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Effect of Surface Tension and Density on the Dynamics of Drop Formation

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ABSTRACT

The objective of this work is to study the effects of physical parameters of the liquid on the drop dynamics process. The investigation is being carried out on an experimentally verified computational domain that gives an accurate result in the commercial software, FLUENT version 14.0. Fine meshing is done near the axisymmetric axis which provides a precise result to track the movement of droplet in the air interface. The effect of parameters i.e. surface tension and density is investigated in detail. The size of the drop increases with increase of surface tension while its decreases with increase in density of the liquid.

Keywords: *Drop formation, Surface Tension, Pendent drop, Volume of fluid, Density.*

1. INTRODUCTION

John R. Richards [1] numericallyinvestigates the ejection of the drop to the breakup of the drop, by solving the time dependent axisymmetric equations of motion and continuity with the help of volume of fluid (VOF) and continuous surface force methods (CSF). Yuriko Y. Renardy[2]studied the effect of inertia on the drop breakup numerically with a volume-of-fluid continuous-surface-force algorithm. Due to inertia effect, drop rotates towards the vertical direction, with a mechanism analogous to aerodynamic lift, and the drop then experiences higher shear, which pulls the drop apart horizontally. Drumright-D. Clarke et al. [3]applied a direct numerical simulation (DNS) with a volume of fluid (VOF) continuous surface stress algorithm to prove the effects of an insoluble surfactant at low concentration on a drop in strong shear. By keeping, viscosity and density constant, they found that addition of surfactant induces a Marangoni force which acts towards the centre of the droplet. For low inertia, viscous force opposes the Marangoni force, so that a stationary drop with surfactant is more elongated and less tilted than without. Fawehinmi et al. [4] relates the computational and experimental techniques of drop formation for different viscosities. They use the two popular commercial CFD packages, CFX and FLOW-3D, for solving drop formation flows; both packages use the VOF method. According to their demonstration, both CFD packages perform well for the drop formation at higher flow rate. VOF-based methods have difficulty in resolving fine interfacial features, such as the long, thin threads between the liquid cone and primary drop that exist at low flow rates, as well as the size and shape of secondary, satellite drops that may form by subsequent break-up of the liquid thread. Ronald Suryo et al. [5] studied the nonlinear deformation and breakup of a compound jet whose core and shell are both incompressible Newtonian fluids has been analyzed computationally by a temporal analysis. When the interfacial tension ratio $\gamma >>1$, the outer interface can dominate the response of the compound jet. Pardeep [6] studied the effect of various parameters on the drop dynamics process. He observed that the size of the primary drop increases slightly with the increase in surface tension and decreasing viscosity whereas while the effect of density on the size of the primary drop is negligible. The effects of viscosity on the drop dynamics is also analyzed. It plays a stabilizing role in the drop growth which enables larger drop elongations by minimizing and eliminating oscillations of the interface.

2. METHODOLOGY

Modeling, Meshing, Processing and Simulation every task is done by using ANSYS fluent (14.0 ver.). In all the cases, the models of the profile surface have been generated, implicating the required boundary conditions. Geometric models of cuboid representing the system (drop) and the surrounding medium (atmospheric air) is modeled and meshed with a size sufficiently small such that the accuracy of the results obtained would be within the desired limit. The size of the system considered is such that accuracy of result is not affected by it. After the breakoff of first drop from the capillary tube, the residual liquid hanging from the tube takes the profile of a section of a sphere. All analysis is performed after the stability occurred.

2.1 Computational Domain Model with Boundary Conditions

The computational domain used for the investigation is verified with the experiment results [7]. The domain consists of two regions: a glycerin- 85% chamber (capillary tube) and an air chamber with coordinate system as shown in Figure 1. The surface inside the capillary is neutrally wettable, while the surface surrounding the capillary orifice is non-wettable. We consider different compositions of glycerin as our base fluid which is being incompressible and Newtonian fluid as shown in Table 1. To analyze the drop formation process from capillary tube into ambient air, we use ‘Volume of Fluid model’ i.e. VOF model in FLUENT version 14.0.

