Accurate thin-film measurement method based on a distribution of laser intensity emitted from optical fiber: Proposal of step light emitted model for ray-tracing simulation

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Abstract
The accurate measurement of thin liquid films in various environments is essential for several industrial applications. In this regard, measurement procedures involving the use of optical fibers are preferred because such fibers are resistant to heat and pressure. Herein, we propose a high-accuracy method to measure liquid films with thicknesses of <100 μm (about fiber diameter) on the basis of the variation in the intensity distribution of the laser light emitted from the optical fiber; the thickness is measured by using the light reflected from the air–liquid interface (called the glare light in this study). First, instead of using light with a Gaussian distribution (characteristic of conventional graded-index fibers), we consider a stepped-index-type optical fiber with a step distribution. We model the distribution of the light emitted from the optical fiber and analyze the reflected light, i.e., glare light, via the ray-tracing method. We model three distributions: the Gaussian, point-like, and step distributions, and then we found that the step-distribution-based approach facilitates high-resolution measurements of liquid films with thicknesses less than optical fiber diameter. Moreover, the reflected light intensities for different film thicknesses closely agreed with the experimental results obtained using a stepped-index fiber. Remarkably, the intensity of the reflected light linearly decreases with the increase in the film thickness when using the step distribution. The numerical results quantitatively agreed with experiments; therefore, these results indicate the possibility of numerical calibration for liquid-film measurements with the use of the proposed step distribution model.

Keywords: Multiphase flow, Measurement, Film thickness, Optical fiber, Laser intensity distribution, Ray-tracing

1. Introduction

Thin-liquid-film flows are frequently encountered in various industrial applications such as steam turbines for power generation (Baumann, 1921; Kawagishi et al., 2011), chemical reaction devices such as falling film evaporators (Li et al., 2016), and single-wafer cleaning in semiconductor-device manufacturing (Handa et al., 2020). Moreover, the film thickness is directly related to the safety, efficiency, and yield improvement of these devices. Therefore, the accurate measurement of thin liquid films with thicknesses ranging from several millimeters to the order of sub-micrometers is necessary. One popular approach for measuring liquid-film thickness involved an electrical method based on resistance and impedance measurements (Fukano, 1998); in recent years, visualization (Schubring et al., 2010a, 2010b; Zadrazil et al., 2014), laser (Takamasa and Hazuku, 2000; Hazuku et al., 2008), and ultrasound (Kamei and Serizawa, 1998) methods have also been developed. However, liquid-film measurements for industrial applications are difficult to perform because of the high-temperature and high-pressure conditions involved and/or the necessity of an observation window.

In this context, this research focuses on a liquid-film-thickness measurement method based on the use of laser light from an optical fiber to overcome the abovementioned problems. Regarding previous studies in this direction, Ohba et
al. (1984, 1985, 1989) developed a liquid-film-thickness-measurement method using the light emitted from an optical fiber, which was reflected at the liquid film’s gas–liquid interface; the intensity of the reflected light was used to calculate the film thickness. The temporal resolution for measuring the liquid film is determined by the bandwidth of the photoelectric sensor of sampling rate of voltage recorder that records the light intensity. Further improvements to this approach have enabled measurement of relatively thick liquid films (up to several millimeters thick) and their wave velocities via increasing the number of fibers or expanding the fiber diameter (Oliveira, 2006). However, the measurement resolution decreases as the film thickness reduces because the light emitted from the fiber has a Gaussian distribution as discussed in the present paper; this distribution is characteristic of the widely used optical fiber (the graded index (GI)-type fiber), designed mainly for long-distance communications.

In this study, we focused on the initial position and direction of the rays emitted from the optical fiber, and we attempted to improve the accuracy of measurement of liquid films with thicknesses of <100 μm (about fiber diameter). Using a 3D ray-tracing method, we investigated the intensity of the light reflected from the free surface of different liquid films (hereinafter referred to as glare light) on the basis of the type of distribution of the emitted light. By means of this approach, we succeeded in improving the measurement resolution less than optical fiber diameter. Importantly, we found that a more uniform distribution of laser light is emitted from a stepped index (SI)-type fiber, which is suitable for accurate measurements.

