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A dual grid level set method based study of interface-dynamics for a liquid jet injected upwards into another liquid

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ABSTRACT

Dynamics and breakup of an axi-symmetric liquid jet injected upwards into another stationary or co-flowing immiscible liquid is investigated numerically. Simulations are done using an in-house code based on a novel DGLSM (dual grid level set method). Furthermore, a novel procedure – based upon physical interpretation of the various functions in Level Set Method – is demonstrated here as a powerful numerical tool to calculate certain parameters (diameter as well as frequency of drop formation and temporal variation of jet length at the axis), which characterize the unsteady interface-dynamics. Six different combination of the dispersed and continuous fluid are subjected to various injection velocity, resulting in a large variation in the non-dimensional governing parameters such as viscosity-ratio and Weber number. From the temporal variation of jet length and instantaneous interface, three drop formation regimes are proposed: *Periodic Uniform Drop formation* (P-UD), *Quasi-Periodic Non-Uniform Drop formation* (QP-NUD) and *Chaotic Non-Uniform Drop formation* (C-NUD); demarcated in a drop formation regime map for various Weber number and viscosity ratio. Their effect on the mean value of jet breakup length ($L_{d,m}$), detached drop diameter ($D_{d,m}$) and drop formation frequency (St_m) is also studied. After a more detailed study on stationary continuous fluid, the effect of co-flowing continuous fluid is studied; and is found to stabilize the drop formation regime and increase the frequency of drop formation.

1. Introduction

A fundamental phenomenon in the coupled fluid and interface dynamics involves changes in the topology of interface between immiscible fluids. Common example of topological changes is pinch-off of a liquid jet into droplet and droplet reconnection. They are encountered in a large variety of situations, in nature, technology and basic science; for example, in nuclear fission, diesel engine technology, DNA sampling, manufacturing, spray, agriculture irrigation, powder technology, ink jet printing and jet engine.

Moreover, during the jet breakup, different flow regimes such as periodic, quasi-periodic and chaotic flow may occur. There are more numerical as compared to experimental studies on the flow transitions. Furthermore, most of them are for single as compared to two phase flow. This is due to better numerical techniques for characterization of flow in a single-phase as compared to that for interface in a two-phase flow. Thus, there is a scope of improvement in the characterization of interface for better understanding of transition in interface dynamics of two phase flow. The present work is an attempt in this direction for an axi-symmetric immiscible liquid–liquid system, using a novel dual grid level set method.

When a Newtonian liquid is injected from an orifice into another immiscible Newtonian liquid, several types of interface dynamics are observed (Homma et al., 2006): dripping mode at low, jetting at intermediate and a transition from 2D axisymmetric to 3D flow at larger injection velocity. A detailed review on theoretical study of jet break-up can be found in Eggers (1994), Eggers (1997), and Eggers and Villermaux (2008).

For the jet injected *along* the gravity, there are numerous experimental study. This was initiated by Rayleigh (1878, 1879) and subsequently several researchers (recently by Longmire et al. (2001), Webster and Longmire (2001), and Milosevic and Longmire (2002)) proposed correlation for breakup length and primary drop volume. Experiments of Chaudhary and Maxworthy (1980a) and Chaudhary and Maxworthy (1980b) reported formation of satellite drop and its merging with the parent drop. Bright (1985), Zhang and Basaran (1995), Brenner et al. (1997), and Cohen et al. (1999) studied the effect of various governing parameters on the unsteady drop dynamics.

For the jet injected *against* the gravity, there are few experimental studies. This was initiated by Scheele and Meister (1968) and Meister and Scheele (1969). Subsequently, Kitamura et al. (1982) observed that Tomotika (1935) linear stability analysis holds good for coflowing – up to the jetting mode – but not for quiescent continuous fluid. This analysis was modified by Teng et al. (1995) to introduce the effect of viscosity on drop diameter.

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Numerical studies on simulation of a jet in liquid–liquid or air–liquid systems are found for Boundary Element Method (BEM) – (Mansour and Lundgren, 1990; Zhang and Stone, 1997), Volume Of Fluid (VOF) method – (Richards et al., 1993, 1994, 1995; Zhang, 1999), Finite Element Method (FEM) – (Wilkes et al., 1999) and front tracking method – (Homma et al., 2006). No such studies are found with Level Set Method (LSM) attempted here; however, such studies using a combination of LS and VOF called as CLSVOF are found in Chakraborty et al. (2009). Ambravaneswaran et al. (2004) have used one dimensional analysis to present transition from dripping to jetting in dripping faucets.

There are less studies are on the jet injected against as compared to along the gravity. This was studied experimentally by Scheele and Meister (1968); Meister and Scheele (1969) and Kitamura et al. (1982); and numerically by Richards et al. (1993, 1994, 1995) and Homma et al. (2006). Most of the work are on establishing the validity of the linear stability theory and almost no work is available wherein systematic study on transition of jet breakup mode is reported. This was done experimentally by Chaudhary and Maxworthy (1980a,b) for liquid–air system and numerically by Homma et al. (2006) for liquid–liquid systems. The present work is an effort in this direction, using the same liquid–liquid system as was used by Homma et al. (2006).

