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FORMATION AND MERGING OF SATELLITE DROPLETS DISINTEGRATED FROM LAMINAR LIQUID JETS

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Abstract

Numerical simulations of the break-up of laminar liquid jets are presented that reveal the formation of satellite droplets resulting from *(i)* the non-linear disintegration of jet liquid core and *(ii)* coalescence of two primary droplets. For the case *(i)*, when satellites disintegrate from the jet liquid core, they tend to show forward, rear and simultaneous merging responses on both the aft side as well as the foreside of the primary droplets that are present downstream that were evidenced experimentally by Vassallo and Ashgriz (1991). However, for the case *(ii)* the satellites that are formed show similarities with that observed by Zhang et al. (2009) for two stationary droplets at the onset of coalescence. However, our numerical results predict that when two primary drops disintegrated from a liquid jet, that undergoes surface oscillations coalesce, satellites can pinch-off from both the ***fore-side and the aft-side*** of the coalesced droplet with effective diameter ratios as small as $\frac{d_1}{d_2}\sim 1.15, 1.97$ respectively. Effect of pressure waves during binary droplet coalescence and the subsequent pinch-off dynamics for satellite formation is presented.

Introduction

The 'downstream dynamics' of droplets disintegrated from liquid jets is a fascinating problem and is of significant interest in many engineering applications such as separation processes, combustion, surface conditioning and cleaning technology. Liquid jet experiments have shown the formation and merging responses of satellites with primary droplets to exhibit complex phenomena such as a forward, rear and simultaneous merging behaviour [1,2]. Numerically, the primary droplets disintegrated from laminar jets themselves have shown several droplet-droplet interaction modes such as (i) permanent coalescence, (ii) partial coalescence leading to a reflexive-like separation and remerge responses [3,4]. Experiments that detailed the unequal static droplet coalescence enhanced our understanding of the formation of satellite droplet under critical parent ratio of 1.55 [5]. The pinch-off dynamics further illustrated that where the satellite that does not entirely separate enters into a second stage coalescence cascade in generating a much smaller droplet [5].In the current work, we present numerical observations of (i) the formation of satellites from laminar jets and their merging responses with primary droplets; (ii) interaction of primary droplets with ratios as small as 1.15, that lead to the creation of satellites that enter into second stage coalescence cascade.

Numerical Model

The liquid, at a constant flow rate Q, that is injected from the nozzle is assumed to be incompressible and Newtonian with viscosity μ_w and density ρ_w and the flow to be axis-symmetric, whose origin lies at the center of the open end of the nozzle. In the present study, we assume that the fluid from the nozzle of radius (R) is injected into an incompressible, quiescent air of viscosity μ_a and density ρ_a.

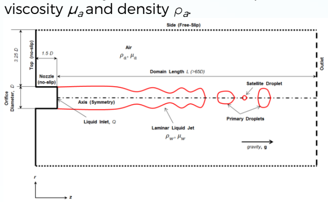


Fig. 1 Schematic of an axisymmetric domain showing boundary conditions, computational domain size used for modelling laminar liquid jet breakup.

The equations that describe the motion of both fluids that are incompressible and present within the system are represented by a single set of Navier-Stokes Equations given as follows:

The continuity equation is given as

$$\nabla \cdot (\rho \vec{v}) = 0 \quad (1)$$

and the momentum equation is described by

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot [\mu(\nabla \vec{v} + \nabla \vec{v}^T)] + \rho \vec{g} + \vec{F} \quad (2)$$

$$\vec{F} = \sigma k \nabla \alpha \quad (3)$$

where k is the local curvature on the interface and is computed as

$$k = -\nabla \cdot \left(\frac{\nabla \alpha}{|\nabla \alpha|}\right) \quad (4)$$

The interface between the immiscible fluids is described using the Volume of Fluid method (VOF) given by:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \vec{v}) = 0 \quad (5)$$

The relevant dimensional numbers are: $We = \frac{\rho_w V_0^2 D}{\sigma}$; $Bo = \frac{\rho_w g D^2}{\sigma}$ and this study is restricted to $Re = \frac{\rho_w V_0 D}{\mu} < 2300$. The present work was developed using the commercial package ANSYS Fluent (Version 18.0) in an explicit formulation with a maximum Courant number of 0.25 solved using the Non-Iterative Algorithm (NITA). The pressure velocity coupling selected was PISO algorithm. The interfacial forces were accounted using the continuum surface force approach.

Results

We compare our numerical results with theoretical estimations for a)breakup of liquid jets, and b) interfacial pressure jump. For details on grid independency, validation and verification, the readers are directed to Refs. [3, 4].

a) Jet Breakup Verification [6]

The mean breakup length of a jet has been experimentally determined by Sallam et al.(2002) for low viscosity liquids, given by the following correlation:

$$\frac{L}{D} = 5\,We^{0.5} \quad \text{valid for } We < 400. \quad (7)$$

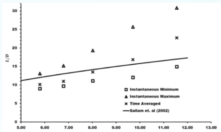


Fig. 2 Comparison of experimental correlation for jet breakup lengths from Sallam et al. (2002) with present simulation for various Weber numbers with Bo=0.0459, D=0.584 mm.

Table 1. Values of jet breakup lengths obtained from the present numerical results compared with Sallam et al. (2002) for two different *Bo* but maintaining the same *We*.

