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Numerical Simulation of Drop Formation at Submerged Orifice in Liquid

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In the present paper, computational fluid dynamics simulation was performed to study the drop formation in single holes in a solvent extraction. The SOLA-volume of fluid (VOF) method was used to simulate the drop formation. In this code, the complete form of Navier-stocks equations was predicted two dimensions and using finite difference method. Also in this study, the effects of the hole size on the droplet diameter and its formation time at low rates was studied.

Key Words: Two phase flow, Drop formation, Numerical simulation, Computational fluid dynamics.

INTRODUCTION

Multi-fluid systems play an important role in many natural and industrial processes such as copper refining, chemical reactors, power plants, *etc.*[1]. Liquid-liquid systems are important in many areas of engineering, physics and chemistry. A few examples of current interests are liquid-liquid extraction equipment, emulsion technology, space applications in propulsion systems, life support and storage, oil-water mixtures in pipeline flow, extrusion of polymers, secondary oil recovery, micro fluidic devices and interfacial tension measurements[2].

Drop formation in liquid-liquid systems has been studied both experimentally and theoretically for the regimes before and after jetting. These studies have generally investigated the hydrodynamics aspects and a few studies have considered the mass transfer aspects[2,3]. The mechanism of drop formation from a capillary tube, nozzle or orifice into another immiscible liquid has received considerable attention for over a hundred years. Experimental work has focused on drop volume, pinch off and satellite drop formation and the effects of flow rates and fluid properties on them[4].

Over the past decade, computational methods have proven to be an effective tool to study the process in which the multiphase flow takes place. Simulation of multiphase flow along surfaces is a frequently met phenomenon in industrial processes, for example in catalysis, phase dispersion, boiling and cavitations, *etc.*[5].

The dynamics of a viscous liquid drop forming from a capillary tube and breaking into a quiescent, ambient fluid that is inviscid and dynamically inactive has been extensively investigated in an earlier study by Zhang[6]. The evolution with time of surface profile and internal flow of the drop is simulated by using a numerical method based on algorithms of volume of fluid (VOF)[10] and continuum surface force (CSF). In the study by Zhang[6], the effects of finite inertial, capillary, viscous and gravitational forces are accounted for in order to classify drastically different formation dynamics and, in particular, to elucidate the feature of satellite generation[6,7].

In this work, computational fluid dynamics type simulation was performed to study the drop formation process resulted from the feeding of a liquid phase through a single hole as schematically shown in Fig. 1. In addition, the effect of liquid flow rate on the drop size and its formation time at low rates was studied.

EXPERIMENTAL

The geometry is shown schematically in Fig. 1. A cylindrical vessel with 4 cm diameter and 5 cm height is initially filled with 4.5 cm of liquid water. On the bottom there exists an orifice of diameter dor, from this orifice is injected constant immiscible liquid flow rate with velocity u_{or}.

The volume of fluid model is used to describe the fluid dynamics of drop formation. The mass and momentum conservation equations for the two-phase flow throughout the domain are then described by:

$$\nabla.\vec{u} = 0 \quad (1)$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla.\rho\vec{u}.\vec{u} = -\nabla P + \mu\nabla^2\vec{u} + \rho\vec{g} + \vec{F}_{SF} \quad (2)$$

Here the properties of a fluid are given by:

$$\rho(\vec{x},t) = F(\vec{x},t)\rho_{f1} + [1 - F(\vec{x},t)]\rho_{f2} \quad (3)$$

$$\mu(\vec{x},t) = F(\vec{x},t)\mu_{f1} + [1 - F(\vec{x},t)]\mu_{f2} \quad (4)$$

where, F is the volume fraction of liquid in a computational cell. The movement of the liquid-liquid interface is tracked based on the distributions of F(x, t) where F(x, t) =1 in the liquid phase and F(x, t) = 0 in another liquid phase[10]. Therefore, the liquid-liquid interface exists in the cells where F(x, t) lies between 0 and 1. From the values of F(x, t) in neighbouring cells, the size and shape of the drop can be reconstructed. The advection equation for F(x, t) is given by:

$$\frac{\partial F(\vec{x},t)}{\partial t} + (\vec{u}.\nabla)F(\vec{x},t) = 0 \quad (5)$$

Simulation of drop formation: In this study, the SOLA-VOF code was used to simulate the drop formation. In this code, it was used a variable grid to solve above equations using finite difference method. Simulations were carried out to study the effects of volume flow rate and hole size on the drop formation in the column shown in Fig. 1.

