A model of bubble coalescence in the presence of a nonionic surfactant

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Highlights

- Developed bubble coalescence model quantifies the effect of surfactants.
- Negative Marangoni stress slows film drainage and increases bubble coalescence time.
- Coalescence time positively correlates with Marangoni stress throughout the concentration range.
- In high concentrations, mass transport dampens Marangoni stress, shortening coalescence time.

1. Introduction

Bubble coalescence, critical in industries like fermentation and water purification, impacts transport in multiphase flows. Surfactants change hydrodynamics, significantly affecting bubble coalescence times, yet studies on their influence are scarce. Developing models that incorporate surfactant-induced Marangoni stress is essential for a deeper understanding of coalescence dynamics. This study presents a model with nonionic surfactant on bubble coalescence, showing a correlation between Marangoni stress and coalescence time. It underscores the damping effect of the mass transport in reducing Marangoni stress and bubble coalescence time at high concentrations [1].

2. Methods

2.1 Experimental methods

Fig. 1(a) shows the setup for binary bubble coalescence experiments using steel tubes in a plexiglass tank to generate 2mm radius bubbles. The process of a typical experiment is shown in Fig. 1(b), where the history of binary bubble coalescence is displayed.

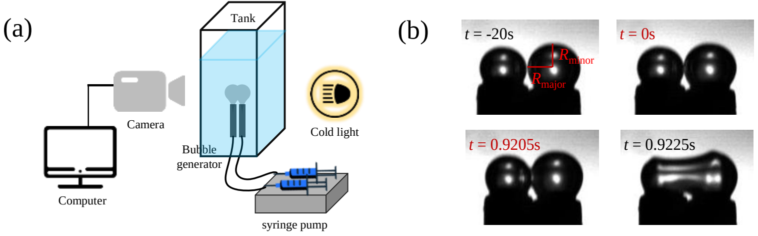

Figure 1. Experimental equipment and results: (a) experimental apparatus for studying binary bubble coalescence; (b) time sequence of a typical experiment.

2.1 Modeling method

N-S equations of the liquid film are simplified to the lubrication theory. From the mass balance in the liquid film, we obtain the thinning rate equation:

$$u_r = U + \frac{1}{2\mu_\mathrm{c}}\left(z^2 - \left(\frac{h}{2}\right)^2\right)\frac{\partial p}{\partial r},\ \ \frac{\partial h}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(rUh) + \frac{1}{12\mu_c r}\frac{\partial}{\partial r}\left(rh^3\frac{\partial p}{\partial r}\right) \tag{1}$$

Film drainage disturbs the interfacial adsorption equilibrium and induces Marangoni stress τ_M:

$$\tau_\mathrm{b} = \tau_\mathrm{f} + \tau_\mathrm{M} = -\frac{h}{2}\frac{\partial p}{\partial r} + \frac{\partial \sigma}{\partial r} \tag{2}$$

Surface concentration Γ follows the convective-diffusion equation, with mass transport flux j_s between film and interface per Fick's law:

$$\frac{\partial \Gamma}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma U - D_\mathrm{s} r\frac{\partial \Gamma}{\partial r}\right) = j_\mathrm{s},\ \ j_\mathrm{s} = -D_L\left(\frac{\partial C}{\partial z} - \frac{\partial h}{\partial r}\frac{\partial C}{\partial r}\right)\Bigg|_{z=\pm h/2} \tag{3}$$

3. Results and discussion

We explore the film drainage process and Marangoni effect (Fig. 2). Film drainage increases bubble interaction, changing film curvature and slowing thinning rate. Early drainage "blows out" surfactants from the film center, creating a negative Marangoni stress [2]. The shear stress balance (Fig. 2(c)) indicates that Marangoni stress significantly offsets fluid shear stress, substantially reducing the film drainage.

