Liquid drop movement over an inclined surface using Volume of Fluid model with finite volume method

A project report submitted in partial fulfillment of the requirement for the Degree of

Bachelor of Technology

in

Mechanical Engineering

by

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Rourkela

CERTIFICATE

It is certified that the project report entitled "**Liquid drop movement over an inclined surface using Volume of Fluid model with finite volume method**" submitted by Bijoy Kumar Duwary (Roll No.109ME0368) has been strictly carried out under my supervision for partial fulfilment of the requirement for the degree of Degree of Bachelor of Technology in Mechanical Engineering from National Institute of Technology, Rourkela, and this work has not been plagiarised from elsewhere to the best of my knowledge.

Place: Rourkela

Date

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A C K N O W L E D G E M E N T

I would like to express my deep sense of gratitude and indebtedness to Dr. Suman Ghosh, Department of Mechanical Engineering, N.I.T Rourkela, for his excellent guidance, suggestions and support. I consider myself extremely lucky to be able to work under the guidance of such a dynamic personality.

I also sincerely thank to Prof. K.P. Maity, H.O.D, Department of Mechanical Engineering, N.I.T., Rourkela for his constant support and encouragement.

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List of symbols

Symbols	Description
ρ	Density(kg/m^3,lb/ft^3)
υ	Overall velocity vector (m/s, ft/s)
E	Total energy, activation energy (J, kJ, cal, Btu)
p	Pressure (Pa, atm, mm Hg, lbf /ft2)
g	Gravitational acceleration (m/s^2, ft/s^2); standard values = 9.80665
F	Force vector (N, lbf).
k_{eff}	Effective Thermal conductivity (W/m-K, Btu/ft-h-F).
T	Temperature (K, $^\circ$C, $^\circ$R, $^\circ$F).
S_h	Volumetric heat source(j/m^3).
t	Time(s).
α_q	Volume fraction of qth phase.
ρ_q	Density of qth phase (kg/m^3, lbm/ft^3).
E_q	Energy of qth phase.
μ	Dynamic viscosity (cP, Pa-s, lbm/ft-s).
k	Turbulence kinetic energy.
ε	Dissipation rate.
c_1,c_2,c_μ	Constants.
σ_k	Turbulent Prandtl numbers for k.
σ_ε	Turbulent Prandtl numbers for ε.

ABSTRACT

When a liquid drop of given volume is placed on an inclined solid surface then it tends to slide down. This depends on various factors like surface Tension of fluid pair, inclination angle, volume of the liquid, nature of solid surface etc. In an inclined plane, the motion of a liquid drop is due to the effect of gravity force, friction force and viscous effect of liquid drop. If we change the different parameters of the liquid drop then the velocity of the drop will also change accordingly. This work represent the study of movement of liquid drop by varying three parameters namely inclination angle ,surface tension and contact angle for the solid liquid pair using VOF model with finite volume method.in the present work we changes these parameter one at a time by keeping other constant and visualize the effect of this parameter on the velocity of the liquid drop. After that different curve which shows the effect of these parameters are drawn for the given liquid.

Keywords: Computational Fluid Dynamics, Volume of Fluid, Multiphase, rolling motion,drop.

1. INTRODUCTION AND LITERATURE REVIEW:

In this section the problem has been first introduced then an exhaustive literature survey has been made. After that the gaps in the literatures have been point out and at last aims and objective for the present work have clearly mentioned.

1.1: Introduction:

The applications based on controlled and regulated movements of liquid drops over a surface has been finding tremendous growth, starting from its most extensive use in cooling of hotspots in electronic circuits, micro pumps, printing and coating techniques (especially over unreachable places), hydrophobic surface designs, valve regulating mechanisms and has a future prospect to be used in controlled nuclear and other micro reactions to have an efficient control over the rate of reaction. The extensive natural biological processes like photosynthesis, absorption of minerals, blood circulation and various other essential phenomena depends upon the process. The well controlled regulated movement of the liquid phases, their intermixing, and regeneration, when fully controlled could enhance the capability of the phenomena to have highly efficient (owing to their low energy requirements) and sophisticated applications. In

recent years, the study of superhydrophobic surfaces has been increases , due to their applications in, different processes.Wettability studies usually involve the measurement of contact angles as the primary data, which indicates the degree of wetting when a solid and liquid interact. Small contact angles (>90°) correspond to high wettability, while large contact angles (<90°) correspond to low wettability.