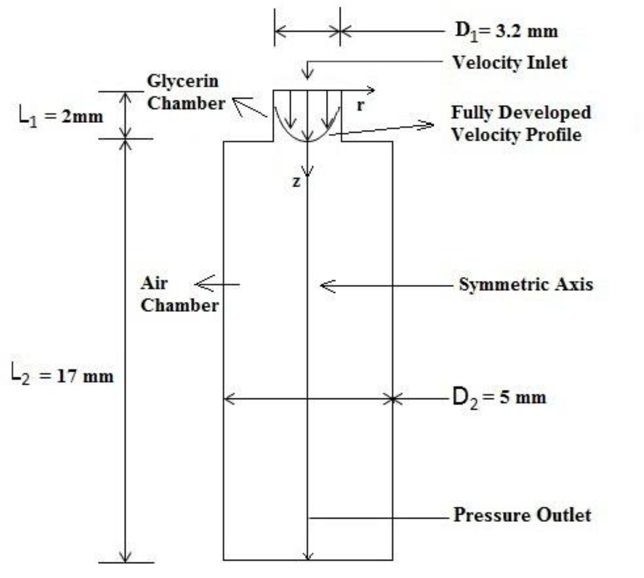

Figure 1 Computational domain with different Boundary Conditions

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Table 1Physical Properties of Glycerin [8]

Liquid	Density (g/cm^3)	Viscosity (poise)	Surface Tension (dyne/cm)
85% Glycerin	1.223	1.129	66.0
70% Glycerin	1.182	0.229	68.5
50% Glycerin	1.272	0.061	70.0
20% Glycerin	1.048	0.018	72.4

At time zero, glycerin-85% fills the capillary tube, while the rest of the domain is filled with the air. Both fluids are assumed to be at rest. To initiate the ejection, the glycerin-85% velocity at the inlet boundary suddenly rises from 0 to 1 ml/min with fully developed profile and drops forms according to a gravitational law. Gravity force which acts towards z direction is also included in the simulation. Due to the axial symmetry of the problem a 2D geometry is used.

2.2 Mathematical Modeling

For free surface flow, the detachment process of a drop depends upon a lot of factors which include velocity of drop liquid flow, viscosity of liquid phase (μ), density of both phases (ρ), surface tension between liquid and air (σ) and the diameter of capillary tube.

The assumptions made in the mathematical formulation and the solution process are the following based on which the governing equations are written as:

1. The Fluid flows are laminar and Newtonian.
2. The model is axisymmetric.
3. The surrounding air can be considered as incompressible.
4. The liquid properties are known and constant.
5. The evaporation of the liquid is neglected.
6. At inlet of the capillary tube fluid flow is assumed to be fully developed flow.
7. Thickness of the nozzle is neglected [8].

With the above assumptions the Navier –Stokes equation in non-dimensional form for the transient motion of the liquid is given as,

$$\nabla . v = 0, \tag{1}$$

$$Re\left(\frac{\partial v}{\partial t} + v.\nabla v\right) = \nabla.\tau + \left(\frac{G}{Ca}\right)j \tag{2}$$

$$\tau = -pI + [\nabla v + (\nabla v)^T] \tag{3}$$

The variable in equation (1) i.e. ∇ is the gradient operator; v is the resultant velocity vector. Similarly, in equation (2), τ is the stress tensor; **j** is the unit vector in z direction. In equation (3), p represents the dimensionless pressure and ***I***is the identity tensor.

The flow is consider as fully developed, so its velocity profile become,

$$v_z = \frac{2Q}{\pi R^2}\left\{1 - \left(\frac{r}{R}\right)^2\right\} \ ,0 \le r \le R \tag{4}$$

Where, r is the radial coordinate of drop phase and v_z is the flow velocity in z direction.

The maximum velocity of liquid phase flow for the fully developed flow is given as

$$U = \frac{2Q}{\pi R^2} \tag{5}$$

The tracking of the interface between two phases (i.e. p_{th} and q_{th}) is completed by solving a mass conservation equation for the volume fraction of one or more phases. The equation is as following for q_{th} fluid:

$$\frac{1}{\rho_q}[\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla.(\alpha_q \rho_q \vec{v}_q) = S_{\alpha_q} + \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp})] \tag{6}$$

Where $\dot{m}_{pq}$ is the mass transfer from phase p to phase q,$\dot{m}_{qp}$ is the mass transfer from phase q to phase p. Generally, the source term, S_{α_q} on the right- hand side is zero. Only the volume fraction for the secondary phase fluid is solved. And the volume fraction of the primary phase fluid can be calculated by the following equation:

$$\sum_{p=1}^{n} \alpha_q = 1 \tag{7}$$

The boundary conditions for the solution of Equations (1) and (2) which are also shown in Figure 1 stated as:

1. Inlet of the domain is velocity inlet.
2. Axis is considered as axisymmetric axis.
3. Free slip velocity condition near wall because the fluid near the wall is air.
4. Outlet of the computational domain is atmospheric pressure outlet.