D (mm)	Bo	Re	We	Experimental fit from Sallam et. al., (2002) $\frac{L}{D}=5We^{(1/2)}$ for $We<400$	Simulation Results $\left(\frac{L}{D}\right)$ minimum	maximum	Average
1.6	0.345	590	6.8	13.038	9.645	16.268	12.258
0.584	0.0459	537	6.8	13.038	9.684	15.164	10.96

b) Interface Pressure jump Verification [4]

Young–Laplace's equation

$$\Delta P = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \quad (8)$$

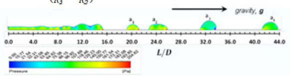
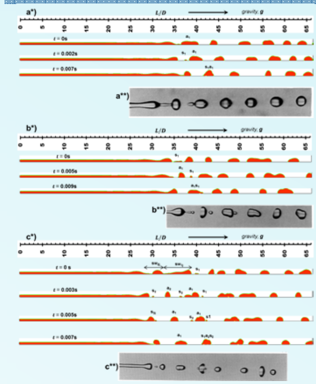


Fig. 3 Pressure distribution on the Laminar Water jet with *We*=6.62 injected into still Air.

Table 2. Comparison of Pressure Differences across Air-Water interface predicted by Young-Laplace Equation (Eq.8) against Simulation Results for various drop sizes disintegrated from a Jet with We=6.62 as shown in Fig. 3.

Droplets (Fig. 2)	Drop Radius from Simulation (mm)	ΔP_{Theory} (Eq. 8) (Pa)	$\Delta P_{Simulation}$ (Pa)	Relative Error (%)
a_1	1.258	115.739	120.212	3.864
a_2	1.728	84.254	89.454	6.171
a_3	1.440	101.090	93.54	7.468
a_4	1.595	91.242	96.333	5.579

c) Formation and Merging of Satellites from Jet core [4]



Satellites from jet show the ability to forward, rear and simultaneously merge with both sides of the primary droplet.

Numerical results further demonstrate that the satellite $\mathbf{s_3}$, although formed on the aft side of the droplet $\mathbf{a_2}$ may be anticipated to rear merge with $\mathbf{a_2}$. Instead, the satellite $\mathbf{s_3}$ is absorbed by the moving jet liquid core, denying the event of $\mathbf{s_3}$ merging with $\mathbf{a_2}$.

Fig.4 Liquid volume fraction profiles showing characteristics of forward merging, rear merging and simultaneous merging of satellite droplets emanated from a liquid jet with We=16.48, Bo=0.194; figures with (*) correspond to numerical result where as figures with (**) correspond to the experimental result obtained by Vassallo and Ashgriz (1991). The formation of satellite $\mathbf{s_3}$ from swelling $\mathbf{sw_2}$ merging back to the moving liquid jet core is seen in the part figure c).

d) Satellite formation during droplet-droplet interaction

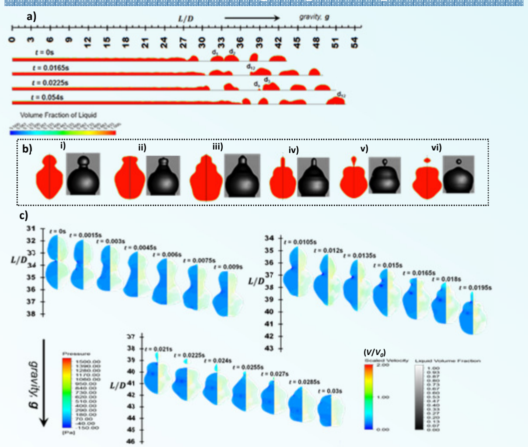


Fig. 5 Numerical prediction of satellite formation (We=16.48, Bo=0.626) in the fore-side during coalescence dynamics of drops $\mathbf{d_1}$ and $\mathbf{d_2}$: a) corresponds to liquid volume fraction of the whole-field jet evolution, b) shows some similarities in satellite formation during droplet interaction during downstream motion (left: numerical) and static droplet interaction (right: experimental result of Zhang et al. (2009)), and c) shows detailed spatial-temporal variations of the pressure field and velocity field on the droplet.

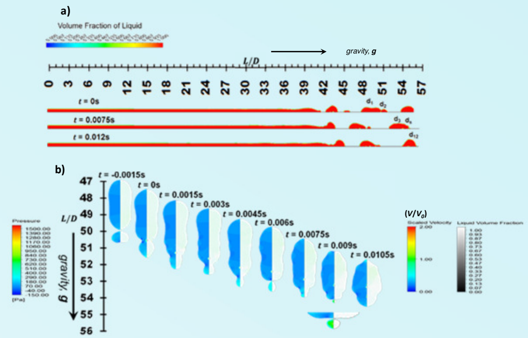


Fig. 6 Numerical prediction of satellite formation (We=16.48, Bo=0.626) in the aft-side during coalescence dynamics of drops $\mathbf{d_1}$ and $\mathbf{d_2}$: a) corresponds to liquid volume fraction of the whole-field jet evolution and b) shows detailed spatial-temporal variations of the pressure field and velocity field on the droplet.

The diameter ratios of colliding drops leading to satellite formation on the fore-side and aft-side correspond to $\frac{d_1}{d_2}\sim 1.15, 1.97$ respectively.

Surface oscillations of drops disintegrated from the jet suggest many complex droplet-droplet interactions may be possible.

Summary

- Numerical predictions of the jet break-up agree with the Experimental correlations of Sallam et al. (2002) and verification of interface pressure-jump for droplets with Young-Laplace's equation.
- Satellite droplets formation during random break-up show merging responses that agree with experimental observations of Vassallo and Ashgriz (1991). Numerical results further detail satellites merging back into moving jet liquid core.
- Droplets from jets show intricate interaction patterns predicted by numerical results such as satellite pinch-off on the fore-side and aft-side of the coalesced drop. Coalescence-cascade is further predicted during a fore-side interaction; some similarities are noticed between the experimental results of Zhang et al. (2009).
- Air-entrapment is predicted numerically during all droplet merging events.

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