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Error analysis and liquid film thickness measurement in gas–liquid annular flow

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ABSTRACT

The parameters measurement of liquid film in gas–liquid two-phase annular flow is of great significance for the study of heat and mass transfer and flow characteristics. The paper focuses on the thickness measurement and flow evolution analysis of the liquid film in downward gas–liquid two-phase annular flow. Compared with the traditional measurement methods, the method combined the laser-induced fluorescence (LIF) technique with the high-speed photography is developed to measure the liquid film thickness and analyze the flow distribution. Firstly, the geometric optical path model of the organic glass pipeline was established based on the Gauss optics to recognize the real and virtual film images and quantitatively estimate the measurement linearity. And then the digital image processing technology was developed to achieve non-intrusive measurement of liquid film thickness. Finally, the film thickness distribution in downward gas–liquid two-phase annular flow was further analyzed. The method can avoid the interference with the flow field. Meanwhile, the measurement results by experiment show that the film thickness manifests stochastic distribution, which corresponds to the features of randomness and small flow in the process of liquid film flow.

1. Introduction

With the development of science technology, gas–liquid two-phase flow has been widely applied in many fields such as aerospace, petroleum, chemical, metallurgy, pharmacy and nuclear energy engineering [1]. Various flow patterns are generated with the combination of different gas and liquid velocity. The mixed flow of liquid and a high-velocity gas stream is usually termed gas–liquid annular flow. Under this circumstance, the thin liquid film flows along the inner pipeline wall and the core of the gas stream passes through the pipeline center. Also sometimes entrainment of liquid drops from the film surface into the gas stream core occurs. The study of liquid film characteristics has been an area of intense scientific interest, and is of great importance and benefit to guide the engineering practice due to the huge heat flux and the coefficients of heat and mass transfer of liquid film [2], which requires less energy consumption.

A lot of scholars have begun to study annular gas–liquid flow in the early 1970s. The techniques such as acoustic methods based on ultrasonic waves [3], electrical methods based on conductance or capacitance [4], optical methods based on light attenuation or light reflection [5], and nucleonic methods based on X-ray attenuation [6] are used in the liquid film thickness and velocity measurement and analysis of two-phase annular flow mechanism. Pederen et al. [7] developed an ultrasonic technique and measured liquid film thickness during condensation on a downward facing surface. They used frequencies up to 10 MHz and measured liquid film thickness from 50 to 500 μm. But the applications of ultrasonic technique are limited because high-frequency ultrasonic waves are preferred as they need provide better signal-to-noise ratio and increasing resolution. The curved film interfaces might change the reflection and refraction direction of ultrasonic waves and the method is restricted to near planar film interfaces. The electrical methods based on conductance or capacitance have brought some advantages that ultrasonic method does not have, which is much easier and more reliable to implement. Most of film thickness measurements have used conductance probes. Zhao et al. [8] developed a group of multiple conductance probes positioned circumferentially and axially along a vertical pipe with inner diameter 34.5 mm to study the existence, development and translation of liquid film in upwards gas–liquid annular flows. Two identical sections that each contains four orthogonally embedded concentric conductance probes were used to measure film thickness. In parallel work, Hou

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et al. [9] used a conductance probe to understand the flow behavior of liquid film by studying the film thickness distributions along the circumferential direction of a horizontal pipe with outside diameter of 20–30 mm. Also the effects on heat and mass transfer of falling film thickness distributions were examined and analyzed. Conductance probes directly measure the conductivity of two-phase flow, and the film thickness measurement is based on the calibration of the probe. The electrical method is relatively reliable and with low cost. But the probes bring a great disturbance to the flow fields. Simultaneously, the data obtained is the average film thickness in the flow spatial region. The much thicker the film becomes, the much lower the measurement sensitivity is. With the rapid development of optoelectronics and digital image processing techniques in recent years, more and more scholars are trying to apply optoelectronics measurement techniques into the fields of gas–liquid two-phase flow [10,11]. Yan et al. [12] developed an optoelectronics method using CCD high-speed camera to capture the freely falling film images at various Reynolds numbers and extract the film thickness by image processing algorithm. Ong et al. [13] investigated the macro-to-micro scale transition during flow boiling in small scale channels of three different sizes through high-speed flow visualization and image processing algorithm. The film thickness at the top and bottom of a horizontal pipe was compared qualitatively. As the laser has the unique advantages of good monochromaticity and directionality, high power and high measurement accuracy, some scholars apply it into the measurement of film thickness. Okawa et al. [14] developed a laser detection method to investigate the effects of sinusoidal forced oscillation of the inlet flow rate on the time variations of local liquid film thickness in steam-water annular two-phase flow. The local film thickness was measured with a laser focus displacement meter, which focus on a target adopted in an automatically focusing camera to measure the displacement. The displacement difference generated during the process of automatically focusing was the film thickness. The laser focus displacement technique can accurately measure dynamic film thickness and improve the spatial resolution up to 0.2 μm and time resolution up to 1 kHz, but it only can achieve single-point measurement. Schubring et al. [15] used planar laser-induced florescence (LIF) to provide direct visualization of the liquid film in upward vertical air–water annular flow. The technique involves the excitation of laser with a certain wavelength, absorption of particular photons by fluorescent particles resulting in energy level transition and fluorescence generation with a certain wavelength. The fluorescence with a certain wavelength excited by the laser is captured by high-speed camera in real time, and the film thickness can be interpreted by the images. The method can figure out the distribution of film thickness and achieve the real-time visualization of liquid film flow, and has good application prospects.