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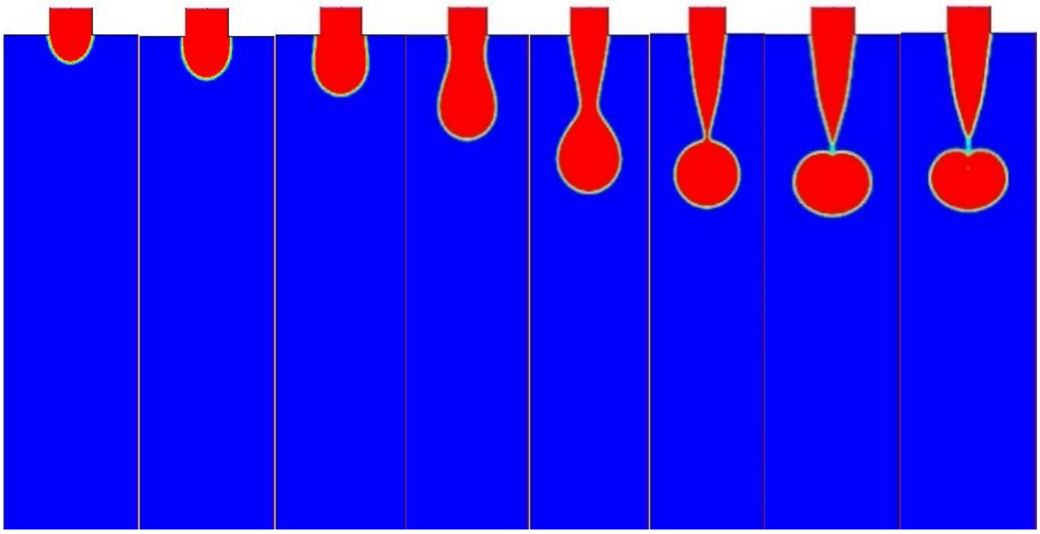
3. RESULT AND DISCUSSIONS

3.1 Effect of Surface Tensionon the dynamics of drop formation

The surface tension plays a major role in the formation of drops. Simulations were runwith different surface tension coefficients to observe the effects of the surface tension on theregimes of drop formation.

Figure 2 compares the dynamics of drop formation for two surface tension values i.e. at 70 dyne/cm and 150 dyne/cm respectively. As shown in Figure 2, Increases in the Surface tension increases the drop breakoff time as well as droplet volume, but it decreases the breakoff thread length of the droplet. It because the surface tensionforces tend to increase the cohesion between the particles on the free surface of the system and compete against the gravitational and inertial forces for equilibrium.

σ = 70 dyne/cm, Flow rate , Q= 1.2064 cm^3/sec
 **10 ms 30 ms 50 ms 70 ms 90 ms 96.5 ms 97.5 ms 98 ms**
σ = 150 dyne/cm, Q= 1.2064 cm^3/sec

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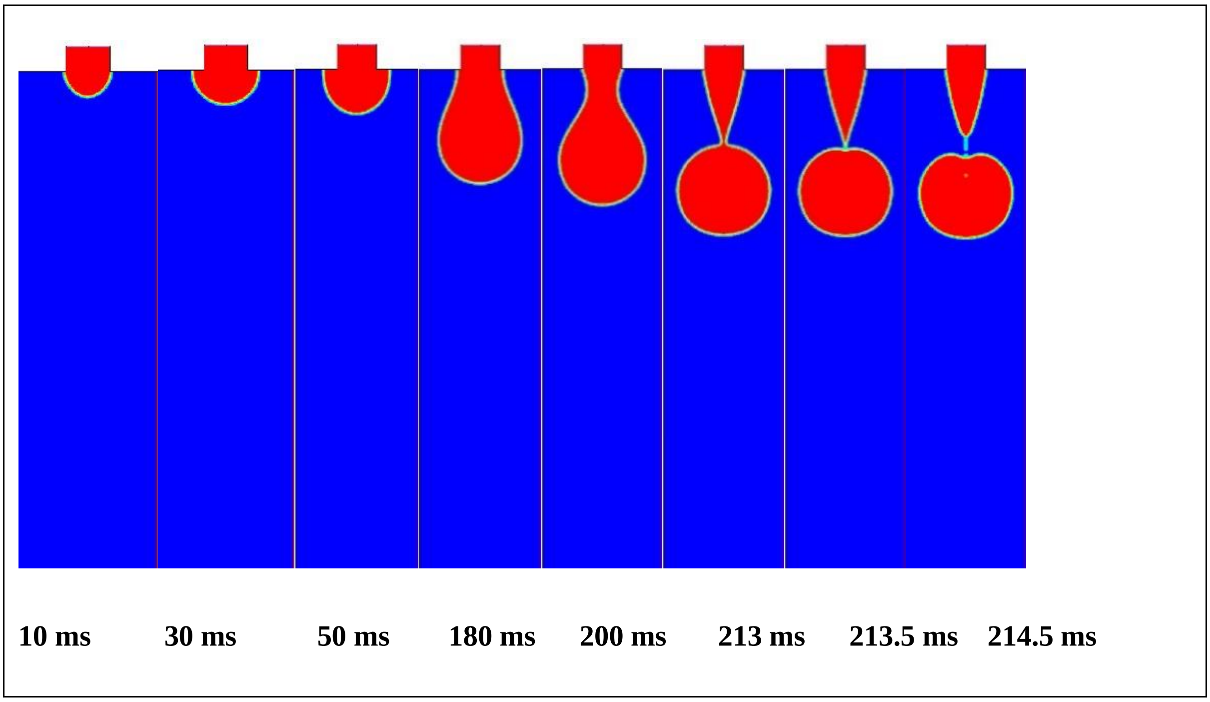

