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TRANSIENT ANALYSIS ON 3D DROPLET OVER HORIZONTAL SURFACE UNDER SHEAR FLOW WITH ADIABATIC BOUNDARY CONDITIONS BY USING FVM

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ABSTRACT

In the present work, an investigation has been made about the shape change and movement phenomena of liquid droplet over a horizontal solid surface under shear flow with adiabatic boundary condition. Finite Volume Method (FVM) with 3D Volume of Fluid (VOF) model has been used to formulate/simulate the complex interface in multiphase flow. The effect of important factors which govern the drop dynamics on a solid surface (like fluid properties: density, surface tension, viscosity and the surface characteristics: surface material, contact angle, roughness) have been studied extensively. Effects of shear strength in terms of air inlet velocity and drop size have also been studied by varying the Reynolds number of inlet air flow and drop volume respectively. Phase contours at different time instant have been produced for each of the case study. Again, the velocity contours and velocity vectors have also been generated for better understanding of the present phenomena. The acquired velocity by the droplet at different time instants has been calculated and the variation of the acquired velocity with time instants is plotted. Again it has been observed that depending upon various boundary conditions and external effects, it may possible to move the drop in any desired direction as per the requirement in various engineering applications like micro pumps, printers, coating devices etc.

KEYWORDS: *Multiphase flow; Droplet; Interface; Volume of Fluid (VOF); Finite Volume Method (FVM); Contact angle, Surface tension, Shear flow.*

I. INTRODUCTION

Dynamics of liquid droplet is one of the most important areas of research not only for academic reasons but also for various engineering applications. For example many industrial and material processing operations require the regulation and control of movement of liquid drops on solid surface. When a drop of liquid makes an impact on a flat solid surface, the movement and the final shape obtained depends upon a large number of factors which mainly influence the drop dynamics. As per various theories the shape and motion of a liquid droplet would be a function of surface tension of the liquid pairs, material properties of the solid surface and liquids, homogeneity of the materials, gravity effects, thermal gradient, surface wettability, surrounding medium, geometry of the surface etc. The dynamics of a small liquid drop is a bit different than that of the bulk fluid because the surface tension force dominates over the inertial and viscous forces. The movement of the droplet is also influenced significantly by contact angle. The contact angle is conventionally measured through the liquid, where liquid interface meets a solid surface. Contact angle quantifies the wettability of a solid surface by a liquid which can be estimated by the Young's equations. The shape of the liquid interface is determined by Young-Laplace equation where the contact angle plays the role of boundary condition via Young's equation as shown in Figure. A solid surface may be categorized as i) hydrophobic surface and ii) hydrophilic surface according to the contact angle of water on the given solid surface as shown in Figure 1.2. The solid surface is said to be hydrophobic if the water contact angle is greater than 90^0 and if the water contact angle is smaller than 90^0, the solid surface is treated as hydrophilic.

