Flow Measurement and Instrumentation 60 (2018) 110–114

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Measurement of liquid water film thickness on opaque surface with diode laser absorption spectroscopy

Huinan Yang*, Wu Wei, Mingxu Su, Jun Chen, Xiaoshu Cai

School of Energy and Power Engineering, University of Shanghai for Science and Technology, No. 516, Jungong Road, Yangpu District, 200093 Shanghai, China

A R T I C L E I N F O

Keywords:
Measurement
Film
Thickness
Laser spectroscopy
Flow

A B S T R A C T

Liquid film is usually formed on opaque surfaces in various industrial processes, and the investigation of liquid film is very important for understanding and optimization of the relevant processes. Here, a novel on-line measurement method based on diode laser absorption spectroscopy (DLAS) was developed to determine the film thickness on opaque surfaces. The evaporation process of static liquid films both on a silver-coated mirror (smooth opaque surface) and an aluminum alloy plate (rough opaque surface) were investigated with the proposed method. Ultrasonic pulse-echo method (UPEM) was simultaneously applied to validate the measurement accuracy of DLAS method, it revealed that the average thickness deviation between these two methods during film evaporation process on silver-coated mirror were 4.9% and on aluminum alloy plate were 7.1%, respectively. A flow liquid film on aluminum alloy surface was then studied, it was found that the average thickness deviation between DLAS and UPEM at low flow speed were 6.5% and at higher flow speed were 9.5%, respectively. And the fluctuation frequency of the liquid film at both flow speeds were also in good agreement with these two methods.

1. Introduction

Formation of liquid film widely exists in various industrial processes. For example, thin film in spray evaporative cooling [1], film on hot surfaces in water mist fire suppression systems during water droplet impingement [2], fuel film within intake pipe of internal combustion engine [3], film in the automotive exhaust pipe during the selective catalytic reduction (SCR) process [4,5], and falling film in the microstructured reactor [6] and type plate-fin condenser [7]. Quantitative measurement of liquid film thickness with high accuracy is essential to improve the performance of relevant industrial equipment.

In the previous research, liquid film thickness was investigated with a variety of numerical simulations and measurement techniques, e.g., concentration and film thickness of urea–water solutions in SCR systems [8] and flow regime of liquid film outside the single horizontal cylinder [9] were studied by Computational Fluid Dynamics (CFD). Liquid film distribution in near-horizontal pipes [10] and free falling film formed in the vertical gas-liquid flow channel were measured by conducting probe [11], however, the measurement range and accuracy of film thickness determined by electrical methods were normally influenced due to the structure of the probe. Condensing /non-condensing liquid films, lubricant film and hydrodynamic oil film were studied by ultrasonic methods, but the sampling rate of ultrasonic techniques are relative lower than optical methods [12–14]. Thin liquid-film flow was investigated with planar laser-induced fluorescence imaging (PLIF) [15], and the local film thickness and temperature distribution in wavy liquid film were determined by laser-induced luminescence [16], however, a tracer is necessary for the laser-induced techniques. In our previous work, the water film thickness, liquid film temperature and vapor-phase temperature above the liquid film deposited on quartz-glass plate was obtained with near-infrared tunable diode laser absorption spectroscopy (TDLAS) [17] and the free-falling film for urea–water solutions on a vertical quartz plate was also investigated [18]. However, the previous developed method was only valid for the liquid film on transparent surface, where the light beam was transmitted through the absorption medium and the transparent substrate. However, in practical industrial processes, liquid film is usually formed on opaque surfaces (such as metal), e.g., formation of liquid film in gas-liquid two-phase swirling flow in heat exchanger [19] and the liquid film in steam turbine [20]. Pan et al. [21] investigated the evaporating process of liquid film deposited on a kind of retro-reflecting foil, where the reflected beams from the film surface and the foil surface can be separated by the arrangement of optical setup.

In this work, a novel method based on Diode Laser Absorption Spectroscopy (DLAS) was developed to determine the liquid film thickness on opaque surfaces without separating these reflected beams

* Corresponding author.
E-mail address: yanghuinan@usst.edu.cn (H. Yang).

https://doi.org/10.1016/j.flowmeasinst.2018.02.005
Received 11 October 2017; Received in revised form 28 November 2017; Accepted 11 February 2018
Available online 13 February 2018
0955-5986/

from film surface and opaque surfaces by optical arrangement, the light intensities of these reflected beams are collected simultaneously and then processed to determine the film thickness. The developed DLAS method was firstly applied to investigate the evaporation process of static liquid water films on a silver-coated plane mirror (smooth opaque surface) and an aluminum alloy plate (rough opaque surface), respectively. The measurement accuracy of the developed DLAS method is difficult to be determined since it is difficult to provide a free film with exactly known film thickness on the opaque surfaces, ultrasonic pulse-echo method (UPEM) was simultaneously utilized to obtain the film thickness and compared with the DLAS results, and the film-thickness measurement accuracy of UPEM is less than 5% [22]. Finally, a flowing liquid film on the aluminum alloy plate was investigated with the developed DLAS and UPEM method, which revealed that the measured results from both methods were in good agreement.

2. Measurement strategies

Based on the Beer-Lambert law, when light passes through absorbing medium deposited on transparent substrate, the transmittance τ at a specific wavenumber position ν is:

$$\tau(\nu) = I_t/I_0 = \exp(-k(\nu)\cdot L) \tag{1}$$

where I_t and I_0 are the transmitted and incident intensities, respectively, L is the path length of the light beam within the absorbing medium, and $k(\nu)$ is the spectral absorption coefficient at wavenumber position ν.

