Development of Fundamental Technologies for Charged Droplet Impact Analysis

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Introduction

Droplet impact is central to processes ranging from high-precision inkjet printing to functional coatings. A persistent challenge is air-bubble entrainment at impact: as a droplet nears a substrate, a thin gas film cushions the approach and forms a dimple; subsequent asymmetric rupture or annular contact can trap bubbles beneath the spreading film. Even sub-micron bubbles disrupt thickness uniformity, causing visible defects and degrading thermal and electrical performance.

Two principal mitigation strategies have been advanced: (i) lowering ambient pressure to weaken air cushioning, and (ii) modifying interfacial stresses by electrically charging the droplet and/or the substrate. While a partial vacuum can be effective, implementing low pressure over large process areas is often impractical and costly. By contrast, droplet charging integrates with high-throughput operations. Electrostatic forces at impact shift the balance among inertial, capillary, viscous, and gas-lubrication effects, thereby influencing the onset of bubble capture without complex enclosures.

The first author's group has experimentally established that the droplet charge correlates with both the characteristic bubble size and the areal number density captured at impact. However, experiments alone are limited: sub-micron gas films evolving over micro- to millisecond timescales hinder direct, artefact-free observation. These constraints motivate a complementary, physics-based model that resolves the coupled liquid–gas–electric interactions governing entrainment.

Numerical method

Accurate prediction of the spreading diameter requires not only global momentum conservation but also "consistency" of the discrete advection operator in the momentum equation—i.e., advection must not spuriously transfer momentum between phases. To this end, we employ the Consistent Mass–Momentum Transport (CMOM) method of Zuzio et al.[1]. Anticipating GPU deployment, we also adopt the evolving pressure-projection method of Yang and Aoki[2], enabling a fully explicit time-integration scheme.

We solve the weakly compressible, isothermal Navier–Stokes equations:

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t}+\boldsymbol{u}\cdot\nabla\boldsymbol{u}\right)=\nabla p+\nabla\cdot\left(\mu(\nabla\boldsymbol{u}+\nabla\boldsymbol{u}^{T})\right)+\boldsymbol{F}, \tag{1}$$

$$\frac{\partial p}{\partial t}+\rho c_s^2\nabla\cdot\boldsymbol{u}=0, \tag{2}$$

where, $\boldsymbol{u}$ is velocity, t is time, ρ is density, p is pressure, μ is viscosity, and $\boldsymbol{F}$ represents body force. The parameter c_s is an artificial speed of sound chosen to satisfy the low-Mach constraint $Ma = |\boldsymbol{u}|_{\max}/C_s \ll 1$.

In future work, we will integrate the classical Taylor–Melcher leaky-dielectric model into this framework and perform numerical simulations of charged-droplet impacts onto substrates.

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References

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