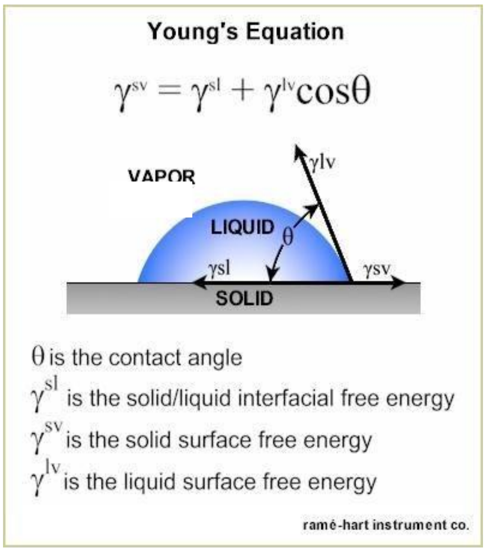


Fig 1.1: Schematic diagram for Young's Equation

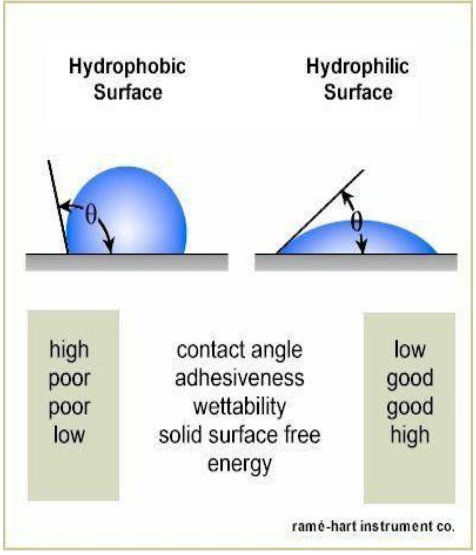


Fig 1.2: Schematic diagram of hydrophobic and hydrophilic surface.

II. APPLICATIONS OF CFD (FVM)

Several numerical methods of Computational Fluid Dynamics (CFD) are available to simulate multiphase flow problem. The Volume of Fluid (VOF) model with 3D Finite Volume Method (FVM) may be a very significant methodology to study and inspect the shape change and movement phenomena of the liquid droplet under shear flow in a flat solid surface.

III. CASE STUDIES

Several studies have been undertaken in last few decades on the liquid droplet motion in a solid surface. The motion of spherical or nearly spherical drops in a channel consisting of two parallel walls has received attention by a variety of exact and approximate methods. The parallel motion of a nearly spherical drop between two channel walls in a quiescent fluid was considered by Shapira and Haber (1988) using the method of reflections. Approximate solutions for the hydrodynamic drag force exerted on the droplet were obtained, which are accurate when the drop-to-wall spacing is not small. Again Chen and Keh (2001) utilized a boundary-collocation technique to examine the parallel motion of spherical drops moving near one plane wall and between two parallel plates as a function of drop size and viscosity ratio. The motion of rigid particles in Stokes flow between two planar walls has also been studied (Staben et al., 2003), where a boundary-integral method was used to find the translational and rotational velocities of spherical and ellipsoidal particles, as functions of particle size and location in the channel.

Also another related study to the problem is the motion of deformable drops through cylindrical tubes, which has received considerable attention and is motivated by several applications in the field of biomechanics. For example, the motion of red blood cells through veins or capillaries, as well as the fate of gas bubbles in the blood stream, is of significant biological and clinical interest. Olbricht and Kung (1992), For many years, the dynamics of drop impact and spreading has been a challenging problem for physicists and engineers. The experimental investigations of Sikalo et al. (2005a-c) with liquids of varying surface tension and viscosity (e.g., isopropanol, water and glycerin) showed that the drop volume, the surface inclination and impact velocity have a significant effect on the drop dynamics and the regimes of drop impact. Besides the experimental investigations discussed above, several numerical studies on the dynamics of liquid droplet spreading over solid surfaces have been reported in the literature like Fukai et al., 1995; Bussmann et al., 1999; Pasandideh-Fard et al., 2002; Gunjal et al., 2005, Sikalo et al., 2005d. Different numerical methods are available for computations of flows with moving interfaces, for example, the level set method (Osher and Sethian, 1988; Sussman and Osher, 1994), the front tracking method (Unverdi and Tryggvason, 1992; Tryggvason et al., 2001) and the lattice-Boltzmann method (Gunstensen et al., 1991; Grunau et al., 1993, Shan and Chen, 1993; Shan and Doolen, 1995; Nourgaliev et al., 2003) and the volume of fluid (VOF) method (Hirt and Nichols, 1981). Gunjal et al., 2005; Sikalo et al., 2005d. Fukai et al. (1995) investigated the effect of the surface wettability on the spreading behavior of a drop. They observed that the impact velocity greatly influences the droplet spreading behavior. The incorporation of advancing and receding angles in the numerical model with adaptive mesh refinement improved their extrapolations. Pasandideh-Fard et al. (2002) studied the three- dimensional solidification of a molten drop on horizontal and inclined surfaces with an interface tracking algorithm and a continuum surface force (CSF) model. Gunjal et al. (2005) carried out an experimental and VOF based numerical study of the drop impact over horizontal surfaces. Their predictions successfully captured the spreading, splashing, rebounding and bouncing regimes of the drop dynamics over horizontal surfaces of different states of wettability. Most of the numerical simulations of drop spreading discussed above were carried for horizontal surfaces and using the Static Contact Angle (SCA) model. Again several experimentations and investigations have been carried out by many authors on dynamics of a liquid drop over an inclined surface with a wettability gradient. Thiele et al. (2004) identified a reaction limited zone below the droplet moving over a gradient surface and proposed that the change of reaction rate causes a different driving force for droplet movement. Later, Pismen and Thiele (2006) developed an asymptotic solution for drop dynamics over a gradient surface using lubrication theory. Subramanian et al. (2005) made some approximation of the drop shape over a gradient surface by collection of over a horizontal surface. For the first time, Huang et al. (2008) employed a numerical technique based on lattice Boltzmann method for the investigation of wettability controlled planar movement of a liquid drop. Recently, Liao et al. (2009) numerically simulated the equilibrium shape of a liquid drop on a surface having a surface energy gradient applying a finite element method.