Consider a liquid drop resting on a flat, horizontal solid surface (Fig. 1.1). The contact

angle is defined as the angle formed by the intersection of the liquid-solid interface

and the liquid-vapor interface (geometrically acquired by applying a tangent line from the contact point along the liquid-vapor interface in the droplet profile).

Figure 1.1 shows the three different values of contact angle for different liquid solid pair here we can see a small contact angle(<90) is observed when the liquid spreads on the surface, here the liquid wet the solid surface, i.e the fluid will spread over a large surface.while a large contact angle (>90)is observed,here wetting of the surface does not takes place so the liquid will form a compact liquid.Furthermore, contact angles are also applicable to the liquid-liquid interface on solid.

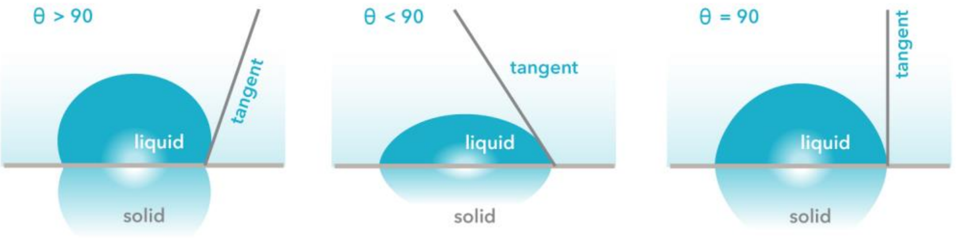


Fig.1.1 Illustration of different contact angles formed by liquid drops on a smooth homogeneousbsolid surface.

As far as shape of the liquid drop is concerned Ideally, the shape of a liquid droplet is determined by the surface tension of the liquid, Surface tension is a contractive tendency of the surface of a liquid that allows it to resist an external force .In a pure liquid, each molecule in the bulk is pulled equally in every direction by neighboring liquid molecules, resulting in a net force of zero. However, the molecules at the surface are not surrounded by molecules in all direction due to this a net force is acting on the liquid drop and they are pulled inward by the neighboring molecules creating an internal pressure. As a result, the liquid freely contracts its surface area to maintain the lowest surface free energy.From our daily experience , we know that rain drop and bubbles are spherical, which gives the minimum surface area for a fixed volume. This intermolecular force to contract the surface is called the surface tension, and it is responsible for the shape of liquid droplets. In practice, apart from surface tension force gravity also acting on the droplet and it is try to deform the liquid drop consequently, the contact angle is determined by a combination of surface tension and external forces (usually gravity). Theoretically, the contact angle of a liquid drop on an ideal solid surface is given by Thomas young's equation defined by the mechanical equilibrium of the dropunder the action of three interfacial tensions.

$\Upsilon lg \cos \Theta = \Upsilon sg - \Upsilon sl$ ………………..1.1

where Υlg , Υ sg, and Υsl represent the liquid-gas, solid-gas, and solid-liquid interfacial tensions, respectively, and Θ is the contact angle. Equation (1.1) is usually called as

to as Young's equation.

