Investigation on heat transfer characteristics of falling liquid film by planar laser-induced fluorescence

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ARTICLE INFO

ABSTRACT

Falling liquid film evaporation is widely used in many industrial applications due to its efficient heat transfer characteristics. In this paper, a quantitative thermometry technique based on planar laser-induced fluorescence (PLIF) was applied to analyze the heat transfer characteristics of falling liquid film with high spatiotemporal resolution. The optimal gray values extraction method was proposed for the calibration of temperature-fluorescence intensity. The quantitative calculation of convective heat transfer coefficient and Nusselt number were conducted based on the liquid film temperature field distribution which was measured by PLIF and the trends of them were shown in different range of temperature and Reynolds number. Finally, the heat transfer correlation was proposed and the heat transfer characteristics of falling liquid film was analyzed. The quantitative correlations analysis shows that most of the correlations are more suitable for the liquid film with low Prandtl number, and the Nusselt number tends to decrease when the temperature of the liquid film increases at the constant flow rate.

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1. Introduction

Falling film flow, which is defined as fluid falling along the smooth vertical pipe surface and under the action of gravity alone, is an important free-surface flow, the falling liquid film is extensively used in chemical, energy, aerospace such as evaporation, condensation, distillation and other industrial production process predominantly owing to its efficient heat and mass transfer characteristics. There will be temperature gradient in a thin layer when the liquid film flows through a wall with different temperature, which was named thermal boundary layer. The thermal resistance mainly exists in the thermal boundary layer, where is also the point of convective heat transfer focusing on. Due to the temperature gradient in the thermal boundary layer, the viscosity, heat transfer coefficient and other related heat transfer parameters of the liquid film in the boundary layer are different, besides, the spatiotemporal variations of liquid film are complex during the flow process, which renders the study on convective heat transfer of falling liquid film particularly challenging and significant.

Aktershev et al. [1] obtained the temperature field distribution of the liquid film on the inclined plate by the semi-analytical method, some parameters related to heat transfer of liquid film were also calculated with the boundary layer conditions. Nusselt [2] first solved the heat transfer problem of the laminar flow on the thermostatic wall, and the relationship between the dimensionless convective heat transfer coefficient and Reynolds number of liquid film was achieved. Chun and Seban [3] studied the heat transfer characteristics of evaporative liquid film which flows along the outer wall of the tube. The different heat transfer correlations of laminar and turbulent flow were obtained by fitting the experimental data under the heating and cooling conditions. Mudawwar et al. [4] associated the change of surface tension and viscosity with the heat transfer characteristics of the turbulent liquid film to derive a new semi-empirical turbulent liquid film heat transfer correlation. Härkönen et al. [5] studied the heat transfer characteristics of the liquid film formed by water and sugar water in the fluted tube, the correlation of liquid film heat transfer in the fluted tube then was compared with the correlations in the normal tube. Gourdon et al. [6] summarized the heat transfer characteristics of the falling liquid film with high Prandt number such as black liquor and dairy product, the corresponding correlation was also obtained. The heat transfer correlations which were proposed by Ahmed et al. [7] and Herbert et al. [8] were fit for the falling liquid film in pipeline, Numrich et al. [9] proposed the heat transfer correlation for the liquid film out of the tube, and the correlation of Schnabel et al. [10] was suitable for the liquid film with

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high Prandtl number. In addition, there were some heat transfer correlations proposed by other scholars such as Wilke et al. [11], Holmberg et al. [12], Asblad et al. [13] and Wadekar et al. [14] for falling liquid film under different condition, however, the difference arise when performing some quantitative calculation with these correlations. Therefore, the calculation of the parameters related to the heat transfer of falling liquid film is still of extremely significance at present.