2. Numerical method and conditions

In this study, we modeled the distribution of the light emitted from an optical fiber, and we analyzed the intensity and distribution of the light subsequently reflected from a liquid free-surface of different thicknesses using numerical calculations based on the ray-tracing method (Sakamoto and Saito, 2012a, 2012b). The ray-tracing method is frequently used for rendering computed-generated (CG) images. Given the geometric conditions, the ray-tracing simulation is performed for light reflection and transmission at an interface by using Snell’s law and Fresnel’s equation. The calculation cost is low, and a wide range of liquid films can be analyzed via this method. Although the ray-tracing method approximates light rays by assuming that the substance through which light propagates is homogeneous, and that the magnetic component of the electric field is negligible (as per the Maxwell equations), it is fully applicable to the air–water thin-film flow targeted in this study. Because light is considered herein in the form of rays, it is possible to verify the time history of light emission as the glare light returns to the optical fiber. Therefore, it is possible to estimate the effective emitted-light distribution for liquid-film measurement. On the other hand, because the method approximates light as rays instead of waves, it is not applicable to evaluate interference effects, and it is also impractical to apply the method to sub-micrometer-scale liquid-film measurements.

Fig. 1  Schematic of the principle for liquid-film-thickness measurement based on the light intensity reflected back to the source optical fiber (glare light). The liquid film thickness is estimated by measuring the glare-light intensity. Here, the optical fiber tip slightly protruded from the wall surface to emphasize, but this difference is not necessary for typical measurement.
Figure 1 shows the schematic of the liquid-film measurement principle based on the light emitted from the optical fiber and the light reflected from the gas–liquid interface. The reflected light intensity is correlated to the film thickness. In this study, we modeled the emitted-light distribution and direction and calculated the intensity of the rays returning to the optical fiber. Figure 2 shows the calculation domain for simulating the film measurement. Here, we remark that our study’s unique feature is the construction of three types of light emission models: Gaussian, step, and point-like distribution models. Each model differs in terms of emission position P of the light and its initial direction. In the Gaussian distribution, the ray-emitting positions are given by normal distribution of random numbers obtained by the Box–Muller method. On the other hand, in the case of the step and point-like distributions, these positions are based on general random numbers. In this study, the initial energy assigned to each light ray was assumed to be equal. Therefore, the Gaussian distribution simulates a GI-type optical fiber that emits light with a high energy density near the center, whereas the step distribution simulates an SI-type optical fiber that randomly emits light from the entire core surface. Note that the emitting points of point-like also spread entire the fiber core. Figure 3 shows initial position P for each model, with the number of emitting points set to 1000. As per Fig. 3, we note that with general random numbers, P spreads across the entire top surface of the circular optical fiber core; however, with normal random numbers, it concentrates around the center of the fiber core.
Next, the direction of the light rays, defined by angles $\theta$ and $\phi$, was defined for two cases. The first case employs the distance of emitting point $P(x,y)$ from the center, while the second method employs random numbers. Here, the maximum value of $\theta$ is $\theta_{\text{max}}$, which can be determined from the numerical aperture of the optical fiber. The first case is adopted for the Gaussian and point-like distributions, wherein the vector direction is specified as the change in the angle from the optical axis center: $\theta = 0$ at the center and $\theta = \theta_{\text{max}}$ at the $R_{\text{core}}$ position. In addition, $\phi$ can be expressed as $\tan^{-1}(y/x)$. In the second case, $\theta$ and $\phi$ are random numbers ranging between $0$–$\theta_{\text{max}}$, and $0$–$2\pi$, respectively. It should be noted that the refractive index of the SI-type core is uniform, and the mode of propagating light is diverse so that the random numbers for $\theta$ and $\phi$ are used. Finally, the point-like distribution simulates emission from a point light source. Table 1 summarizes the initial position and direction of ray vectors $r$ for each model.

