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主 論 文 の 要 旨

論文題目 Numerical study of the liquid ligament formation from a liquid layer by Faraday instability and Rayleigh-Taylor instability (ファラデー不安定性とレイリー・テイラー不安定性による液層からの液糸の形成に関する数値研究)

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論 文 内 容 の 要 旨

In this dissertation, we numerically investigated the large surface deformation from a liquid layer due to the interfacial instabilities caused by the time-dependent and constant inertial forces, which are usually referred to as "Faraday instability" and "Rayleigh-Taylor (RT) instability", respectively. These instabilities can form a liquid ligament (a large liquid surface deformation that results in disintegrated droplets having outward velocities), which is important for atomization because it is the transition phase to generate droplets. The objectives of this dissertation are to reveal the physics underlying the ligament formation due to the Faraday instability and the RT instability.

Previous investigations explained the mechanism of ligament formation due to the Faraday instability by only using the term "inertia" without detailed elucidation, which does not provide sufficient information on the physics underlying the ligament formation. Based on the numerical solutions of two-dimensional (2D) incompressible Euler equations for a prototype Faraday instability flow, we explored physically how each liquid ligament can be developed to be dynamically free from the motion of bottom substrate. According to the linear theory, the amplified crest, which results from the suction of liquid from the trough portion to the crest portion, is always pulled back to the liquid layer no matter how largely the surface deformation can be developed, and the dynamically freed ligament is never formed. Situation is changed when the nonlinear effect is considered. The impingement of the liquid flow from the trough portions arouses pressure enhancement at the high crest (ligament) root. This pressure enhancement has two major effects. The first one is lowering the capability of sucking liquid from the trough portion, which abates the increase of crest height compared to the linear theory. The second one is causing a local maximum pressure location at the crest root. Thus, the ligament above this location becomes dynamically free from the motion of bottom substrate in the laboratory reference frame. The liquid elements passing through the maximum pressure location elongate the dynamically freed liquid region and cause a slender ligament from the liquid layer.

For industrial application of Faraday instability, the threshold condition for the spray formation is of the main concern. Previous experimental studies on the ultrasonic atomization have shown that, when spray forms, there exists a predominant surface wave mode from which the drops of the mean diameter following Lang's equation are generated. In this dissertation, we determined this predominant surface wave mode physically and studied the threshold condition for spray formation based on a cell model of the predominant surface wavelength that excludes the effects of the container walls. We defined the condition in which the broken drop holds a null area-averaged vertical velocity in the laboratory reference frame as the criterion for spray formation. The calculation results indicated that spray formation onsets in the sub-harmonic instability region, at a critical dimensionless forcing strength value $\beta_c \sim O(1)$, which is two orders larger than the previous experimental determined threshold condition for the rare drop ejection event. Spray formation due to the Faraday instability can be considered as a process that the liquid layer absorbs energy from the inertial force, and releases it by producing drops leaving the liquid layer. In this study, we demonstrated that for a deep liquid layer, the threshold condition for spray formation is determined only by the forcing strength, and does not depend on the initial liquid layer condition used in the calculations.

The RT instability can be deemed as a limit case of the Faraday instability under the condition that the forcing frequency approaches zero and the forcing displacement approaches infinity. In this case, the constant descent velocity of the trough surface leads to a steady liquid atomization rate. Analytical results revealed two key mechanisms underlying the steadiness: (1) the bulk liquid layer was dynamically freed from the long liquid ligament by the formation of a maximum pressure point at the ligament root, and (2) the inertial force was only effective at the ligament root region to drive outward the liquid concentrating from the trough portion. Analytical expressions were derived for characteristic surface deformation quantities. The velocity and width of the liquid entering the freed liquid ligament at the maximum pressure location mirrored those associated with a vertical jet emanating downwards from an orifice injector under gravity. Thus, the results from laboratory low-speed jet emanation experiments were useful to predict the disintegration behavior of a liquid ligament formed by an RT instability.