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Coalescence and conjunction of two in-line bubbles at low Reynolds numbers

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HIGHLIGHTS

- The co-axial coalescence of bubbles at low Reynolds numbers (lower than 2) can be divided into two forms based on whether bubbles undergo a conjunct stage.
- The effects of bubble volume, approaching velocities, liquid viscosity, and adsorption of surfactants on conjunct coalescence were investigated.
- The critical conditions of conjunct coalescence as well as the duration of drainage stage and conjunct stage were determined.

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ABSTRACT

The conjunction and coalescence between two in-line bubbles at low Reynolds numbers were studied. The co-axial coalescence process between the bubbles had two forms: coalescence without conjunction, which could be divided into a contact stage and a drainage stage, and coalescence with conjunction (conjunct coalescence), which had an extra conjunct stage. In the coalescence without conjunction, the velocities of the gas and liquid phases and the change of the liquid film were analyzed by high speed camera and the VOF model. In conjunct coalescence, bubbles became difficult to coalesce and were easy to slide over one another as the liquid viscosity decreased or a surfactant was added, and the coalescence time could be divided into the drainage (film thinning) and the conjunct time (film rupture). The drainage time was directly proportional to the liquid viscosity, while the conjunct time indicated the complicated effects of viscosity and surface tension on this quantity. Accordingly, a model based on the hydrodynamic stability theory was used to predict the conjunct time of conjunct bubbles.

1. Introduction

Bubbly flows are of fundamental importance in many physical, chemical and biological processes as well as a number of natural phenomena. All these processes involve bubble–fluid and bubble–bubble interactions, of which bubble coalescence plays a crucial role in determining the interfacial area and thereby affects the mass and the heat transfer between the two phases. Knowledge of the coalescence of two bubbles can lead to a better description of the bubbly flow behavior and a better design in multiphase systems.

Numerous results have been obtained on the interaction and coalescence of two bubbles rising in a vertical line (Ramírez-Muñoz et al., 2011; Stewart, 1995). It is well accepted that the consecutive coalescence process consists of the following steps: the approach and collision of bubbles, formation and thinning of a liquid film, and rupture of the film at some critical thickness (Almatroushi and Borhan, 2006; Nguyen et al., 2013). The first step is of great importance in capturing trailing bubbles and their subsequent coalescence behavior (de Nevers and Wu, 1971; Hasan and Zakaria, 2011). The wake effect of the leading bubble is found to be a primary factor that leads to bubbles interactions, and is greatly influenced by the liquid viscosity (Katz and Meneveau, 1996; Ruzicka, 2000). Two rising in-line bubbles have been studied in detail at low Reynolds numbers (Brenner, 1972; Rushton and Davies, 1978) as well as high Reynolds numbers (Yuan and Prosperetti, 1994), and some valuable wake-coalescence models and methods to calculate the drag force on the bubbles have been proposed.

The remaining steps of the coalescence process after bubble collision have long been difficult to study because the drainage and rupture of liquid films are complex and instantaneous, so that mechanisms are derived by simplifying the coalescence model. Ideal mathematic models were developed for the dynamics of a drainage film in which the interfacial mobility was recognized (Chesters and Hofman, 1982; Li and Liu, 1996). The interaction and

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coalescence between a bubble and a free surface, which can be treated as a bubble of infinite volume, were probed both experimentally and numerically (Ghosh, 2004; Mu1ller et al., 2007; Sanada et al., 2005), and the effects of bubble size and impact velocity were studied. Dynamic analyses of the liquid film during the coalescence of deformable bubbles were carried out (Chan et al., 2011; Derjaguin and Kussakov, 1992; Doubliez, 1991).

Studies on the coalescence of bubbles show that the coalescence time is not a constant value, but a distribution effected by multiple factors, even under fixed experimental conditions. Two film thinning mechanisms as well as a film rupture mechanism based on the hydrodynamic stability theory were discussed by Lee et al. (1987). The stability of foam films was analyzed in the model of Duerr-Auster et al. involving a binary coalescence cell (Duerr-Auster et al., 2009). The adsorption of surfactants at air–water interfaces is also a common case in the coalescence of bubbles. It is well known that the presence of a surfactant at an interface exerts repulsive forces and stabilizes bubbles against coalescence (Kumar and Ghosh, 2006). A stochastic model was developed to describe the coalescence time distributions in the presence of surfactants (Giribabu and Ghosh, 2007).

Over the past decades, computational fluid dynamics (CFD) has become a powerful tool for the description of multiphase flow. Various multiphase models, such as the VOF model (Li et al., 1998; Wei et al., 2013), the front-tracking (FT) method(Pan and Chen, 2014; van Sint Annaland et al., 2006), the level set method (Chakraborty et al., 2013; Lakdawala et al., 2014), and the lattice Boltzmann method (Cheng et al., 2010; Yang et al., 2000), have been developed to simulate bubble interactions. A common feature of CFD methods is that bubble motion is simulated by solving the Navier–Stokes equations that are coupled with an interface tracking or capturing method. The VOF model has been frequently used in modeling the formation, coalescence, and breakup of fluid particles. Although it has disadvantages such as too much dependence on mesh size, the VOF model is relatively simple and accurate, and good for substantial topology changes on the interface. The dynamics of the coalescence of two co-axial bubbles with different diameters in various liquid phases have been studied by the VOF model (Hasan and Zakaria, 2011; Liu et al., 2014; Watanabe and Sanada, 2006).