| Model   | $P(x,y)$                  | $\theta$                    | $\phi$                    |
|---------|---------------------------|-----------------------------|---------------------------|
| Gaussian| Normal random variable    | $\theta_{\text{max}} \times \frac{\sqrt{x^2 + y^2}}{R_{\text{core}}}$ | $\tan^{-1}\frac{y}{x}$   |
| Point-like| Uniform random plots     | $\theta_{\text{max}} \times \frac{\sqrt{x^2 + y^2}}{R_{\text{core}}}$ | $\tan^{-1}\frac{y}{x}$   |
| Step    | Uniform random plots     | Random range [0–$\theta_{\text{max}}$] | Random range [0–2$\pi$]  |

In this study, the calculated number of rays was set to 10,000. The refractive indices were 1.457 for the fiber core, 1.440 for the cladding, 1.3 for the liquid phase, and 1.0 for the gas phase. The numerical aperture of the fiber was set as 0.22, and the diameter ratio of the fiber core to the cladding was set as 1:1.4. A cylindrical calculation space was used; the outer diameter was set to 500 times the fiber core diameter, and the length (height) along the $z$-axis direction was 25 times the maximum liquid-film thickness. The rays beyond the calculation space were excluded from the calculation without being reflected. The rays returning from the liquid film to the fiber-core’s ray-emitting surface were extracted as glare rays. The calculation required approximately 30 s for each calculation condition.

3. Results and discussion

Figure 4 shows the spatial development of the energy distribution of the emitted light for each cross-section ($\varepsilon/R_{\text{core}} = 0, 2, 4, 6, 8, 10$). Here, $\varepsilon$ denotes the energy per cross-sectional unit area of annulus, and the $r$ coordinate is defined as $r = (x^2 + y^2)^{1/2}$. We also note that point light sources cannot practically be realized as light emitted from an optical fiber, but they are used for the ideal-distribution case in this study. In Fig. 4 (a), we note that the Gaussian model affords a normal distribution, wherein the light diffuses with increasing distance away from the fiber core; this result is consistent with the measurement results of Ohba et al. (1984). In Fig. 4 (b), the point-like model affords a uniform distribution, with the light energy decreasing with increasing distance. This difference between the two models is due to the distribution of initial ray positions $P(x,y)$ because the angles $\theta$ and $\phi$ are imposed under the conditions listed in Table 1. From Fig. 4 (c), we note that the step model can be considered as a combination of both the Gaussian and point-source models ((a) and (b)); the distribution gradually shifts from the uniform point-like distribution to the Gaussian distribution with increasing distance. This shift is due to the existence of the rays along the direction of the axis center. This central concentration of energy is due to the imposed condition of randomly defined $\theta$ and $\phi$. 
Next, we investigated the intensity of the glare light (i.e., the light returning to the optical fiber core after reflection) for each model on the basis of the characteristics discussed above. Figure 5 shows the relationship between glare-light intensity $I$ and $L/R_{\text{core}}$, which denotes the liquid-film thickness normalized by the core radius, for each model. For the point-like model shown in Fig. 5 (a), $I$ drastically decreases for $L/R_{\text{core}} < 3$; this result indicates that extremely thin films can be measured using this type of light. In contrast, regarding the Gaussian model in the thin-film case, as shown in Fig. 5 (b), $I$ hardly changes when $L/R_{\text{core}} < 1$. This result indicates a very low resolution for the measurement of the liquid-film thickness. Again, this difference between the two cases is due to the difference in the initial distribution of $P$. Meanwhile, the glare-light $I$ decreases to approximately 0.8 when $L/R_{\text{core}} = 2$ for the step model, the variation is several times that of the Gaussian model, as shown in Fig. 5 (a). This result indicates that a liquid film with a thickness of <100 μm can be measured more accurately by using the step distribution when $R_{\text{core}} = 50$ μm. In addition, from Fig. 5, we note that the $I$ values for the step distribution linearly decrease with respect to the liquid-film thickness up to $L/R_{\text{core}} < 6$, which corresponds to nearly the same range of the central energy concentration region shown in Fig. 4 (c). We speculate here that the step distribution is both point-like (leading to the sudden intensity decrease) and Gaussian (resulting in a nearly constant intensity); this is why the step model exhibits a linear intensity change. More precisely, the random distribution of $P$ and the existence of the rays in the axis-center direction underlie the observed linearity.

