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Variation of the liquid film thickness distribution between contacting twin air bubbles during the coalescence process in water and ethanol pools

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ABSTRACT

This study aims to investigate the characteristics of coalescence phenomena by precise measurement of the liquid film thickness distribution between approaching bubbles. This study targeted the coalescence of bubbles in pure water and ethanol pools to reveal the rupture characteristics of the liquid film formed between the approaching bubbles, which has a direct correspondence to the occurrence of coalescence phenomena. In this study, new and more precise measurements were performed for water and ethanol, whose physical properties are greatly different from one another. The basic experimental system, in which the approach velocity was easily controlled, was chosen to realize precise measurement of liquid film behaviors. That is, the coalescence of horizontally contacting twin bubbles was experimentally investigated using isothermal air–water and air–ethanol systems. The liquid film thickness formed between the contacting bubbles was measured using an improved laser extinction method. The variation of liquid film thickness between the bubbles at the rupture location and the distribution of the liquid film thickness were evaluated. The experimental parameters were the airflow rate and the measurement position for both water and ethanol. The bubble approach velocity and the contact duration, which is the time from the start of the bubbles' collision to the commencement of coalescence, were measured. When relatively quick bubble coalescence (short contact duration) occurs, the liquid film thickness is thinnest near the film center. The thinnest film thickness appeared just before coalescence and was approximately 1.0–2.5 μm and 0.3–1.0 μm for water and ethanol, respectively. An annular-shaped thinner area in the liquid film emerged and shifted from the center toward the periphery of the liquid film with the increase in the bubble approach velocity and short contact duration. The thinnest liquid film thickness just before the commencement of rupture in the ring-shaped areas was approximately 0.2–0.9 μm and 0.1–0.3 μm for water and ethanol, respectively. Trends of film thickness variation were qualitatively similar to each other for water and ethanol.

1. Introduction

Bubble coalescences broadly occur in gas–liquid two-phase systems, such as in boiling phenomena and bubble flow equipment. Concerning the coalescence phenomena, bubble dynamics have been broadly investigated, but many questions still remain. However, it is important to elucidate the bubble coalescence because it affects the flow and heat transfer behavior near a heating surface, and studies continue to be reported [1–4].

Previous reports state that the bubble approach velocity is an important parameter in coalescence phenomena [5,6], although different researchers have adopted different bubble coalescence conditions. Chesters and Hoffman [5] performed a numerical analysis of the behavior of the liquid film between two approaching bubbles. They constructed a model in which the liquid film ruptures when it becomes very thin, disregarding the viscosity of the liquid. The model predicts the boundary between the bubble coalescence, and the bubbles bounce off each other. Duineveld [6] experimentally investigated the air bubble coalescence in ultrapure water to determine the conditions of the boundary between coalescence and bouncing without coalescence. The boundary has often been expressed in terms of the Weber number in which

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Nomenclature

A	extinction coefficient, m^{-1}
d	internal diameter of the tube, mm
E	detector output, V
h	position of the detector surface, mm
I	laser intensity W/m^2
I_o	incident laser intensity, W/m^2
I_R	reference laser intensity, W/m^2
I_{RO}	reference incident laser intensity, W/m^2
i	incident angle from air to liquid, degrees
L	bubble contact length, mm
L_0	bubble contact length at the occurrence of bubble contact, mm
L_r	bubble contact length at the occurrence of bubble coalescence, mm
Q	supply air flow rate, μL/s
r_t	distance from the liquid film center to the position of the thinnest liquid film, mm
s	mean square error, μm
$s_{\delta R}$	mean square error of the corrected liquid film thickness, μm
t	time, ms
t_c	contact duration, ms
V_b	bubble approach velocity, mm/s
V_b^*	modified bubble approach velocity, mm/s
We	Weber number, dimensionless
X	optical path difference by beam refraction, mm
x	horizontal direction, mm
y	vertical direction, mm
z_p	distance between tube outlets, mm