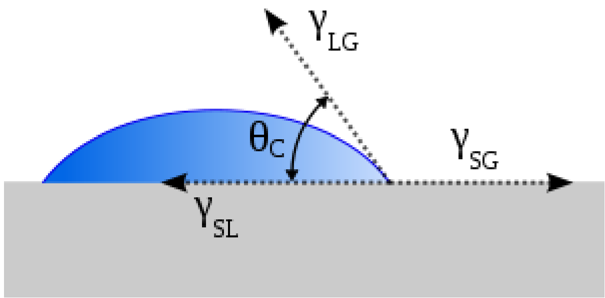


Fig. 1.2 Contact angle of a liquid drop on a solid surface

When a drop of liquid is placed over an inclined surface, the dynamics of liquid drop depends upon a large number of factors that are a function of nature of the fluid, the contact angle between the fluid and solid surface, the inclination angle,the surface tension of the liquid, nature of interaction between them, gravity effects, surrounding medium and geometry of the surface. The dynamics of a small liquid drop is a bit different than that of the bulk fluid because of the surface tension force dominating over the inertial and viscous forces. . The nature of the motion is determined by the balance between the motivating force and the resisting hydrodynamic force from the solid surface and the surrounding gaseous medium. Similarly, if there is a variation of contact angle of a liquid drop on an inclined plane, there exist a contact angle hysteresis over the circumferential plane which makes the drop assume an asymmetrical shape with a net unbalanced force. when liquid drop is placed on an inclined surface then the drop start to move the movement of the liquid can be sliding or rolling in nature and it is mainly depends on the contact angle between the liquid drop and solid surface, if the surface is super hydrophobic(contact angle more than 150˚) then the drop movement is rolling in nature on the other hand if the drop partially wet the surface then movement will be sliding in nature. When a liquid drop is placed on an inclined surface ,there occurs an imbalance of surface tension over the circumferential plane of a droplet base, with a net unbalanced force in the direction of increasing contact angle, hence, the center of mass of the system tries to attain the minimum position and a net rearrangement of the particles occur finally resulting in the movement of the drop in this work Computational Fluid Dynamics method based on Volume Of Fluid model has been used to simulate the movements of liquid drops for various values of surface tension and contact angle. The effect of the various factors on the overall movement of the liquid drop have been tabulated and Mobility maps representing volume versus inclination angle and wettability curves plotting wettability gradient versus velocity of the drop have been prepared for different fluid materials over different solid surfaces.

1.1.2: Literature Review:

The first official theory established dates back to 1978 when Greenspan (1978) inspired by the work of Carter, developed a model for the movement of a small viscous droplet on a surface is and is based on the lubrication equations he uses the dynamic contact angle to describe the forces acting on the fluid at the contact line. A method had been suggested by Gingold et al. (1977) to use of statistical technique to get analytical expression for a physical variable from a known distribution of fluid element. Brochard (1988) has been explained The effect of chemical and thermal gradients on the motion of droplets on solid surfaces quantitatively in terms of spreading coefficient for partial wetting and complete wetting fluids. Chaudhury and Whitesides(1992) shows experimentally the uphill motion of water droplet by producing hydrophobic and hydrophilic gradients over a small distance apart on the surface of a polished silicon wafer by exposing it to the diffusing front of a vapour of decylthrichlorosilane. Fluid mechanics has been applied by Shikhmurzaev (1997) to predict the dynamic spreading of a macroscopic liquid droplet where the energies associated with the volume are dominant and on reducing the droplet size to sub-millimeter level, surface energy becomes a dominant factor. It has been discovered by Gau et al. (1999) that chemically structured faces lead to morphological wetting transitions at which the wetting layer changes its shape in a characteristic and abrupt manner. He plotted the morphology diagram as a function of the aspect ratio of the channel and the contact angle. A microfluidic capillary system that autonomously transports aliquots of different liquids in sequence has been demonstrated by Gallardo et al. (1999) observed a rapid motion of similar water drops when condensation occurred on cold surfaces has been observed by Daniel et al. (2001).

The behavior of liquid drops on solid substrates is very important for different processes. Examples include spray cooling of surfaces was study by Grissom, W. M. and Wierum, F. A.(1981) they gave a conduction-controlled analytical model of droplet evaporation which gives fairly good agreement with experimental measurements at atmospheric pressure , solder jetting was study by Attinger et al. (2000) they use Eutectic solder (63Sn37Pb) to know the dynamics of molten solder microdroplet impact and solidification on the substrate it was investigated using a flash microscopy technique this study presents the first published experimental results on the transient fluid dynamics and solidification of molten microdroplets impacting on a substrate at the abovementioned time and length scales that are directly relevant to the novel solder jettingtechnology. However, in recent days, the dynamics of microdrops becomes an major topic for many researcher, Squires and Quake (2005) whose behavior is critical to the functioning of a number of microfluidic devices. The ink-jet printer behavior is study by Burns et al. (2003); Calvert (2001) and it is beginning to become a viable alternative to traditional fabrication methods apart from them Derby (2010) analyse the building of complex 3D structures through additive manufacturing. In such processes, the interaction of the microdrops with the solid substrate on which it impacts is directly related to the quality of the product, so that it is important to be able to predict and understand the behaviour of microdrops in such situations.