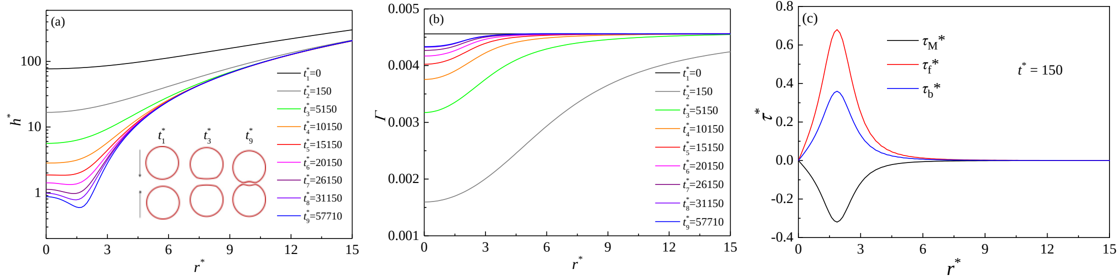

Figure 2. Numerical results of MIBC-water (x = 1.22×10^{-6}): (a) film thickness and bubble shape evolution; (b) surface concentration changes; (c) shear stress balance at t^*=31150.

Fig. 3 shows calculated results align with experimental data. Coalescence time in dilute MIBC-water rises with concentration, while the coalescence time in ethanol-water increases rapidly at low concentrations but drops gradually at high concentrations.

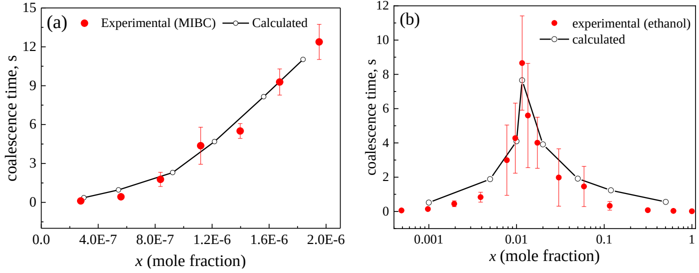

Figure 3. Comparison of calculated coalescence time with experimental data: (a) MIBC-water system; (b) ethanol-water system.

Fig. 4(a) illustrates opposing trends in r direction between surface concentration distribution and mass transport, indicating mass transfer reduces surface concentration perturbations, dampening the Marangoni effect. As Fig. 4(b) shows, mass transport flux grows with bulk concentration, significantly damping Marangoni stress in high concentrations and coalescence time.

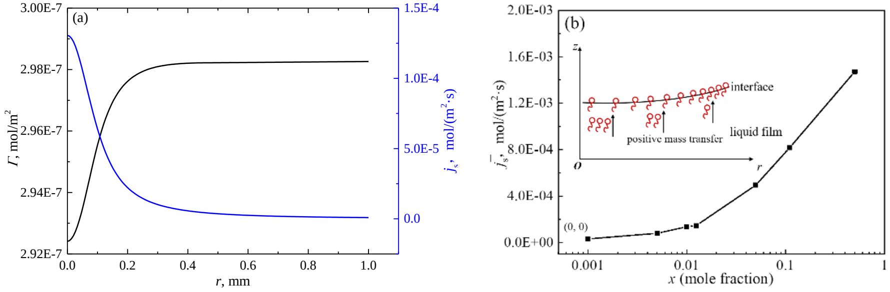

Figure 4. (a) Distribution of the surface concentration and mass transport fluxes between the interface and liquid film calculated at x = 0.001, t = 0.080s; (b) Variation of the $\bar{j}_s$ with bulk concentration of ethanol-water system (Illustration is a schematic diagram of damping effect).

4. Conclusions

A model quantifying surfactant effect on bubble coalescence was developed and validated with MIBC-water and ethanol-water solutions. It revealed that negative Marangoni stress, induced by surface tension gradient, slows the film drainage, thereby extending coalescence time. Coalescence time positively correlated with Marangoni stress, increasing with bulk concentration in dilute ranges but decreasing in high concentrations. This trend suggests mass transport acts as a "damper" especially pronounced at higher concentrations, reducing Marangoni stress and coalescence time. The study clarifies the mechanism behind the reduction of coalescence time at high surfactant concentrations.

References

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Keywords

Bubble coalescence; Marangoni stress; Nonionic surfactants; Numerical calculation