Figure 2 Images of the drop detachment for the systems with different surface tension of the disperse phase through a capillary tube of diameter 3.2 mm. The velocity of the disperse phase was v = 0.15 m/s.

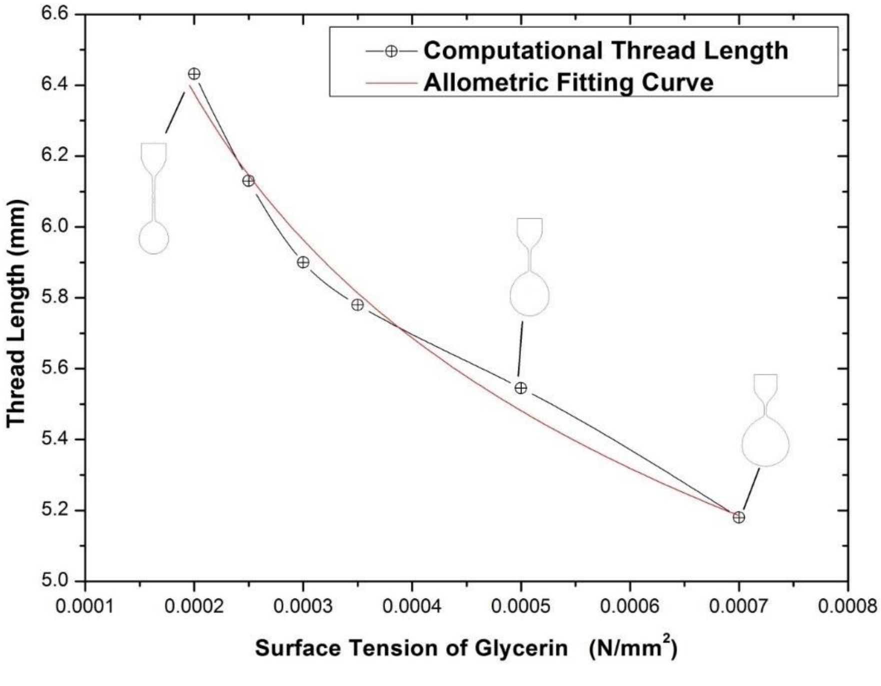

Figure 3 Variation of thread length as a function of surface tension of Glycerin

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Figure 3 shows the variation of drop thread length with the surface tension by keeping density and viscosity constant. The sequence of the drop's shown is 1 ms before the detachment period.

Surface tension is the basic force due to which the liquid drop adopts the spherical shape near the capillary tip. The surface tension force plays a critical role in manipulating the behavior of the detachment droplets. The drop at the needle is gripped by the interfacial tension force, due to which the time taken for the equilibrium of forces is less for systems with lower interfacial tension. Surface tension shows the mutual interactions of the liquid volume. Higher the surface tension indicates the more cohesive power of the liquid.

Due to this reason, with an increase of surface tension, the following happens –

a) Increase in the size of the pendent drop,
b) Decrease in the thread length, as shown Figure 3
c) Increase in the breakup time of the pendent drop.

