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Combination of laser interferometric and laser extinction methods for precise thickness measurement of liquid film between coalescing twin air bubbles

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ABSTRACT

A combined laser extinction and laser interferometric measurement system was developed for the measurement of the change in thickness of a liquid film formed between colliding twin bubbles. The liquid film thickness during the bubble coalescence process is measured based on the bubble approach velocity and the contact duration. The proposed method affords a ten-fold spatial resolution (~6 μm) of the liquid film thickness distribution compared to the current laser extinction measurement method. Through the use of the proposed method, it was found that the liquid film in the vicinity of its thinnest area immediately before coalescence was wedge-shaped, with the minimum film thickness immediately before coalescence being 0.3–1.3 μm, which is ~0.6-μm thinner than the value determined by the current laser extinction measurement method. Greater precision of the proposed method is enabled by its improved spatial resolution.

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1. Introduction

Although numerous studies have been conducted on thermal-fluid phenomena such as bubbling [1–4], there remain some important outstanding issues such as elucidation of bubble coalescence, which continues to be a major topic of research. It has nevertheless been shown that the approach velocity of coalescing bubbles is a crucial factor in the process [5–7]. Duineveld [6] experimented with pure water and illustrated the boundary of the coalescence/rebound of the bubbles using the Weber number, which considers the approach velocity of the bubbles as the representative velocity. Sanada et al. [8] performed experiments using different types of silicone oil and described the boundary of the bubble coalescence for each Morton number under a fixed Reynolds number and increasing bubble rise velocity. Further, experiments have been conducted on colliding bubbles generated by a nozzle [9–12], with a particular focus on the coalescence transition concentration of the utilized alcoholic aqueous solution or surfactant-containing liquid. In a binary liquid, there is the so-called transition concentration at which a few liquid bubbles coalescence. Therefore, pure bubble coalescence such as that occurs in pure water cannot be treated in the same manner as that in a binary solution. However, only few studies have considered the coalescence of colliding bubbles in a pure liquid, and the mechanism of the process remains insufficiently established. Indeed, there are significant variations among the coalescence conditions that have been presented by different researchers, with the absence of a unified understanding of the phenomena. Furthermore, as described below, elucidation of the rupture of the liquid film between colliding bubbles is essential to a proper understanding of the bubble coalescence phenomenon. However, the nature of the liquid film between bubbles in a pure liquid is currently unclear.

The present authors have previously used the laser extinction method to measure the distribution and time variation of the liquid film thickness formed between horizontally opposed bubbles in pure water and experimentally examined the properties of the liquid film during the coalescence process [13,14]. However, previous works on the rupture of the liquid film only considered conditions under which changes that occurred between the formation of the liquid film and its fracture was slow, such as the condition under which the change in thickness occurs during the suction of

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Nomenclature

A	area [m^2]
I	laser intensity [W/m^2]
I_0	incident laser intensity [W/m^2]
Q	supply air flow rate [μL/s]
s	mean square error [μm]
t	time [ms]
t_c	contact duration [ms]
u_b	bubble approach velocity [m/s]
x	horizontal direction [mm]
y	vertical direction [mm]
β	extinction coefficient [μm^{-1}]
δ	liquid film thickness between bubbles [μm]
λ	wavelength [nm]
ν	kinetic viscosity [m^2/s]
σ	surface tension [N/m]
Suffixes	
b	bubble
e	extinction
min	minimum
R	reference beam

