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Lattice Boltzmann simulations of particle-laden liquid bridges: Effects of volume fraction and wettability

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ABSTRACT

The influence of particles on the dynamics and eventual rupture of stretching liquid bridges is demonstrated experimentally in a drop-forming case. To analyze the particle-scale basis for the influence of particles in this flow, a lattice Boltzmann algorithm for a three-phase system of liquid, gas, and solid particles, has been developed. This provides full coupling between particles and fluids, fluid interfacial forces, and possible entry of particles into the interface (i.e. full and partial wetting by the liquid are considered). This work details the numerical method and its validation, and presents results of the simulations and related experiments. Fully-wetting particles up to a solid volume fraction of $\phi = 0.3$ monotonically increased the rupture length of liquid bridges, as seen in experiments; experimental results show that the increase continues to a maximum at $\phi \approx 0.4$, a condition beyond the present numerical capability. Depending on the wettability and volume fraction of the particles in the liquid bridge, particles can alter the structure of the bridge at pinch-off, suppress satellite drops, or produce asymmetrical pendant/sessile suspension drops as a result of their discrete nature. Particles with a neutrally wetting contact angle ($\theta = 90^\circ$) can reside in the bulk or be immersed in the interface if fluid deformation brings them into contact with it, and capillary forces are found to bring the interfacial particles near the narrow region (or "throat") of the bridge prior to rupture. Fully wetting particles ($\theta \approx 0^\circ$) remained interior to the liquid bridge, leaving less space to escape the throat region. Neutrally wetting particles increased the rupture length and altered the pinch-off structure relative to the particle-free case, but less so than fully wetting particles.

Introduction

Solid particles suspended in a fluid alter the behavior of many physical flow situations relative to the particle-free case. The particles resist deformation in bulk fluid regions, leading to *effective* suspension properties distinct from the properties of the interstitial fluid (Guazzelli and Morris, 2012). Suspension flows that involve a free surface can also exhibit capillary forces due to particles which cause deformation of, or become embedded in, the interface. The wetting properties of the particles and the local deformation of the interface can result in surface tension forces that transport particles along the interface (Kralchevsky and Nagayama, 2000). The stretching and rupture of a liquid column containing particles exhibits these complications. This is a complex situation, but one that has increasingly important applications in jet stability and drop formation which arise in the printing of particle-laden ceramics, textiles, electronics, and inks (Zhao et al., 2002; Daplyn and Lin, 2003; Ko et al., 2007; Wang et al., 2012) as well as biological cells (Yusof et al., 2011). In this work, we focus on the well-controlled case of stretching a particle-laden liquid bridge.

There has been extensive effort devoted to understanding the physics related to the rupture of a particle-free liquid bridge, as summarized by Eggers (1997). A liquid bridge is stretched in one of two typical situations. When a drop is extruded from a nozzle, gravity forces overcome the surface tension forces adhering the bulk of the drop to the nozzle. As the drop falls away, a thin filament connects the bulk of the drop to the liquid still being extruded from the nozzle. The other mode of stretching occurs when a volume of fluid simultaneously wets two solid objects that are pulled apart. In either case, the bridge of liquid thins, or necks, and finally ruptures.

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The rupture process of a Newtonian liquid is governed by a competition between surface tension, viscosity, and inertia. In general, the filament contraction is driven by surface tension, and is retarded by viscosity. Surface tension causes perturbations of a liquid cylinder to be unstable, thus initiating an exponential thinning process. Sufficiently close to rupture, the necking behavior of liquid bridges exhibits a universal self-similar character regardless of the mode of stretching. The minimum neck radius, R_m of the liquid bridge scales as $R_m \sim \tau^\alpha$, where $\tau = t_{breakup} - t > 0$ where $t_{breakup}$ is the moment in time t when breakup, or rupture, occurs. The exponent α corresponds to different regimes. For inertia-dominated flows (the inviscid regime), $\alpha = 2/3$ (Eggers, 1997), and for viscosity-dominated flows, $\alpha = 1$ (Papageorgiou, 1995). There is a critically small thickness of the thread where both viscosity and inertia take on similar importance (Eggers, 1997). Viscosity becomes more important for inertia-dominated flows as the dimensions of the thread become small. Capillary pressure forces related to inertia also take on added significance for viscous-dominated flows because of the large curvature associated with the thin thread. Any bridge will sample this regime just prior to rupture, where $\alpha = 1$, which is the same as the viscous dominated-regime, but with a different constant of proportionality.