More recently, Das A.K. and Das P.K. (2010) investigated the motion of liquid drops over an inclined gradient surface using a 3D computational technique. Simulation results reveal that drop motion is dependent on the surface inclination, volume of the droplet and the strength of the wettability gradient. It has been found that, depending on these parameters, a droplet can experience downward or upward motion or can remain stationary on the inclined plane. Finally, drop movement plots which give an idea about the regimes of uphill and downhill movement of a drop over gradient surfaces have been proposed. In addition to above discussions as the formation, growth and detachment of a drop are initial phenomena that take place during every process involving drops, many investigations have been accomplished in this field. Regardless of being critical to some industrial applications, the formation of a drop is a challenging, controversial free boundary problem. Also, Loth (2008) reported various theoretical efforts in this field. These investigations showed that the Weber number dominates the shape of the drops for a wide surface tension, and determined different types of deformation dependent on the relevant dimensionless numbers. In most of the theories, variations of important parameters which influence the drop dynamics have been plotted with respect to dimensionless time.

IV. AIM AND OBJECTIVES

The main objective of the present work is to visualize the effects of key parameters on drop formation, drop movement and to capture the drop dynamics on horizontal solid surface under shear flow with adiabatic boundary condition. The shape change and movement of the liquid droplet has been examined by varying the air inlet velocity and drop volume. The effects of variation of contact angle and surface tension have also been studied on the above mentioned phenomena.

V. PROBLEM STATEMENT

5.1 Problem Descriptions

The shape change and movement phenomena of liquid droplet over a horizontal solid surface under shear flow with adiabatic boundary condition have been studied in the present dissertation. Finite Volume Method (FVM) with 3D Volume of Fluid (VOF) model has been used to formulate/simulate the complex interface in multiphase flow.
For this study, a rectangular parallelepiped domain of air with dimension 40 mm × 40 mm × 20 mm has been chosen where the hemispherical water droplet (in terms of diameter) has been placed in the bottom horizontal surface (40 mm × 40 mm) as shown in Figure 2.1. *Velocity inlet* boundary condition has been used at the left plane of the rectangular parallelepiped. A uniform velocity profile ($u = u_{in}$, $v = 0$, $w = 0$) is prescribed at the inlet. At the right plane *Pressure outlet* boundary condition ($p = p_{atm}$) and at the top plane *Pressure inlet* boundary condition ($p = p_{atm}$) have been considered. At the front, rear and bottom plane *Wall* boundary conditions (*no slip* and *no penetration* boundary condition) have been used. The effects of key parameters on the present phenomena have been studied by varying contact angle (angle of contact between the water droplet and solid surface), and surface tension. Effects of shear strength in shear flow in terms of air inlet velocity and drop size have also been studied by varying the Reynolds number of inlet air flow and drop diameter respectively. For better understanding, six different cases have been considered and studied about this dynamics of the droplet under the said boundary conditions.