As shown in Fig. 1a, when the light beam is directed onto the liquid film on a smooth opaque surface, two reflected beams from liquid film surface and smooth opaque surface will be formed, respectively. The reflected light from smooth opaque surface undergoes refraction from liquid film and then transmits into the air, and it is partially internally reflected at the liquid/gas interface when leaving the film. The reflected light from film surface is an interference signal and it should be eliminated to determine the effective path length of absorption, i.e., the film thickness. In this case, the transmittance τ' at wavenumber ν can be obtained as:

$$\tau'(\nu) = \frac{I'_t/(1-R)}{(I_0 - I_s)} = \frac{(I_t - I_s)/(1-R)}{(I_0 - I_s)} = \exp(-k(\nu)\cdot L) \tag{2}$$

where R is the reflectivity on the liquid/gas interface, I_s is the reflected light intensity from the liquid film surface. I'_t is the intensity of light reflected by the smooth opaque surface and refracted by the liquid film. I_t is the sum of I_s and I'_t. I_s can also be expressed as:

$$I_s = R\cdot I_0 \tag{3}$$

If the incident angle of a light beam is fixed, the surface reflectivity of same material is constant [23]. R can be obtained according to Fresnel's formula:

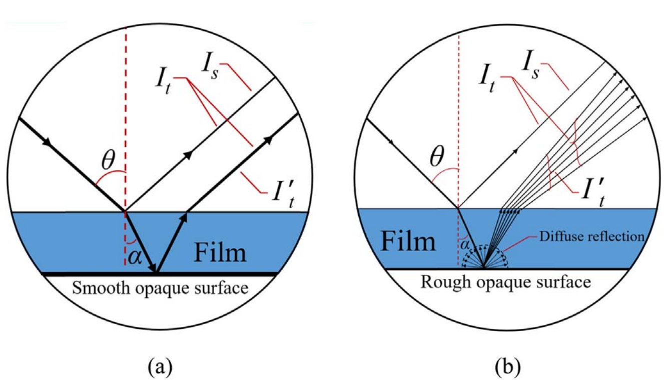

Fig. 1. Schematic drawing of liquid film on opaque surfaces.

Table 1
The reflectivity on liquid water/air surface at different incident angles.

angle	Reflectivity /R
5°	0.0204
10°	0.0204
15°	0.0204
20°	0.0206
25°	0.0209
30°	0.0214
35°	0.0225
40°	0.0245

$$R = \frac{1}{2}\cdot\left(\frac{\sin^2(\theta-\alpha)}{\sin^2(\theta+\alpha)} + \frac{\tan^2(\theta-\alpha)}{\tan^2(\theta+\alpha)}\right) \tag{4}$$

where θ is the incident angle and α is the refracted angle. Table 1 shows the reflectivity on the liquid water/air interface at different incident angles.

When the light beam is directed onto a liquid film on a rough opaque surface, diffuse reflection exists (Fig. 1b), and multiple light beams are reflected by the rough opaque surface. In this case, I'_t is the sum of light intensities of the diffuse reflection lights ($I_{t1}, I_{t2}, I_{t3},\ldots I_{tn}$), τ' can be then expressed as:

$$\tau'(\nu) = \frac{(I'_{t1} + I'_{t2} + I'_{t3}+\ldots+I'_{tn})/(1-R)}{I_{01} + I_{02} + I_{03}+\ldots+I_{0n} - I_s} = \frac{I'_t/(1-R)}{I_0 - I_s} = \frac{(I_t - R\cdot I_0)}{I_0(1-R)^2} = \exp(-k(\nu)\cdot L) \tag{5}$$

where $I_{01}, I_{02}, I_{03},\ldots I_{0n}$ are the incident light intensities impinging on the film surface. In the work, the light intensities I_t both on smooth and opaque surfaces are received by an integrating sphere with an input port of 1.25 cm in diameter, and it is positioned 6 cm above the opaque surfaces. It is assumed that all the reflected light beams are transmitted into the integrating sphere and the path lengths of the multiple reflected light beams from the rough opaque surface within the absorbing medium are considered as L, the maximum measurement error of this assumption would be 2.9%.

The film thickness d can be expressed as:

$$d = \cos\alpha\cdot\frac{L}{2} = \cos(\sin^{-1}(\sin\theta\cdot\frac{n_1}{n_2}))\cdot\frac{L}{2} \tag{6}$$

where n_1 and n_2 are the refractive indexes of air and liquid absorption medium, respectively. Based on above-mentioned equations, the film thickness d can be expressed as:

$$d = -\frac{\ln((I_t - R\cdot I_0)/(I_0(1-R)^2))}{2k}\cdot\cos(\sin^{-1}(\sin\theta\cdot\frac{n_1}{n_2})) \tag{7}$$

It should be noted that I_t is stronger than I_s within the measurement range in the work (under 750 μm), especially for thinner film. For example, if the incident angle is 30°, I_s is about 3.9% and 19% of I_t for film thickness at 100 μm and 400 μm, respectively. Therefore, the systematic error introduced by subtracting I_s is not considered here. Fig. 2 shows the film thickness deviation caused by the interference signal I_s at different incident angles. For a 500 μm-thick film, the deviation between the obtained film thickness without eliminating I_s and theoretical film thickness at incident angle 30° is 11.6%, and the average thickness deviation is 11.2% for incident angles range from 5° to 40°. It reveals that the thickness deviation caused by I_s increases with the increasing θ and film thickness. Therefore, I_s must be eliminated to determine the film thickness with the DLAS method, and the incident angle should be chosen as small as possible for practical film thickness measurement. However, due to the limitation on the layout of the experimental setup, 30° was chosen here.