It has been demonstrated by Beltrame et al. (2001) that the onset of droplet motion on non-ideal real substrates under lateral driving is strongly influenced by substrate defects and a finite driving force is necessary to overcome the pinning influence of micro scale heterogeneities. The movement of a liquid drop towards the more wettable part of the gradient with typical speeds of 1-2mm/s has been experimentally demonstrated by Daniel and Chaudhury (2002). It has been claimed that the observed lower speed was due to the effect of contact angle hysteresis over the driving force. Application of periodic force to a drop resting on such a gradient surface enhances the force along the gradient. The driving force due to a contact angle gradient over a drop using a flexible glass micro needle was directly measured by Hitoshi and Satoshi (2003). It has been concluded that a balanced drag force with the driving force need to be reconstructed, using a new concept of solid like friction. The effects of size of the chains composed of the drop and initial velocity of the drop on the drop terraced spreading have been studied by Wu et al. (2003). The chain size effects on the base radius of drop have been studied at zero initial velocity. The longer the chain, the slower is the spreading. With a nonzero initial velocity, the drop base radius increases with increasing initial velocity before the drop splits into smaller separated drops. Experiments have been performed over a variety of liquids by Daniel et al. (2004) and the results reported the enhanced velocities by vibrating the substrates. The movement of a drop as a result of the hydrodynamic force experienced by a spherical cap drop over a solid surface with a wettability gradient has been demonstrated by Subramanian et al. (2005). Experiments have been reported by Grand et al. (2005) on the shape and motion of millimeter sized droplets sliding down a plane in a situation of partial wetting. One of the solutions has been based on an approximation of shape as a collection of wedges and the other based on the lubrication theory which is good when the length scale of the drop is large as compared with the slip length. A comparative study of contact angle measurements over a variety of polymeric materials and its hysteresis behavior of static and dynamic contact angles was made by Krasovitsky (2005). An asymptotic model using lubrication theory has been proposed by Pismen and Thiele (2006) to demonstrate the motion of a drop over a gradient surface. Experimental results on the motion of tetraethylene glycol drops in a wettability gradient present on a silicon surface with a developed theoretical model have been verified by Subramanian et al. (2006). Experiments have been performed on the motion of drops of tetraethylene glycol in a wettability gradient present on a silicon surface and these are compared with recently developed theoretical model by Moumen et al. (2006) according to which, the velocity of the drops are a strong function of position along the gradient. To explain this behavior a quasi-steady theoretical model has been given which balances the local hydrodynamic resistance with the local driving force. It was shown that a model in which the driving force is reduced to accommodate the hysteresis effect inferred from the data is able to remove most of the discrepancies between observed and predicted velocities. Contact angle hysteresis on chemically patterned and super hydrophobic surfaces, as the drop volume is quasi statically increased and decreased both two (cylindrical drops) and three (spherical drops) dimensions have been investigated by Kusumaatmaja et al. (2007)using analytical and numerical approaches to minimize the free energy of the drop. Axisymmetric droplet spreading has been investigated by Ding et al. (2007) numerically at relatively large rates of spreading, such that inertial effects also have a role. Results have been presented for the apparent contact angle as a function of dimensionless spreading with various parameters like Ohnesorge number, slip length and initial conditions. The results indicate that there is no such universal relation when inertial effects are important. In two dimensions, the result obtained reveals that a slip, jump, stick motion of the contact line. In three dimensions, this behavior is present, but the position and magnitude of the contact line jumps are sensitive to the details of the surface patterning. For the first time used a numerical technique based on lattice Boltzmann method to investigate the motion of a liquid drop over a chip under a wettability gradient was proposed by Huang et al. (2008). Theoretically and experimentally the effects of gravity on the shape and focal length changes of liquid droplets with the effect of droplet size and outside atmospheric conditions have been demonstrated by Hongwen et al. (2010).The motion of a liquid drop over a surface using a 3D technique that combines diffuse interface in a smoothed particle hydrodynamics simulation to study the internal fluid structure and the contact line dynamics has been demonstrated by Das and Das (2010). The study reveals the impact and interdependence of a variety of factors like volume, inclination and strength of the wettability gradient over the movement of the droplet.

When a liquid drop is placed on an inclined plane then there is always an ambiguity that the drop will slide or roll on the inclined surface yarnold (1938), was the first to observed this phenomenon by observing the dust particle on the mercury droplet as slides down the inclined plane,based on his observation he proposed that mercury droplet rolls on the surface later on Alle and Benson,(1975) uses an injected dye into mercury droplet and found similar results. Recently Sakey et al.(2006) study this behavior on number of hydrophobic surfaces,for this they had taken water as the moving liquid. A similar method was used by Song F. (2008) to study water droplet motion on superhydrophobic methyl-terminated organosilane-modified silicon wafer surfaces.The droplet size and surface hydrophobicity were found to determine the type of drop motion.