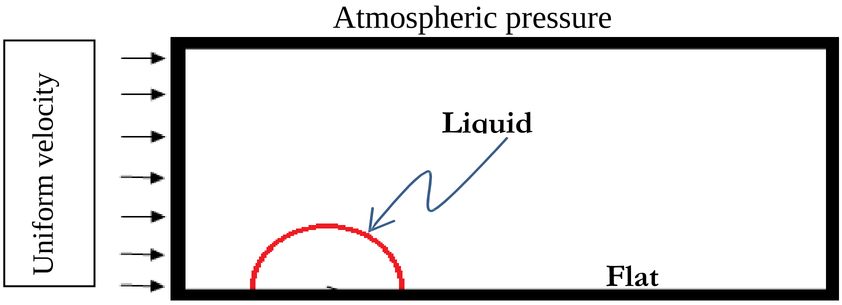


Figure 5.1: Schematic representation of the selected problem.

Six different cases have been considered and studied successfully. They are mentioned below:

i. Dynamics of liquid droplet with diameter: 5 mm, contact angle: 90 degree and without any shear flow.
ii. Dynamics of liquid droplet with diameter: 5 mm, contact angle: 90 degree and laminar air flow (*Re*: 1500)
iii. Dynamics of liquid droplet with diameter: 5 mm, contact angle: 90 degree and turbulent air flow (*Re*: 3000)
iv. Dynamics of liquid droplet with diameter: 10 mm, contact angle: 90 degree and turbulent air flow (*Re*: 3000)
v. Dynamics of liquid droplet with diameter: 10 mm, contact angle: 150 degree and turbulent air flow (*Re*: 3000)
vi. Dynamics of liquid metal (*Hg*) droplet with diameter: 5 mm, contact angle: 150 degree and turbulent air flow (*Re*: 3000)

VI. SOLUTION STRATEGY

Commercial CFD software Gambit and Fluent have been used to analyze the problem. The rectangular parallelepiped domain of air has been modeled and meshed in Gambit with suitable boundary conditions and Fluent has been used for hydrodynamic and heat transfer calculation (numerically).

6.1 Numerical calculation

In the present work, the 3D Volume of Fluid (VOF) multiphase modeling with Finite Volume Method (FVM) has been used to analyze the shape and movement of water droplet under shear flow on a horizontal flat plate. Volume of Fluid (VOF) is a surface tracking technique used for two or more immiscible fluids by solving a single set of momentum equation. Here, the VOF technique with pressure-based solver in 3D version has been used to analyze such a complex, non-linear, unsteady problem. Then Pressure Implicit solution by Split Operator (PISO) has been used to simulate the complex interface. The pressure-based approach has been used where the pressure field is extracted by solving a pressure or pressure correction equation which is obtained by manipulating continuity and momentum equation. In addition, for turbulent modeling, *k-ε* turbulent model is used.

6.1.1 Governing equations

The governing equations used to simulate this multi-phase flow problem are;

The Continuity Equation: As we know continuity equation is derived on the basis of principle of conservation of mass, it is most important governing equation in any CFD problem. Moreover, stability of the solution depends on this equation. The continuity equation in the vector form for each the individual phase is given by;

$$\frac{\partial \rho}{\partial t} + \nabla . \left(\rho \vec{v} \right) = 0 \text{...}(6.1)$$

The Navier-Stroke's Equation (Momentum equations): In VOF multiphase flow modeling with pressure-based solver, a single set of mo equations has been used throughout the domain. The Navier-stroke's Equation which governs the flow field is given by;