Laser-induced fluorescence is an optical diagnostic technique, which is widely employed for quantitative measurements in flow field with high accuracy. For example, nonintrusive measurements of temperature, concentrations and velocity field can be achieved by LIF with high spatiotemporal resolution. Planar laser-induced fluorescence (PLIF) is the most common application of LIF because it can obtain the scalar field in two-dimensional planar in fluid field. Coolen et al. [15] measured the temperature field distribution in a water tank with a natural convection by PLIF. Quantitative measurement of the free convection heat transfer process in the water tank was implemented by Jaszczur et al. [16] with PLIF. Bøgild et al. [17] had proved the feasibility of PLIF for convective heat transfer in mini channels by experiments. To eliminate the influence of laser fluctuation, the two-color/two-dye PLIF technique was first described by Sakakibara and Adrian [18]. The two-color/one-dye PLIF technique proposed by Nakajima et al. [19] made the measurement independent of the dye concentration, and Bruchhausen et al. [20] and Lemoine et al. [21] successfully applied this method to temperature measurement of single phase flow and droplet, respectively. Hishida et al. [22] combined PLIF and PIV (particle image velocimetry) for investigating the turbulent heat transfer performance of stratified flow and natural convection, and the three-dimensional structure of temperature was acquired by the two-color/two-dye PLIF. Turber et al. [23] firstly validated the simultaneously imaging temperature and mole fraction by using dual-wavelength acetone PLIF, which was suitable for the quantitative imaging of the mixing fluid with large temperature and mole fraction variations. Crimaldi [24] summarized the theory, evolution, applications of PLIF in aqueous, the source of errors and the methods to correct were also revealed, then the good prospects of PLIF was predicted. Schubring et al. [25] provided a machine vision solution for the air-water annular flow film thickness distribution and interface detection by PLIF. Charogiannis et al. [26] investigated the hydrodynamic characteristics of the thin liquid film on the inclined plate combined with PLIF, PIV and PTV (particle tracking velocimetry), where PLIF was applied for film thickness measurements, PIV and PTV were employed in order to enhance the spatial resolution of the velocity measurements. Besides, PLIF has been applied extensively for temperature measurements by lots of scholars, as it allows for the non-intrusive measurement and the visualization of the flow, the temperature distribution of the whole flow field in many circumstances can be presented with high spatial-temporal resolution by using PLIF, which makes up for the deficiencies of traditional methods such as using the probes. While the publications relating to the falling liquid film based on PLIF are seldom found till now, and it is promising to reveal the heat and mass transfer mechanism under complex conditions.

In this currently study, the quantitative thermometry technique based on PLIF was applied to study the heat transfer characteristics of falling liquid film in pipeline. The heat transfer coefficient and Nusselt number were calculated with the accurate calibration which was based on the optimal gray values extraction method proposed in this paper. Combined with the heat transfer theories and experimental data, the heat transfer correlation was acquired, and the different correlations of falling liquid film were further discussed.

2. Experimental methodology

2.1. Principles of PLIF

Some dyes will emit fluorescence which is temperature dependent when they are induced by the incident light with specific wavelength. The molecules or atoms of fluorescent dyes transition from the ground state to the excited state spontaneously after absorbing the energy of incident light, part of molecules or atoms will transition from the excited state to the ground state due to the collision and other reasons. The whole process is completed instantaneously and the natural fluorescence is induced. This phenomenon is named PLIF in the case of incident light is a laser sheet, the fluorescence intensity I can be described by the following equation:

$$I = I_e C \varphi \varepsilon \frac{\lambda_e}{\lambda_f} \tag{1}$$

where I_e is the intensity of excitation beam, C is the fluorescent agent solution concentration, φ is the quantum efficiency, ε is the molar absorption coefficient, λ_e / λ_f is the wavelength ratio between fluorescence and excitation light. Molar absorption ε is a constant and quantum efficiency φ is related to the temperature for the majority fluorescent dyes, which makes it possible to acquire the temperature field distribution of fluid field by calibration. Rhodamine B has been selected as fluorescence dye in this study, its temperature sensitivity coefficient is about (2–3)% per °C, which is beneficial to the calibration accuracy. In addition, the narrow overlapped area of absorption and emission spectra is conductive to extract fluorescence intensity.

2.2. Experimental setup

A schematic drawing of the experiment system is presented in Fig. 1. The water in the lower tank of the pipeline is pumped into the tank at the top of the pipe, and the electromagnetic flowmeter can record the flow rate of the flow through the pipe in real time, with a precision of 0.5%. V1 and V2 are two ball valves, where V1 is used to adjust the bypass flow and V2 is used to adjust the main circuit flow. The liquid film distributor in the top tank is designed to produce the stable liquid film and its size is $300 \times 300 \times 300$ mm, the inner and outer diameter of pipe are 25 mm and 35 mm, respectively, its length is 2.7 m. The material of pipe is plexiglass for the convenience of image acquisition.

The high-speed imaging system and the real-time measurement and control system of liquid film temperature are depicted in the left side of Fig. 1. A continuous laser sheet with a wavelength of 532 nm is produced by the laser. The high-speed camera and the laser are perpendicular to each other in the same shooting plane and the images are stored in the computer. The front of the camera is a 570 nm high-pass filter, which is used to extract the fluorescence information from the laser. The PT1000 is used to measure the liquid film temperature with the accuracy of ±0.2 °C, and the liquid film is heated to the desired temperature by the heating tube in the top tank. The temperature values are acquired by the Advanced RISC Machines (ARM) controller, which is connected with the host computer through the serial port. The temperature of the liquid film is read and controlled in real time by the man-machine interface of the host computer. In order to generate the temperature difference between the liquid film and the pipe wall, the heating band is entangled on the outer pipe wall, which is above the field of camera. The power of heating band is 25 W/m with 10 mm width, and the heating temperature can finally stabilize at 65 °C.