The scope of the present work is to cover both computational as well as flow physics aspects of a numerical study. The objective to perform a first time application of LSM – for the study on jet dynamics – not only as an accurate method but also its capability to characterize the unsteady interface dynamics for a better Computational Multi-Fluid Dynamics (CMFD) analysis; using the physical interpretation of various functions (Gada and Sharma, 2009) used in the level set method. Furthermore, the objective is to propose various regimes of unsteady interface dynamics – different from the way it is reported in the published literature – using the time signal of tip of the jet at the axis of the axisymmetric liquid jet. The motivation is that the time-signal analysis is a powerful technique commonly used for the unsteady flow in single phase to probably for the first time in the two phase flow. For different values of viscosity ratio and Weber number, the objective is to present a drop formation regime map and study the effect of the flow transitions on the parameters characterizing the jet dynamics. Finally, the objective of the present work is to present the effect of co-flowing continuous fluid on the drop formation regime as well as the jet-dynamics parameters.

2. Physical description of the problem

Fig. 1 shows the axi-symmetric computational domain and boundary conditions for the physical problem considered in the present work. The figure shows an axi-symmetric view of a stationary cylindrical tank of non-dimensional length L and radius $R_2 = 5$ filled-in with a stationary continuous fluid 1. At the bottom of the tank, it can be seen that dispersed fluid 2 is injected vertically upwards with a fully-developed non-dimensional velocity profile: $V_i = 2\left(1 - \left(\frac{R}{R_1}\right)^2\right)$ from a circular hole (orifice) of non-dimensional radius $R_1 = 0.5$. The figure also shows an important parameter in the present problem called as jet length and represented here as L_j, resulting due to formation of an axi-symmetric jet and its breakup into droplets.

For non-dimensionalization, diameter of the orifice d_1 and average inlet velocity at the orifice $\bar{v}_i$ are taken as the characteristic length and velocity scale, respectively; and continuous fluid 1 is considered as the reference fluid. Both the fluids are considered here as incompressible and immiscible.

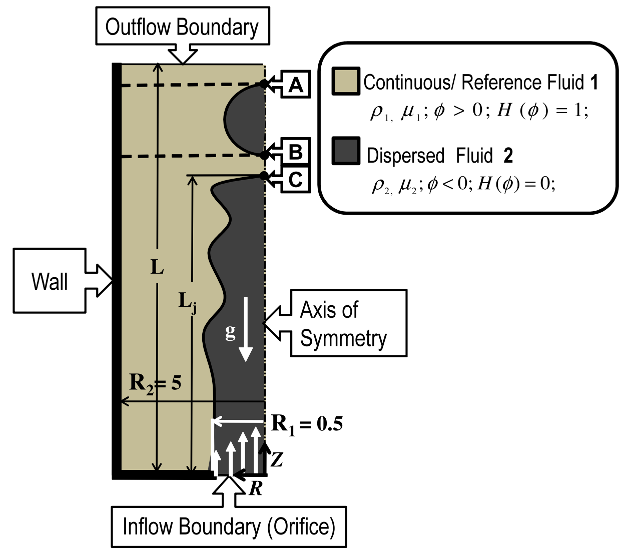

Fig. 1. Computational domain and boundary conditions for an axisymmetric liquid jet injected into another immiscible liquid.

3. Mathematical formulation

In case of single-phase flow, Navier–Stokes equations are solved to obtain velocity and pressure; however, in case of two-phase flow, the governing equation for the interface also needs to be solved. For the present work, LSM (Sussman et al., 1994) is used to model the temporal evolution of interface where the interface is represented by a signed normal-distance function called as level set function ϕ – with zero value at the interface, positive value in one and negative value in the other fluid. Although the physically relevant interface is of zero thickness and is represented in LSM by $\phi = 0$, the numerically relevant interface is taken as finite thickness 2ϵ. This is done to smear the sharp change in thermophysical properties and surface-tension force across the interface; and thus, avoid numerically instability. The smeared interface is defined as $-\epsilon < \phi < \epsilon$ where ϵ is the half thickness of interface and is commonly taken as a factor of grid spacing with $2\epsilon = 3\Delta R$.

In the present work, the governing equations for flow and interface are coupled by invoking the single field formulation, where a single velocity and pressure field is defined for both the fluids. Although origins of the LSM lie in mathematical sources (Sussman et al., 1994), Gada and Sharma (2009) proposed physical interpretation of various functions used in LS method and used it for conservation law based derivation of the various equations used in LSM based simulation of two-phase flow. The non-dimensional form of the conservation equations used in the present work are given as

Volume Conservation (Continuity) Equation:

$$\nabla \cdot \mathbf{U} = 0 \tag{1}$$

Mass Conservation (Level-Set Advection) Equation:

$$\frac{\partial \phi}{\partial \tau} + \mathbf{U} \cdot \nabla \phi = 0 \tag{2}$$

Momentum Conservation Equation:

$$\frac{\partial(\rho_m \mathbf{U})}{\partial \tau} + \nabla \cdot (\rho_m \mathbf{U}\mathbf{U}) = -\nabla P + \frac{1}{Re} \nabla \cdot (2\mu_m D) - \frac{\rho_m}{Fr^2} j + \frac{1}{We} \kappa \hat{n} \delta_\epsilon(\phi) \tag{3}$$

For the above equations, the non-dimensional variables are expressed as