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla . (\rho \vec{v} \vec{v}) = -\nabla p + \nabla . \left[\mu \left(\nabla \vec{v} + \nabla \vec{v}^T \right) \right] + \rho \vec{g} + \vec{F} \text{........................}(6.2)$$

Grid pattern employed

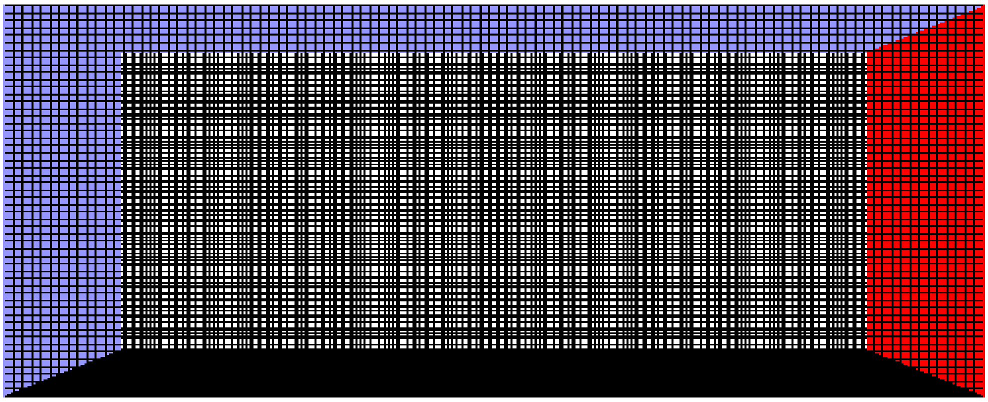


Figure 6.1: Modeling of parallelepiped domain with suitable mesh and boundary conditions.

It has been found that 'Hex/Wedge' element is the most suitable grid pattern for this multiphase flow problem which can influence the accuracy of the solution. So the 'Hex/Wedge' elements with 'Cooper' type grid have been considered for meshing the geometrical model as shown in Figure 6.1. Finally for the better shape and size of the hemispherical water droplet a grid size of 0.000375 has been chosen through a grid independent test.

VII. RESULTS AND GRAPHS

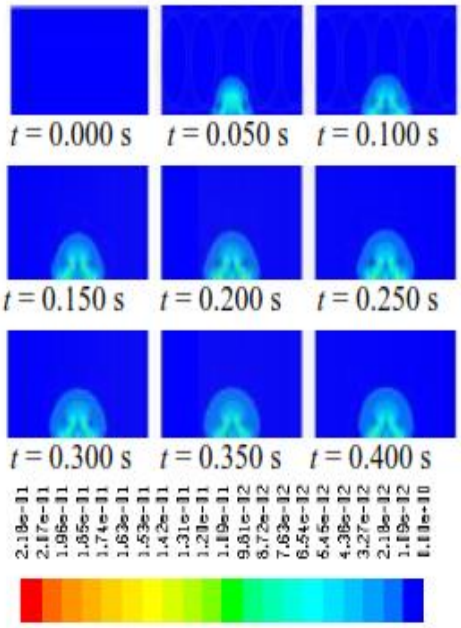


Fig 7.1: Velocity contours at the vertical mid-plane at different time instants (for droplet with diameter: 5mm, contact angle: 90^0 and without any shear flow)