the fluid into the thin liquid film [15], and the condition under which the liquid film ruptures in a binary solution [16–18]. Among them, the measurement of the liquid film thickness is mostly measured in the drainage process of the liquid film stretched in the ring [17–20], and the measurement of the liquid film thickness in the coalescence process of bubbles was measured only by Cain and Lee [16] for binary mixture [21]. The process between bubble contact and coalescence occurs quickly in a pure liquid such as that considered in the present study. Hardly has any attempt been made to measure the thickness of the liquid film between the bubbles during this rapid process. There was a few measurements of the liquid film thickness in the pure liquid system such in the collision process of the bubble to the gas - liquid interface [15], and its liquid film was regarded as uniform thickness. In the use of the laser extinction method for measurement of the thickness [13,14], the local liquid film thickness at the time of coalescence of the air bubbles is measured. However, to obtain the thickness distribution of the entire liquid film at the time of the film rupture and during its change, it is necessary to determine the time variation of the entire liquid film thickness by examining multiple bubbles with good reproducibility. This requires the development of a method for simultaneously measuring the entire liquid film between the bubbles to obtain a more detailed and accurate liquid film thickness distribution at the time of bubble coalescence.

The objective of the present study was to develop a measurement system for simultaneously measuring the entire liquid film thickness between a pair of bubbles by combining the interferometric and laser extinction measurement methods. The proposed method was verified by examining the distribution and time variation of the liquid film thickness during the formation of the film between a pair of bubbles in pure water, employing the said method. The proposed combined measurement method was found to afford improved spatial resolution of the liquid film thickness compared to the current method that utilizes only laser extinction. The proposed method thus enables more accurate determination of the liquid film thickness distribution at the time of rupture of the liquid film.

2. Experiments

2.1. Experimental device

Fig. 1 shows the outline of the complete experimental system, while Fig. 2(a) and (b) show the details of the test section, the optical path of the laser light, and the geometry of the liquid film between the bubbles. The equipment added to those of Morokuma et al. [13] to enable the simultaneous measurement of the entire film are enclosed by the broken-line ellipses in Fig. 1. The added equipment were used for the laser interferometric measurement. The red arrows in Fig. 1 and the red-filled area in Fig. 2(a) indicate the optical path of the infrared He-Ne laser beam (wavelength 3390 nm) used for the laser extinction measurement. The green arrows and green-filled area in Fig. 2(a) and (b) indicate the optical path of the visible Nd:YVO_4 laser (wavelength 532 nm) used for the laser interferometric measurement. As shown in Fig. 2(a) and (b), the infrared laser beam transmits through the liquid film, while the visible laser is reflected by both surfaces of the liquid film.

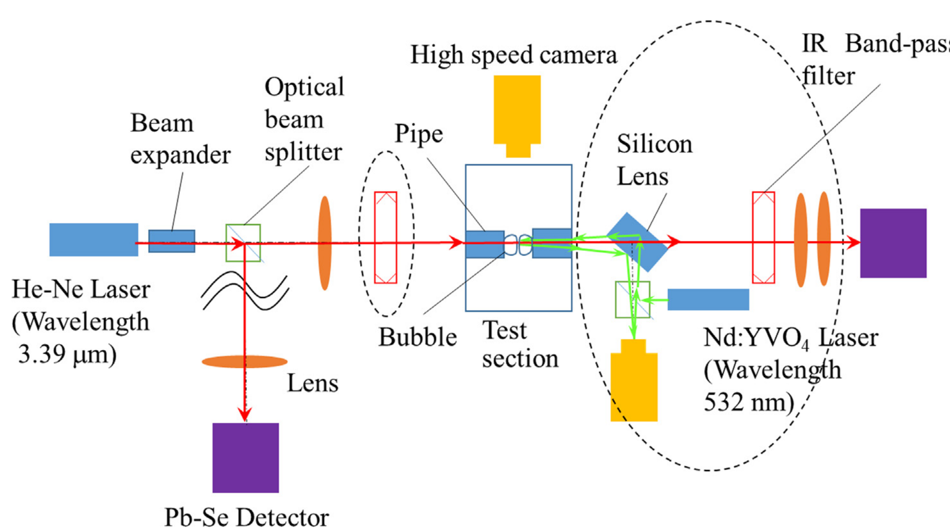

Fig. 1. Experimental system.

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