Fig. 4 Normalized energy distribution of emitted light from the optical fiber. As $z$ increases, (a) the peak energy of the Gaussian distribution reduces and light diffuses into the surroundings, (b) the point-like distribution retains its shape, and the energy decreases uniformly, whereas (c) the step distribution retains energy around the central region up to $z/R_{\text{core}} = 6$ (see the dashed line on the figure).
Finally, we compared the intensity change obtained using the step model with the experimental results obtained using an SI-type optical fiber (Mizushima, 2019). The liquid-film thickness was measured accurately by combining a camera visualization and a positioning device in oil-water interface. Note that the reflected light measurement is essentially the same as the pre-signal of the bubble measurements performed by Mizushima and Saito (2012). In particular, we compared the numerically obtained data for the linear region. Figure 6 presents the intensity change in the range of $L/R_{\text{core}} < 6$ as an output voltage obtained by fitting to the linear range of the experimental results ($L < 300 \, \mu m$). The 95% confidence interval for the uncertainty of the averaged film-thickness measurements of 4 times is included in the figure. The numerically obtained intensities are fitted to the experimental results to minimize the residue in the linear region. We observe that both data sets show good agreement even outside the linear range (300–1000 $\mu m$). Note that the voltage value at zero-film thickness is impossible to decide only from the experiments. Because the returned light comes from the optical fiber tip by the difference of refractive index between liquid and gas, and this is a different physical phenomenon.

![Figure 5: Variation in glare-light intensity $I$ as a function of film thickness $L$. Here, the three emission distributions, Gaussian, point-like, and step, are compared. The intensity in the step-distribution case decreases linearly with increase in the film thickness, whereas the intensity in the Gaussian case is nearly unchanged near the region of $L/R_{\text{core}} \sim 1$.](image1)

![Figure 6: Comparison between numerically obtained intensity change with the step-distribution model and experimental results (Mizushima, 2019). The proposed step distribution closely reproduces the experimental results.](image2)
In this study, we conducted numerical analyses of the film thickness using three types of light-emission models: Gaussian, point-like, and step distribution, and we confirmed that the sensitivity of the glare light with the step model for the thin-film case is several times that of the Gaussian model. In addition, the step-model results closely reproduce the experimental film-thickness measurement results obtained using an SI-type fiber; the measurement accuracy is improved upon using an SI fiber to measure liquid-film thicknesses of <100 μm when $R_{core} = 50$ μm. Furthermore, we believe that this ray-tracing simulation using the step model can be applied to the SI-fiber measurements of multiphase flows involving liquid films and bubbles.

5. Summary

When a thin liquid film is measured with the use of a GI-type optical fiber, which is generally employed for long-distance optical communication, the measurement resolution deteriorates for thin films of thicknesses <100 μm ($L/R_{core} = 2$) owing to the Gaussian distribution of the emitted light intensity. To improve the measurement accuracy, we proposed the use of SI-type fibers to ensure the uniform distribution of the emitted light, and we compared this step distribution with that of the light emitted from a GI fiber. In particular, we modeled the intensity distribution of the light emitted from the SI fiber, which does not exhibit a normal distribution, and we performed numerical simulations using the ray-tracing method. Our results demonstrated that the measurement resolution significantly improved with our modeled distribution over the Gaussian distribution; furthermore, the results closely agreed with the experimental data. We therefore conclude that SI-type fibers, which are not preferable for long-distance optical communication, are suitable for measuring thin liquid films.

Although calibration experiments are indispensable for general liquid-film measurements, our results suggest that the accurate measurement of thin liquid films of thickness <100 μm ($L/R_{core} = 2$) can be achieved using the ray-tracing model and implemented for actual industrial usage under extreme conditions without the need for calibration. While we considered herein only the horizontal gas–liquid interface in this study, in the future, we plan to investigate interfaces with angles and curvature and wave velocities based on calculations and experiments.