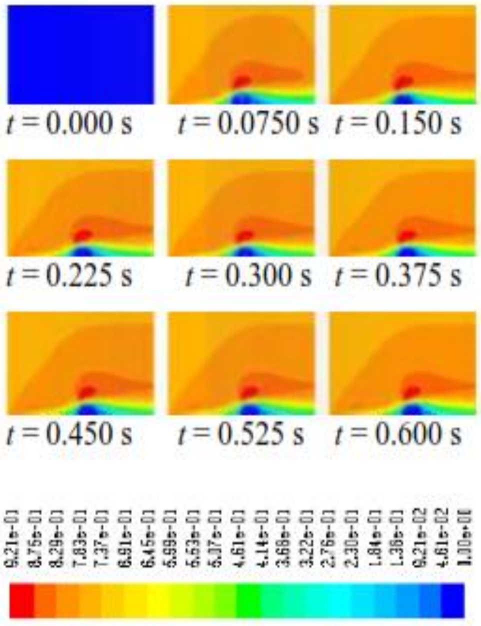


Fig 7.2: Velocity contours at the vertical mid-plane at different time instants (droplet diameter: 5 mm, contact angle: 90 degree and laminar air flow, Re: 1500)

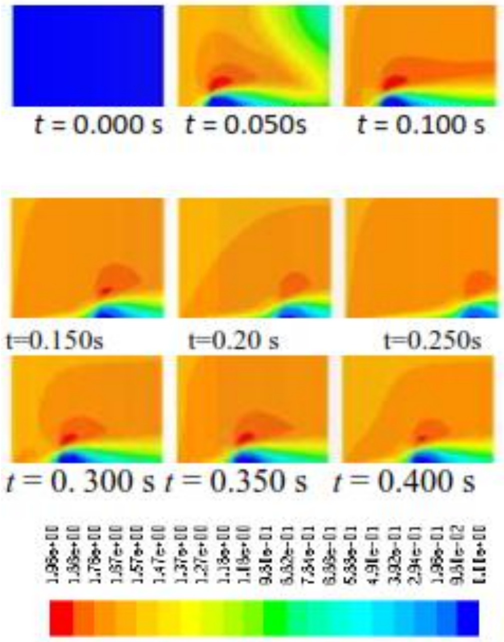


Fig 7.3: Velocity contours at the vertical mid-plane at different time instants (for droplet with diameter: 5 mm, contact angle: 90^0 and with turbulent air flow, *Re*: 3000)

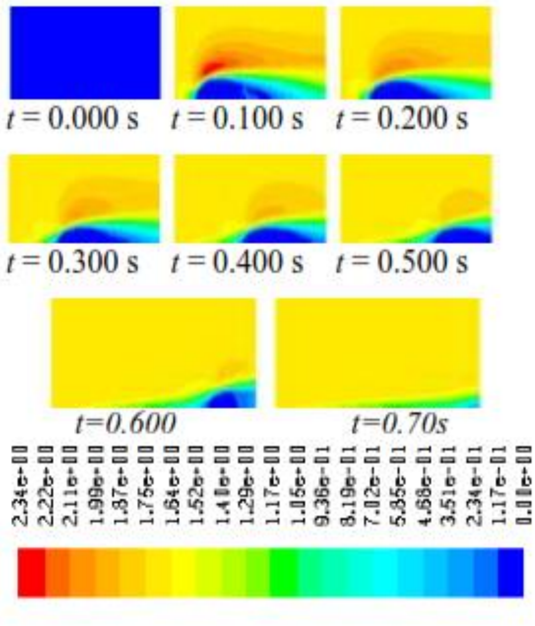


Fig 7.4: Velocity contours at the vertical mid-plane at different time instants (droplet diameter: 10 mm, contact angle: 900 and with turbulent air flow, Re:3000)

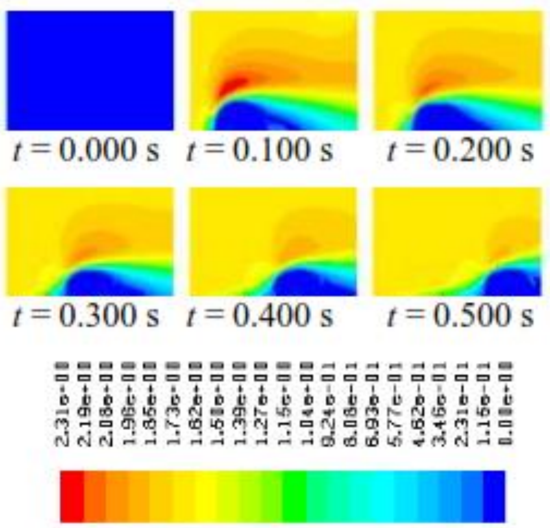


Figure 7.5: Velocity contours at the vertical mid-plane at different time instants (drop diameter: 10 mm, contact angle: 150^0 and with turbulent air flow, Re: 3000)