Greek symbols

α	incident angle from liquid to air, degrees
β	refraction angle from liquid to air, degrees
γ	refraction angle from air to liquid, degrees
δ	liquid film thickness between bubbles, μm
δ_r	rupture liquid film thickness between bubbles, μm
δ_{min}	minimum rupture liquid film thickness between bubbles, μm
θ	tilt angle of liquid film, degrees
θ^*	wedge angle of liquid film, degrees
σ	surface tension, N/m
ν	kinetic viscosity, m^2/s

Subscripts

1	path1
2	path2
E	ethanol
W	water

the bubble approach velocity is used as a representative velocity. Sanada et al. [7] used several types of silicone oils to experimentally investigate the coalescence of rising bubbles that are adjacent to each other. For a high liquid kinematic viscosity, the threshold between bubble coalescence and bouncing increased with a decrease in the Reynolds number of the moving bubble, which indicates the importance of the liquid kinematic viscosity and bubble wake for bubble coalescence.

There have been many previous reports stating that rising bubble behavior is influenced by hydrodynamics. In those cases, bubble coalescence is affected by the ambient flow field, such as the bubble wake flow, where the dynamic behavior of the bubbles is complexly dependent on the experimental conditions. It is difficult to control the bubble approach velocity in such a case due to the unstable behaviors of rising bubbles and interference among bubbles. Therefore, a simple experiment system in which the approach velocity of bubbles is easy to control is desirable for precision measurement of the liquid film thickness between bubbles. Various investigations focused on bubble coalescence have implemented the collision of twin bubbles generated from orifices. These studies employed binary liquid solutions, such as aqueous alcohol solutions [8–10] or surfactant solutions [11], as test liquids and investigated the boundary concentration of occurrence of bubble coalescence for each liquid. However, the bubble coalescence mechanism remains unclear, especially for pure liquids in which the coalescences occur very quickly.

When bubbles approach each other, the behavior of bubble coalescence is affected by various factors, such as bubble size and the liquid properties of viscosity and surface tension. The effects of these factors have previously been investigated [8–11]. Because the bubble coalescence involves the rupture of the liquid film between bubbles and is directly associated with the thickness of the liquid film between bubbles, it is considered that the formation of the liquid film between bubbles and the variation and distribution of the liquid film thickness are the most important parameters related to bubble coalescence phenomena. However, due to the difficulty of measurement, there have been only a few empirical investigations of the thickness of the ruptured film performed in binary solutions, where the coalescence proceeds rather slowly compared to the case of pure liquids [12–14], or of the drainage process of microscopic aqueous films [15]. These studies on liquid films have indicated that the variation of the liquid film thickness monotonically decreases over time. As such, experimental knowledge regarding the behavior of liquid films in the case of bouncing bubbles (reported by Chesters and Hoffman [5] using numerical calculations) remains uncertain. Moreover, the time variation of the thickness distribution of the liquid film between bubbles during the coalescence process of pure liquid, which is widely used in industry, has not been clarified. For example, it was proposed that the threshold between bouncing and coalescence in rising bubbles is $We = 0.18$ [6] for water, which is used often in boiling phenomena. Although the threshold was applied only for rising bubble systems, there were limitations in applying the correlations based on the characteristics of macroscopic bubble motion to the microscale phenomenon such as the liquid film rupture. The direct measurement of the rupture process of the liquid film between the bubbles, which is the origin of coalescence, is important for understanding the coalescence phenomenon. Therefore, liquid film rupture characteristics were examined as a fundamental aspect of the bubble coalescence process by performing precise measurement of the time variation of the liquid film thickness between approaching bubbles by applying the improved laser extinction method.

In this study, the comprehensive measurement accuracy of liquid film thickness is investigated not only by the error analysis of the detailed liquid film thickness measurement for water shown in the previous report [16] but also by considering the irradiation area of the emitted laser beam on the detector acceptance surface. Furthermore, the measurement at a low-airflow-rate region was added to the former report [16] for the sake of investigating under more extensive conditions. In addition, ethanol, having quite different physical properties from water, is added as a test liquid. By measuring the variation of the thickness distribution of the