

Instability of a Planar Liquid Sheet Formed with Surfactant Aqueous Solution

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Abstract

In this study, we clarified the growth characteristics of the instability waves of a planar liquid sheet formed with a surfactant solution. It has been widely reported that a liquid sheet jet oscillates in a sinuous shape because of Kelvin–Helmholtz instability, and that the growth rate of the instability wave depends on the surface tension. In addition, a surfactant solution has time-dependent surface tension, which is referred to as “dynamic surface tension,” because the adsorption of surfactant molecules into a newly formed surface requires a certain time. For this reason, the surface tension on a new surface decreases from the surface tension of a solvent to the equilibrium surface tension of the solution for a specific relaxation time. This suggests that the surface tension of the liquid sheet formed with the surfactant solution decreases downstream. In this study, wave growth as affected by dynamic surface tension was clarified using the planar liquid sheet. The planar liquid sheet was ejected from a slit nozzle with a 0.5-mm gap and 150-mm width at a velocity of 8 m/s, and an artificial perturbation of 250 Hz was introduced at the nozzle to induce precise periodical instability waves. Polyoxyethylene-(10)octylphenyl ether was selected as a surfactant. Fluorescence dye was dissolved in the surfactant solution, and the cross section of the wavy liquid sheet was visualized with a laser sheet to measure the amplitudes of the waves. This study consists of four stages. First, the dependency of the spatial growth rate of the wave on surface tension was determined experimentally using ethanol aqueous solutions, which have a time-invariant surface tension. The measured growth rates of the ethanol solutions at different concentrations indicated that the growth rate decreases linearly with an increase in surface tension. Second, the dynamic surface tensions of the surfactant solutions were measured at concentrations of 250, 1500 and 5000 ppm, and the locally varied surface tension of the liquid sheet was estimated. The relaxation times t_r of the dynamic surface tensions at 250, 1500 and 5000 ppm were 99, 9.6 and 0.13 ms, respectively. Because the liquid sheet produced at the nozzle required time $t_f = 5$ –15 ms to reach the measurement zone of the wave amplitude, the magnitude relations between t_r and t_f at 250, 1500 and 5000 ppm were $t_r \gg t_f$, $t_r \approx t_f$ and $t_r \ll t_f$, respectively. Third, the wave amplitudes of the surfactant solutions were predicted using the results of these two steps. The dependency of the spatial growth rate on surface tension and the measured dynamic surface tension gave a spatially varied growth rate. The wave amplitude was calculated from the integration of the growth rate. Finally, the calculated wave amplitude was compared with the measured amplitude of the surfactant solution. The good agreement between the calculated amplitude and the experimental one proved that the growth characteristic of a surfactant solution depends on dynamic surface tension. In addition, the measured amplitudes at 250 and 5000 ppm were almost the same as the amplitudes that were calculated under the assumption of a constant equilibrium surface tension of the solvent and solution, respectively, because these solutions have a short/long relaxation time t_r in comparison with time $t_f = 5$ –15 ms required for the flow.

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