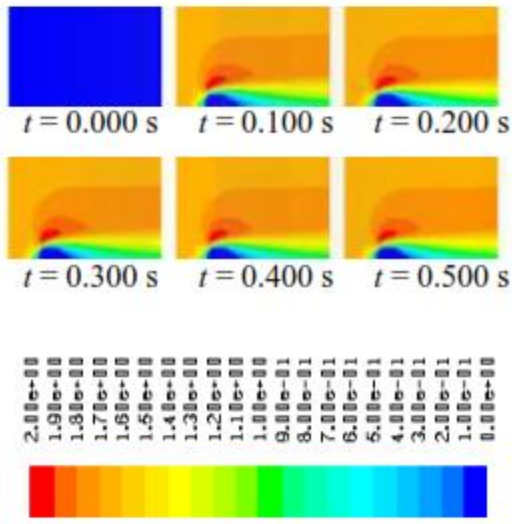
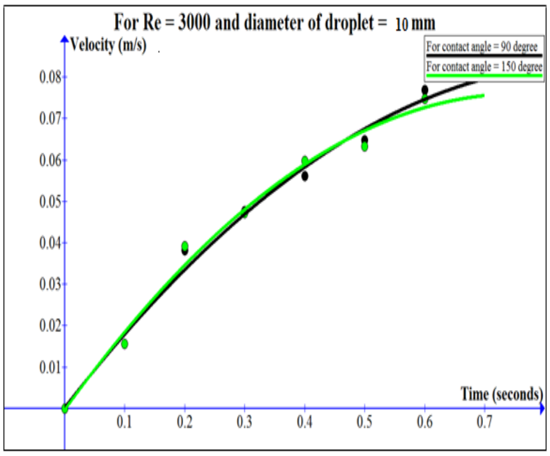
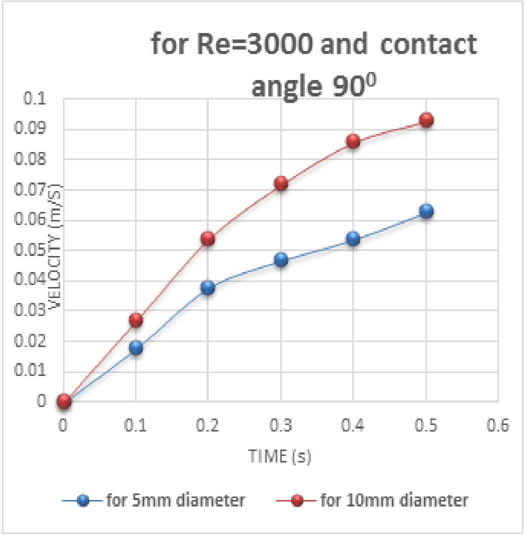