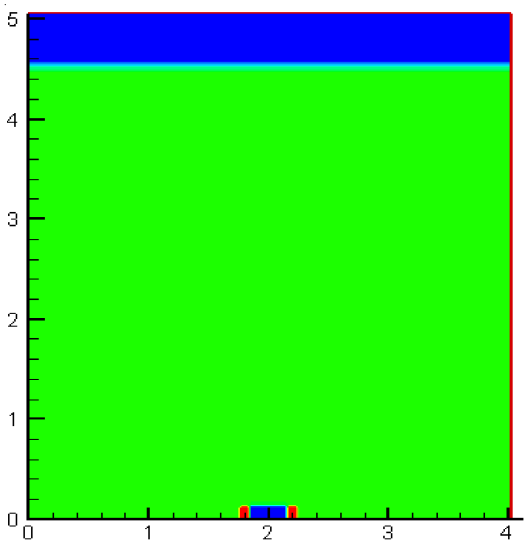

Fig. 1. Schematic picture of the device used in this study

RESULTS AND DISCUSSION

In this study, four cases were investigated. In the first case, hole diameter was about 1 mm and in the second case, it was 2 mm, third 3 mm and fourth 4 mm. The superficial velocity in the hole was 1 cm/s.

Effect of orifice diameter on droplet diameter: Table- 1 shows the effect of orifice diameter on droplet diameter.

There are four major forces, which act on a drop during its formation at the tip of an orifice. The buoyancy and kinetic forces act to separate the drop from the capillary. The drag force and the interfacial tension exerted by the continuous phase act in opposite direction. At low flow rates, it was assumed that the drag and kinetic forces are very low and hence can be neglected. The buoyancy force is given by:

$$F_B = V_D \Delta\rho g \quad (6)$$

The interfacial tension force is given by:

$$F_\sigma = \pi D_{Or} \sigma \quad (7)$$

At static condition, these forces are equal and opposite, hence the volume of the drop at this stage can be written as[8,9]:

$$V_D = \frac{\pi D \text{ or } \sigma}{\Delta\rho g} \quad (8)$$

Hence droplet diameter can be written as:

$$D_{drop} = \left(\frac{6V_D}{\pi}\right)^{1/3} \quad (9)$$

or,

$$D_{drop} = \left(\frac{6D_{or}\sigma}{\Delta\rho g}\right)^{1/3} \quad (10)$$

The purpose of the above equations is the comparison between the results of simulation and the results of equation (10), although these equations are approximate.

TABLE-1
EFFECT OF ORIFICE DIAMETER ON DROPLET DIAMETER

D_{OR} (mm)	3.	4.	5.	6.
D_{drop} (Eq.10) mm	5.71	6.28	6.77	7.19
D_{drop} (CFD) mm	6.14	6.71	7.7	8.57

Results show that the droplet diameter increases with increasing the hole size. Also there is little difference between the results of computational fluid dynamics simulation with the equation (10). This difference is due to approximate equation (10).

Effect of orifice diameter on the time of drop formation: Table-2 shows the effect of orifice diameter on the time of drop formation. As illustrated in Table-2, the time of drop formation decreases with increasing the hole diameter.

TABLE-2
EFFECT OF ORIFICE DIAMETER ON THE TIME OF DROP FORMATION

D_{OR} (mm)	3.	4.	5.	6.
$t_{formation}$ (s)	1.42	1.26	1.12	1.05

Study of drop shapes: The process of droplet formation in a liquid column using SOLA-VOF code is showed in Fig. 2.

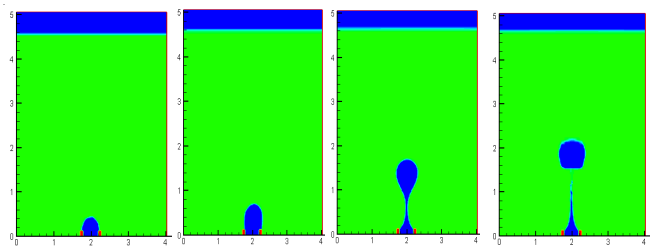

Fig. 2. Drop formation process in water

Conclusion

In this study, the droplet formation process in a cylindrical container with an orifice submerged in water was simulated. Simulation was performed using SOLA-VOF numerical model. In this process, four orifices with different diameters were used and liquid flow rate is assumed very low. It shows that SOLA-VOF code is enabling in hydrodynamic simulation of drop formation process.

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