The optical measurement methods of film thickness have unparalleled advantages that other traditional methods do not have, and can achieve non-intrusive, wide range measurement. The paper focuses on the film thickness measurement and analysis of film flow evolution based on LIF and high-speed photography technology. Firstly, the geometric optical path model of organic glass pipeline was established based on the Gauss optics to recognize the real and virtual film images and quantitatively estimate the measurement linearity. Then the high-speed photography techniques were used to capture fluorescence images of vertical, downward film stream flow, and non-intrusive measurement of film thickness was complemented through digital image processing. Finally, the film thickness distribution in downward gas–liquid two-phase annular flow was further analyzed. The method, combined the laser-induced fluorescence with high-speed photography technology, avoids the interference with the flow fields and has high precision. The measurement results show that the film thickness manifests stochastic distribution, which corresponds to the features of randomness and low flow in the process of liquid film flow.

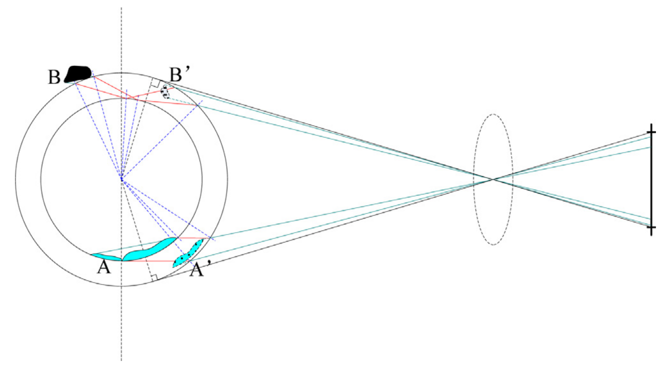

Fig. 1. Optical imaging model on the inner and outer surface of pipeline.

The paper is organized as follows, Section 2 establishes the geometric optical path model and analyses the optical error which may affect liquid film thickness measurement. Section 3 describes the measurement principle of liquid film thickness and experimental setup. Section 4 develops complete image processing method for liquid film in downward two-phase annular flow. Section 5 provides the experimental results. Real measurement data are used to validate the method and analyze the flow characteristics. Last, we give concluding remarks in Section 6.

2. Error analysis of optical imaging

According to the principles of geometrical optics, multiple reflection and refraction occur on the outer surface of the organic transparent glass pipeline, the solid–liquid interface and the gas–liquid interface, which would bring interference with virtual images of the liquid film. In order to accurately measure the liquid film thickness flowing along the pipe wall, the error analysis of optical imaging is necessary.

Optical imaging model on the inner and outer surface of pipeline was established based on pinhole imaging principle, which is shown in Fig. 1. The inner diameter of pipeline is 50 mm and the outer diameter is 70 mm. As shown in Fig. 1, the reflection light from the object A, which attached on the inner pipeline wall, transmits into the camera through two refraction processes. The reflection light from the object B, which attached on the outer pipeline wall, transmits into the camera through reflection of the inner wall and refraction of the outer wall. Based on the principle of pinhole imaging and principle of reversible optical path, the objects A′ and B′s shown in Fig. 1 are also imaged on the CCD image plane. It is obvious that virtual and distorted images A′ and B′ will be emerged on the transparent organic glass pipeline, which must be discriminated and eliminated in the image processing of the liquid film.

In order to further analyze the measurement linearity of the liquid film thickness, the study on quantitatively measurement of the film thickness based on the liquid film imaging mechanism was developed. According to Gaussian optics, the geometric-optics model of liquid film thickness measurement was established, as shown in Fig. 2. The angle i_1, i_1' represent the incident angle and emergence angle on the surface of inner wall respectively. The angle i_2, i_2' represent the incident angle and emergence angle on the surface of outer wall respectively. n_1, n_2 and n_3 are the refractive index of air, glass and liquid film respectively, generally with $n_1 = 1.0$, $n_2 = 1.5$ and $n_3 = 4/3$. The angle θ is angle between the incident light to the camera and the horizontal line, the point A is the incident point to the camera, and α is the angle between the vertical line and the line which connects the point of incident light at the first refraction surface and the center O of the pipeline.