1.1.3: Gaps in the Literature:

As could be concluded from above, Inspite of the advancements in the field of dynamics of a drop, as can be seen, not much advancement has been made to study the feasibility and accuracy of the computational fluid dynamics model using VOF method to investigate and correlate the theoretical results with the observed motions. a very few theoretical models have employed to show the behavior of liquid drop against surface tension. and hardly any few of them are perfectly able to correlate the effect of surface tension ,contact angle and the inclination angle. Besides, very few theories above have been accurately able to describe the observed velocities under different boundary conditions and the changes in their behavior as a consequence of alteration in external forces. Hence there is a need for a systematic study and analysis on the overall dynamics of bubble drop movement under the variance of external effects and their correlation with the observed behavior for an efficient knowledge over the above phenomena.

1.1.4: Aims and Objective:

The present work undertaken lies on the application of Computational Fluid Dynamics method on the Volume of Fluid model which has been used to analyze the dynamics of the motion of drop movement over different surfaces. The result for effect of different parameters on the dynamics will be obtained and will be compared with previous experimental data results and any correlation between them would be inferred and explained, if possible in the form of a model equation or any other form. Also the effect of the type of mesh adopted and the element size on the convergence of the results with those actually observed would be inferred to develop an overall efficient method of evaluation. Attempts will also be made for some corrections and approximations, if applicable, to sort out any discrepancies in the observed behavior.

2. PROBLEM STATEMENT:

In the present work, Computational Fluid Dynamics with finite volume method using the Volume of Fluid model has been used to numerically analyze the movement of a water drop over a solid surface for different values of contact angle, surface tension and inclination angle. The drop would start to slide over the inclination surface until the surface force will balance the component of the gravitational pull along the plane. As a consequence, the drop no longer remains axisymmetric. Similarly, drops with different parameters for same volume of liquid over the plane of different materials have been taken and the results have to be plotted to find the effect of these parameters on the movement of the drop. Cuboidal models representing the system(drop) and the surrounding medium (atmospheric air) has been modeled and meshed with a size sufficiently small such that the accuracy of the results obtained would be within the desired limit. Using the appropriate boundary conditions the phenomena of attainment of the final equilibrium shape of the drop has been studied over finite time duration. Taking one of the examples, the cuboidal model of dimensions 40mm×40mm×15mm has been modeled with a hemispherical droplet of radius 3mm resting at the centre of the inclination plane with angle of inclination 10˚ as shown below. The boundary conditions for different value of surface tension and contact angles have been defined for the fluid solid interface and the resulting movement towards equilibrium position has been recorded over time steps.

3. METHODOLOGY:

The softwares to be used for the analysis include gambit for modeling and fluent for processing and simulation. In most of the cases, the model of the profile surface has to be generated, implicating different boundary conditions. The 3-D model are meshed with interval sizes with such values that the results obtained won't go beyond the desired accuracy. The bounding surfaces are named as per data. The mesh files obtained are imported in the fluent solver in 3d version. Using an unsteady pressure-based solver with Volume of Fluid multiphase model, with two phases' viz. water and air and using a laminar flow model, the operating conditions of gravity acting vertically downwards are set. The interaction of the water drop with the surface, under the influence of atmospheric air is set by specifying constant surface tension acting between them. The contact angle between the solid surface and the drop over it is first assumed to be constant at 90° initially. Here the PISO velocity coupling solver was adopted.

3.1 Numerical calculation:

The computational approach adopted in the present study is based on finite volume method of the three dimensional unsteady pressure based Navier-Stokes with Volume of Fluid model and k-ε turbulent model. VOF model is used when there are two or more immiscible fluids are present to track and locate the fluid- fluid interface. Here all the fluid shared the same single set of equations, and the volume fraction of each of the fluids in each computational cell is tracked throughout the domain. A single momentum equation is used for both the fluid i.e., water and air.

3.1.1 Governing Equation:

The different governing equations used are:

(1) The Momentum Equation:-In VOF model a single momentum equation has been used throughout the domain and it is given by,

$$\frac{\partial}{\partial t}(\rho v) + \nabla.(\rho.v.v) = -\nabla p + \nabla.[\mu(\nabla v + \nabla v)] + \rho g + F \qquad \text{..............} (1)$$

It depends on volume fraction of each phase and the fluid properties.