To determine the relationship between thread length and surface tension, the Allometric curve is selected as the best fit curve for the computational variation. The value of the coefficient of determination is 0.9869 for the regression. Equation (8) represents the relation between thread length and different values of the glycerin's surface tension.

$$L_i = 1.56263 \times \sigma_i^{-0.16511} \quad (8)$$

Where, L_i = Thread length (mm), σ_i = Various Surface Tension values (N/mm^2)

3.2 Effect of Density of dynamics of drop formation

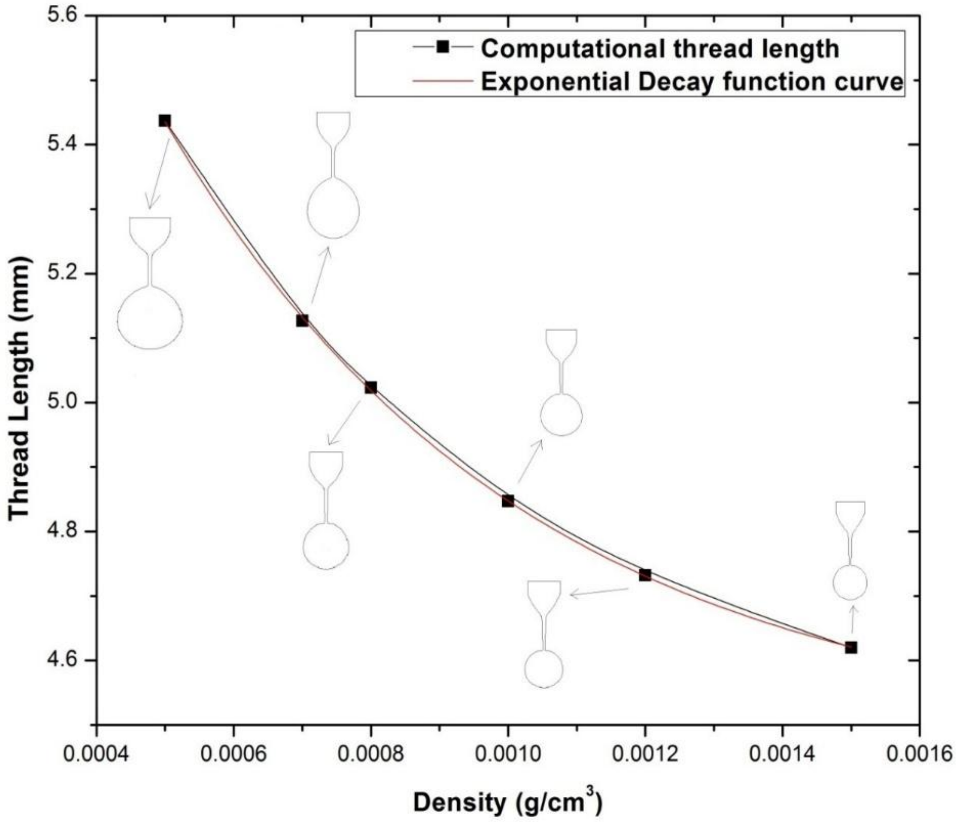

Figure 4 Variation of thread length as a function of density of the glycerin

Figure 4 shows the variation of density on the detachment profile of the pendent drop by keeping surface tension and viscosity constant. Given variation shows that, with a decrease in the density of the pendent drop liquid, the breakoff volume of the drop increases. As we say that a denser body has more weight, which means more gravitational pull is exerted on the pendent drop. So, for high-density value and due to more pulling force, the pendent drop detaches earlier as compared to the other ones. Also, the thread length of the high-density liquid pendent drop is small, as well as the satellite drop formation will not occur with the value of density being high.

Equation (9) shows the dependence curve of thread length upon the density of the liquid. The curve having exponential decay function superlatively fits the computational domain thread length curve as shown in figure 4. The value of the coefficient of determination is 0.999886 which indicates a perfect fit of the exponential decay function curve with the computational results. Equation (9) is valid for Q =1 ml/min and the values of density used in the computational analysis that is shown in Figure 4.

$$L_i = 2.48446 \times e^{\frac{\rho_i}{5.2389e^{-4}}} + 4.479 \quad (9)$$

where, L_i = thread length (mm) , ρ_i = various density values (g/cm^3)

4. CONCLUSION

In the present work, an experimentally verified computational model is used to study the various parameter effects on the dynamics of drop formation. The volume of fluid (VOF) method is used for the numerical simulation of the computational domain. VOF method is one of the best methods for studying the free surface problems. Through numerical analysis, it is found that for low surface tensionbetween the fluids, the volume of the drop is lowwhile if thesurface tensionbetween the fluids is high, the detachment thread lengthof the droplet decreases but the volume of the droplet increases. The variation in density of the liquid has reverse nature as compared to the that of surface tension variations. The thread length of the drop as well asits volume decreases with the increase in the density. This investigation also proves that the CFD tools are quite efficient and accurate forthe free surface flow problems.

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