°]

\( \Gamma \)  film mass flow rate on one side per unit length of cylinder, [kg·m\(^{-1}\)·s\(^{-1}\)]

\( \eta \)  dynamic viscosity, [Pa·s]

\( \delta \)  film thickness, [mm]

\( \lambda \)  wave length of the light, [nm]

Subscripts

\( G \)  gas

\( L \)  liquid

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