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References

Baumann, K., Some recent developments in large steam turbine practice, Journal of the Institution of Electrical Engineers, Vol.59, No.302 (1921), pp.565–623.
Fukano, T., Measurement of time varying thickness of liquid film flowing with high speed gas flow by a constant electric current method (CECM), Nuclear Engineering and Design, Vol.184, No.2–3 (1998), pp.363–377.
Handa, N., Hiyama, H., Amagai, K. and Yano, A., Experimental and modelling investigation of re-adhesion mechanism of detached nanoparticles to wafer surface in spin rinse process, ECS Journal of Solid State Science and Technology, Vol.9, No.6 (2020), 064001.
Hazuku, T., Takamasa, T. and Matsumoto, Y., Experimental study on axial development of liquid film in vertical upward annular two-phase flow, International Journal of Multiphase Flow, Vol.34, No.2 (2008), pp.111–127.
Kamei, T. and Serizawa, A., Measurement of 2-dimensional local instantaneous liquid film thickness around simulated nuclear fuel rod by ultrasonic transmission technique, Nuclear Engineering and Design, Vol.184, No.2–3 (1998), pp.349–362.
Kawagishi, H., Onoda, A., Shibukawa, N. and Niizeki, Y., Development of moisture loss models in steam turbines, Transactions of the Japan Society of Mechanical Engineers Series B, Vol.77, No.775 (2011), pp.882–893 (in Japanese).
Li, M., Lu, Y., Zhang, S. and Xiao, Y., A numerical study of effects of counter-current gas flow rate on local hydrodynamic characteristics of falling films over horizontal tubes, Desalination, Vol.383 (2016), pp.68–80.
Mizushima, Y., New development of a liquid film thickness measurement using pre-signal of a single tip optical fiber probe, Proceedings of 11th International Symposium on Measurement Techniques for Multiphase Flow (ISMTMF-2019) (2019), Paper No. 19-06-16-066.

Mizushima, Y. and Saito, T., Detection method of a position pierced by a single-tip optical fibre probe in bubble measurement, Measurement Science and Technology, Vol.23, No.8 (2012), 085308.

Ohba, K., Takada, H. and Kawakami, N., Twin fiber optic liquid film sensor for simultaneous measurement of local film thickness and interfacial wave velocity, Japanese Journal of Multiphase Flow, Vol.3, No.1 (1989), pp.50–66 (in Japanese).

Ohba, K., Origuchi, T. and Shimanaka, Y., Multi-fiber optic liquid film sensor, Proceedings of the 4th Sensor Symposium (1984), pp.33–37.

Ohba, K., Origuchi, T. and Takada, H., Multi-fiber optic liquid film sensor II, Proceedings of the 5th Sensor Symposium (1985), pp.63–67.

Oliveira, F. S. D., Yanagihara, J. I. and Pacifico, A. L., Film thickness and wave velocity measurement using reflected laser intensity, Journal of the Brazilian Society of Mechanical Sciences and Engineering, Vol.28, No.1 (2006), pp.30–36.

Sakamoto, A. and Saito, T., Computational analysis of responses of a wedge-shaped-tip optical fiber probe in bubble measurement, Review of Scientific Instruments, Vol.83, No.7 (2012), 075107.

Sakamoto, A. and Saito, T., Robust algorithms for quantifying noisy signals of optical fiber probes employed in industrial-scale practical bubbly flows, International Journal of Multiphase Flow, Vol.41 (2012), pp.77–90.

Schubring, D., Ashwood, A. C., Shedd, T. A. and Hurlburt, E. T., Planar laser-induced fluorescence (PLIF) measurements of liquid film thickness in annular flow. Part I: Methods and data, International Journal of Multiphase Flow, Vol. 36, No.10 (2010), pp.815–824.

Schubring, D., Shedd, T. A. and Hurlburt, E. T., Planar laser-induced fluorescence (PLIF) measurements of liquid film thickness in annular flow. Part II: Analysis and comparison to models, International Journal of Multiphase Flow, Vol.36, No.10 (2010), pp.825–835.

Takamasa, T. and Hazuku, T., Measuring interfacial waves on film flowing down a vertical plate wall in the entry region using laser focus displacement meters, International Journal of Heat and Mass Transfer, Vol.43, No.15 (2000), pp.2807–2819.

Zadrazil, I., Matar, O. K. and Markides, C. N., An experimental characterization of downwards gas–liquid annular flow by laser-induced fluorescence: Flow regimes and film statistics, International Journal of Multiphase Flow, Vol.60 (2014), pp.87–102.