However, the mechanism of bubble coalescence is extremely complex and a full understanding has not been reached yet. Most studies focus on the mechanisms that cause bubbles to approach each other due to viscous wake interactions, but not on the fine details of collision and/or coalescence of two freely rising bubbles.

We previously found that a conjunct bubble with regular shape may form after two bubbles collide with each other at low Reynolds numbers (Cai et al., 2012), and this type of quasi-steady conjunct bubble is commonly encountered in highly viscous liquid systems (Manga and Stone, 1993, 1994). The conjunct bubbles rise with a steady velocity, and the shape of both the bubbles and the liquid film are axis-symmetric until the film ruptures suddenly and coalescence occurs. There is little information available in literature on the conjunct bubble behavior and how it influences the coalescence of bubbles. In coalescence with conjunction (conjunct coalescence), there is sufficient time for bubble interaction before the coalescence, and the duration of conjunction ranges from 10 ms to several seconds, which is rarely observed in low-viscosity liquids (Kirkpatrick and Lockett, 1974). Studies on conjunct coalescence can contribute to further understanding of the bubble coalescence mechanism.

In the present work, the coalescence between in-line bubbles was divided into coalescence without conjunction and conjunct coalescence. The shapes and velocities of the bubbles during the whole coalescence process were determined by a high speed camera, while the flow field as well as the thickness of liquid film between bubbles was obtained by numerical simulations. The Reynolds numbers of the bubbles were lower than 2, while most previous investigators focused on the interaction of bubbles with Reynolds numbers higher than 10. The conjunct coalescence of two bubbles was studied systematically for the first time, including the effects of bubble volume, approaching velocities, liquid viscosity, and addition of nonionic surfactant. In addition, the critical conditions for bubble coalescence as well as the timescales of the different stages of conjunct coalescence were determined.

2. Materials and methods

2.1. Experimental apparatus and materials

Similar to the experimental apparatus used by Cai et al. (2012, 2010), a plexiglass column with inner dimensions 250 mm $\times$ 250 mm $\times$ 600 mm was utilized, in which glycerin and its aqueous solutions were used as the continuous phase. The liquid viscosity was changed by accurately controlling the weight concentration of glycerin and the ambient temperature. The surface tension coefficient was changed by adding nonionic surfactant coconut diethanol amide (CDEA), which is dissolved in glycerin after being stirred for four hours at 358 K. The absolute viscosity of continuous phase was measured by a Rheostress RS150 (HAAKE, Germany), while the surface tension was measured by an automatic tension apparatus (JYW-200B, Kecheng Testing Machine, China). More than two hundred pairs of bubbles were tested in each liquid. The solution properties are listed in Table 1.

Air bubbles were injected into the liquid at the base of the column by a syringe pump system (TS-1B, Longer Pump, China) for the accurate control of bubble volume. This experiment focused on pairs of in-line bubbles with equivalent diameters of 6.5–9.5 mm for the leading bubble and 7.0–10 mm for the trailing bubble, and the Reynolds numbers of most bubbles are less than 1. The behavior of the interacting bubbles was recorded by a 1024 $\times$ 1024 pixel high speed CMOS camera (FASTCAM-ultima APX, Photron, Japan) equipped with a Nikkor Micro 60 mm F2.8D lens at 1000 fps (shutter speed 0.5 ms).

2.2. Image analysis

Fig. 1 shows the formation and coalescence moment of the conjunct bubble recorded by the high speed camera. The gray level of the images changed when back light passed through the gas–liquid interface because of reflection and refraction, and it could help distinguish the edges of the bubbles and the liquid film. A very thin arch-shaped gray curve, which represents the position of the liquid film, is trapped inside of the conjunct bubble in Fig. 1a, but the film ruptures and this gray curve disappears at the coalescence moment in Fig. 1b. Algorithms of Canny edge detector (Zuo et al., 2004) were

Table 1
Properties of solutions.

	S1	S2	S3	S4	S5	S6
Glycerin mass fraction	1	1	1	0.95	1	1
Density, kg/m^3	1267	1265	1264	1254.8	1264	1264
Temperature, K	288 ($\pm$0.2)	294.5 ($\pm$0.5)	298.5 ($\pm$0.4)	299.5 ($\pm$0.5)	294.9 ($\pm$0.4)	295.1 ($\pm$0.3)
Viscosity, Pa s	2.306	1.248	0.867	0.58	1.229	1.185
Surface Tension, mN/m	70.5	68.8	68	67.5	61	48
Morton Number (Mo)	661.83	56.242	14.454	1.69	70.83	206.46
Re for single bubble	0.170–0.302	0.424–0.848	0.631–1.272	1.135–1.997	0.461–0.796	0.435–0.808