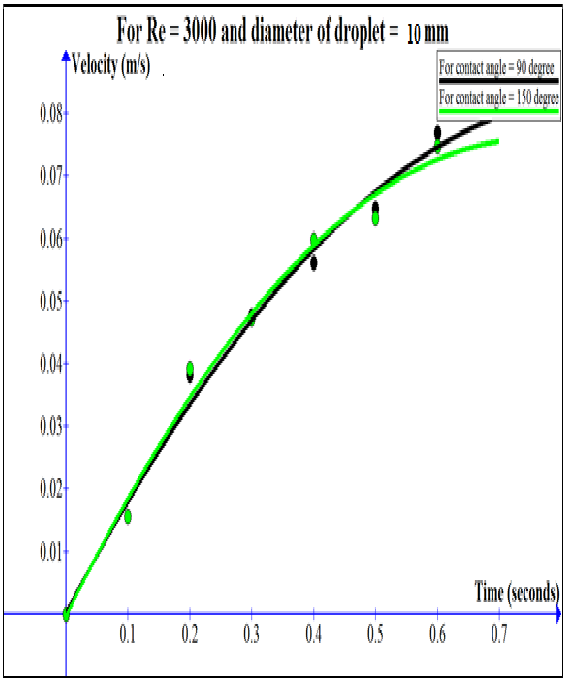
Fig7.6: Velocity contours at the vertical mid-plane at different time instants (mercury drop diameter: 5 mm, contact angle: 90^0 with turbulent air flow, Re: 3000)



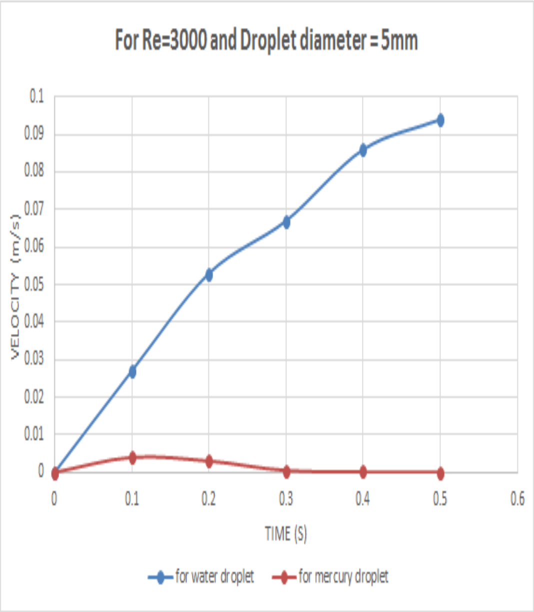
Graph7.1: Variations in drop velocity with time instant in laminar flow (*Re*: 1500).



Graph7.2: Variations in drop velocity with time instant in turbulent flow (*Re*: 3000) for different drop diameters



Graph7.3: Variations in drop velocity with time instant in turbulent flow (*Re*: 3000) for different contact angles.



Graph7.4: Variations in drop velocity with time instant in turbulent flow (*Re*: 3000) for different viscous liquids.

The velocity of the droplet under turbulent flow for different viscous liquids has been calculated similarly at different time instants and is plotted against time instant as shown in Graph7.4 It has been observed that the movement of mercury droplet is very slow as compared to water droplet with the same pre-defined boundary conditions and key parameters (*Re*: 3000 and drop diameter: 5 mm). Again it has been observed that mercury droplet is approaching towards zero velocity just after 0.5 seconds.

VIII. CONCLUSION

From the extensive study on six different cases the important concluding remarks have been made as mentioned below:

Simulation results without shear flow shows that the shape of the drop changes continuously before reaching the final shape though it has no movement .Air inlet velocity basically influences the movement phenomena of droplet .On shape change phenomena it has not so much influence. It has been observed that for the same drop size, the velocity of movement of the droplet increases with increasing the strength of the shear flow.

The velocity of movement of the drop strongly depends on its size. Shape change phenomena is also significantly depends on drop size. Contact angle has not so much effect on drop movement phenomena but in shape change phenomena it has a considerable effect. Movement and shape change phenomena also depends strongly on the viscosity of the liquid.

IX. SCOPE FOR FUTURE WORK

Following studies may be entertained for the further study of this 3D drop dynamics problem;

- Dynamics of droplet with phase change process through conduction and convection.
- Investigation of drop dynamics for other viscous liquids (as only two viscous fluids have been considered in this study).Dynamics of liquid droplet by varying contact angles within the maximum possible range. Analysis of the problem by changing the atmospheric conditions. i.e. at different density and temperature of the atmospheric air.

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