There has been little work, in comparison, analyzing stretching liquid bridges with particles. Furbank and Morris (2004, 2007) performed experiments in which neutrally-buoyant (density-matched) particle-laden liquids were extruded from a nozzle, at a range of particle volume fractions, $0 < \phi \leq 0.4$. They demonstrated that the addition of noncolloidal particles at large concentrations in this drop-forming process slowed the neck thinning far from rupture, as expected from increase of effective viscosity. While this generally increased the time to rupture, the granularity of the material was associated with a second stage of thinning which was localized along the axis of the filament and was notably more rapid than in a similar-viscosity pure liquid. The pinch-off structure was found to be qualitatively different when comparing a suspension to a pure liquid with viscosity equal to that of the suspension. Based on these observations, Furbank and Morris proposed a two-stage pinch-off process where particle effects are governed by bulk properties (effective viscosity) followed by one where the discrete size effects of the particles dominate. This and subsequent experimental work of which we are aware has been carried out with fully-wetting particles, meaning the contact angle of the suspending liquid with the particle surface is close to zero.

Bonnoit et al. (2012) extended the investigation to address final detachment and observed thinning in three regimes. The previously mentioned effective viscosity regime transitions to a regime that behaves like the interstitial fluid. This happens when the volume fraction in the neck is very low, meaning the particles do not interact with the thinning fluid. Finally, there is a transition to an accelerated regime just before rupture. van Deen et al. (2013) studied systems with very low volume fraction and concluded that the accelerated regime begins when a particle in the thread directly interacts with the thinning dynamics. In this regime, thinning proceeds faster than a pure fluid with either effective *or* interstitial viscosity. Miskin and Jaeger (2012) demonstrated the minimum radius scaling as $R_m \sim \tau^{2/3}$ for drops with large volume fractions of particles. They argued that the scaling results from particles forming bulges in the neck, creating a Laplace pressure that must be balanced by inertia. Bertrand et al. (2012) studied the effects of volume fraction on the drop shape at pinch-off. Roché et al. (2011) showed that concentration fluctuations in the thread can arise due to heterogeneous particle rearrangements directly linked to the onset of rupture. Furbank and Morris (2004) demonstrated that satellite drops at rupture are suppressed by adding particles.

The noted experimental work makes clear a range of behaviors occurs, depending on the properties of the interstitial fluid, combined with the size relative to the size of the nozzle and solid fraction ϕ. To gain further insight to this complex process, analytical and numerical methods have been applied. Hameed and Morris (2009) developed a matched asymptotic expansion model that was solved by an implicit finite difference scheme. They used their model to investigate the influence of a single particle in the thread using a symmetric force dipole (known as a stresslet) to represent the particle. McIlroy and Harlen (2014) developed a one-dimensional model for an axisymmetric particle-laden bridge stretched between parallel plates, where point particles (smaller than the grid) were advected by the fluid, and their local concentration determined the local viscosity as a feedback mechanism. Although this model predicts quite acceptably the thinning behavior and variations in local particle density, it does not represent the finite size of the particles, and cannot predict aspects of pinch-off when the thread approaches the size of the particles.

To address the issues of finite-size particles in drop-forming and related processes, we have developed a numerical approach that captures both the fluid–fluid interface and particle–fluid interactions. This approach is based on the lattice Boltzmann method (LBM), which has become a widely-used tool for solving continuum scale fluid flows. Of most relevance here, there has been success using the LBM to simulate flows with multiple fluid components (Lee and Liu, 2010) and suspended particles (Ladd, 1994; Haddadi and Morris, 2014), two aspects of the problem of particle-laden interfacial flows. In this method, the full Navier–Stokes equations, inclusive of both inertial and viscous effects, are recovered in the fluid domain, where flows in the liquid and ambient gas are solved in three dimensions. Finite-sized particles are transported by Newtonian dynamics, where a full two-way coupling is accounted for, meaning particles are transported due to pressure, viscous, and surface tension forces applied by the fluid at their boundaries. The resulting traction forces on the fluid in turn affect the fluid flow. This provides a unique and powerful tool to gain insight into the complicated behaviors of particle-laden interfacial flows. In this work, we study specifically the effects of particle wettability and solid fraction for a suspension bridge stretched between parallel plates. We analyze the rupture length and pinch-off structure for suspensions that use fully wetting (contact angle $\theta \approx 0^\circ$) and neutrally wetting ($\theta = 90^\circ$) particles. We further discuss the suppression of satellite drops and the post-rupture asymmetry of the volumes resulting from bridge rupture.

The rest of the paper is organized as follows. The numerical method is described in Section "Numerical method"; fuller details are available elsewhere (Connington et al., 2015). The code is validated for the particle-free stretching liquid bridge with comparison to experiment in Section "Code validation". Results of our lattice Boltzmann simulations and the experimental studies of this work are discussed in Section "Results". Concluding remarks are given in Section "Conclusions".

Numerical method

The numerical method consists of a multi-component lattice Boltzmann algorithm for the fluid, coupled with Newtonian dynamics for finite-sized particles. The fluid evolves according to the discrete Boltzmann equation, inclusive of surface tension forces at fluid interfaces. Imposed boundary conditions for the distribution function recover the no slip condition on solid surfaces, but allow for diffusion of the contact line to avoid a stress singularity. Given the location and velocities of solid boundaries at a particular time, the first aspect of the coupling is set. The evolution of the