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Droplet bounce simulations and air pressure effects on the deformation of pre-impact droplets, using a boundary element method

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Abstract

An inviscid axisymmetric model capable of predicting both droplet bounce and the detailed pre-impact motion that is influenced by ambient pressure has been developed using a boundary element method (BEM). Previous simulations could not accurately describe the effect of the gas compressed between a falling droplet and the impacting substrate because most droplet impact simulations assumed that the droplet was already in contact with the impacting substrate at the beginning of the simulation. To properly account for the surrounding gas, the simulation must begin when the droplet is released from a certain height. High pressures are computed in the gas phase in the region between the droplet and the impact surface at instances just prior to impact. This simulation shows that the droplet retains its spherical shape when the surface tension energy is dominant over the dissipative energy. When the Weber number is increased, the droplet's surface structure is highly deformed due to the presence of capillary waves and, consequently, a pyramidal surface structure is formed. This phenomenon was verified experimentally. Parametric studies using our model include the pre-impact behavior that varies as a function of the Weber number and the surrounding gas pressure.

Keywords: Droplet impact; Compressed gas; Splashing; Two-phase flow; Bouncing droplet

1. Introduction

Droplet impact phenomena are readily encountered in raindrop impact and in numerous industrial applications such as inkjet printing, painting, spray-wall impact within IC-engines, and fire suppression sprays. As shown in classical experiments [1,2], a droplet will stick to the impacting substrate when the droplet surface tension energy is not high enough to overcome the droplet's dissipative energy [3]. Upon sticking, the droplet spreads radially and forms a toroidal ring when it has a relatively low Weber number. At an intermediate Weber number, an azimuthal instability develops and forms "fingers" at the rim of the spreading ring. If the Weber number is increased, the droplet "splashes" upon contact with the substrate and the fingers shed additional individual drops.

There are two schools of thought as to the reason of the fundamental instability of the splashing and the subsequent finger formation: one theory is based on the Rayleigh–Taylor-type buoyancy driven instability and the other presumes a Kelvin–Helmholtz-type shear layer driven instability [4]. The debate about which instability is the primary source for causing the splashing and the finger formation is a subject that needs further scrutiny.

The debate on whether or not liquid viscosity plays an important role for the formation of fingers is another idea that further complicates this subject. Impacting substrate conditions such as porosity, roughness, and temperature are also known to play a prominent role during droplet impact. All of the aforementioned studies of a single droplet impact have been used as the basis for the polydisperse spray simulation. Sivakumar and Tropea [5],

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however, concluded that using the results from a single droplet should not be extended to the model for the spray simulation because of the interaction between multiple droplets. In other words, the results from a single droplet could not be linearly extrapolated to accurately explain what happens within a spray that is comprised of many droplets.

While one may be astounded and puzzled by the magnitude and complexity of liquid impact physics, one thing is clear: the effect of gas pressure on splashing is conspicuously manifested when the gas pressure is varied from 100 to 17 kPa as shown in Fig. 1 of Xu et al.'s experiment [6] and in the induced vortex rollup motion of gas due to a falling droplet as shown in Fig. 2 of our experiment. We attempt to address this gas pressure effect on the pre-impact condition of a falling droplet using the BEM. The boundary element technique is ideal for this type of problem due to the established accuracy of the methodology for highly deformed free-surface problems.

As mentioned earlier, there are numerous parameters, such as liquid viscosity, surface roughness, porosity and temperature, which can substantially change the spreading behavior of a droplet after impact. The objective of this study is to assess contributions of air to the pre-impact deformation process using BEM. It is noted that the current model is not capable of simulating the actual splashing that occurs after impact. We also note that the Kelvin–Helmholtz shear layer driven instability plays a major role in causing the initial disturbance, which we believe is capable of causing the splashing and the subsequent finger formation at the spreading edge. Allen [7] claimed that the accelerating light air against the decelerating heavy liquid of a ''spreading'' droplet poses the unstable interface of the Rayleigh–Taylor instability. Allen [7] did not consider that the case of a ''falling'' droplet was not only subject to the Rayleigh–Taylor instability, but also to the Kelvin–Helmholtz instability. The inviscid assumption applied in the BEM approach should be valid since the Kelvin–Helmholtz/Rayleigh–Taylor debate over the dominant instability mechanism in causing splash are both based on the inviscid assumption at an infinitesimally small length scale: $\lambda \to 0$.

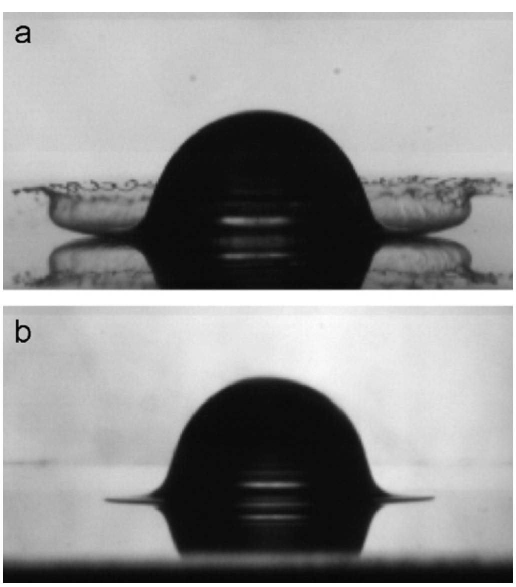

Fig. 1. Xu et al.'s [6] experiment. When the gas pressure is reduced, splashing is prevented. Reprinted under the permission of Prof. Nagel of University of Chicago.

Furthermore, the current modeling effort is unique in that the droplet falls from a certain distance above the impacting wall. Other similar numerical efforts [8–15] begin their simulation at the time when the impacting droplet comes in contact with the wall and thus, the compressed air effect due to the falling droplet could not be resolved. Certainly, the gas effect on the droplet's initial disturbance and subsequent splashing and fingering is a new phenomenon that was recently discovered by Nagel's group. To the authors' knowledge, there has been no relevant numerical modeling effort found in literature; therefore, our current modeling results are merited.

To validate the modeling results, we considered the ''non-splashing'' case of a spreading droplet. The maximum spreading radius data will be quantitatively compared to the existing experimental data of Mao et al. [16] and with the correlation proposed by Aziz and Chandra [3]. The shapes of the rebounding droplet were then quantitatively compared to the photographic images of the experiments. After the validation studies, the deformed shape and induced slip velocities of a liquid droplet were presented at various atmospheric pressures.

2. Modeling

2.1. Two-phase flow modeling

Heister [17] provides a complete description of the basic modeling elements involved with a BEM application to

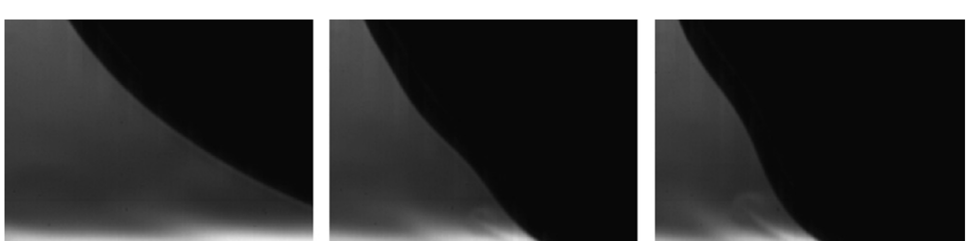

Fig. 2. Development of the vortex rollup motion while gas being compressed due to a falling drop. Photographs are from our ongoing experiment.