(2) The Energy Equation:-

$$\frac{\partial}{\partial t}(\rho E)+\nabla.(v(\rho E+p))=\nabla.(k_{eff}\nabla T)+S_h \quad \text{............... (2)}$$

Here E treated as mass averaged variables,and it is given by,

$$E=\frac{\sum_{q=1}^{q=n}\alpha_q\rho_q E_q}{\sum_{q=1}^{n}\alpha_q\rho_q} \quad \text{............... (3)}$$

For k-ε turbulent model:

$$\frac{\partial\rho k}{\partial t}+\frac{\partial\rho ku}{\partial x}=\frac{\partial}{\partial x}(\frac{v_t}{\sigma_k}\frac{\partial k}{\partial x}+v\frac{\partial k}{\partial x})+p_k-\rho\varepsilon \quad \text{............... (4)}$$

$$\frac{\partial\rho\varepsilon}{\partial t}+\frac{\partial\rho\varepsilon u}{\partial x}=\frac{\partial}{\partial x}(\frac{v\partial\varepsilon}{\sigma\partial x})+c_1\frac{\varepsilon}{k}p_k-c_2\rho\frac{\varepsilon^2}{k} \quad \text{............... (5)}$$

where the generated item of turbulent kinetic energy,

$$p_k=v_t[\frac{\partial u_i}{\partial x_i}+\frac{\partial u_j}{\partial u_j}]\frac{\partial u_i}{\partial x_j} \quad \text{............... (6)}$$

the turbulent viscous coefficient $v_t=\frac{\rho c_\mu k^2}{\varepsilon}$ and the constant value:

C_1=1.44,C_2=1.92,σ_z=1.0,σ_ε=1.3,C_μ=.09

3.1.2 Boundary conditions:

Pressure inlet boundary at top face has been used to define the pressure at inlet along with all other scalar properties of flow, and all other faces i.e. left, right, front, rear and bottom part of the cube was set as wall. In wall boundary condition stationary wall was selected as wall motion and in shear condition no slip was chosen. The no slip condition indicates the fluid sticks to the wall and moves with same velocity of wall, if it is moving.

3.1.3 Grid employed:

A body fitted hexagonal grid has been taken as shown in Fig. The type of meshing scheme was cooper type in cooper meshing scheme GAMBIT treats the volume as consisting of one or more logical cylinders each of which is composed of two end caps and a barrel. Faces that include the caps of such cylinders are called “source” faces; while the other cylinders are called “non-source” faces. Finally interval size of the grid was set to a value of 0.000375 m.

3.1.4 Residual and convergence:

Residuals are used for checking convergence of the solution. Here we have used scale residual because it is a more appropriate indicator of convergence of this type of problem. FLUENT scales the residual using a scaling factor which represent the flow rate of a general variable through the domain. In this study a fixed value of 0.00001 was selected for the absolute criteria of continuity, *x*- velocity, *y*-velocity, *z*-velocity and energy.

4. RESULTS OBTAINED:

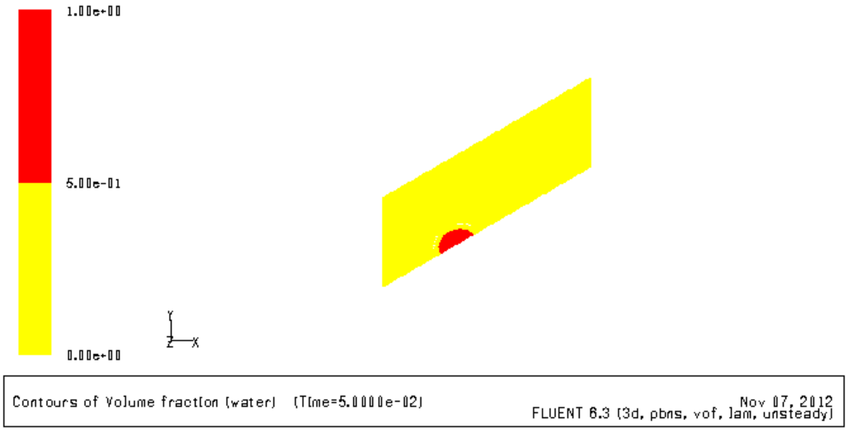
The VOF model is used to investigate numerically the movement of the water drop over an inclined plane. Here we have observed the movement of liquid drop by varying three parameters namely 1)inclination angle, 2) surface tension and 3) contact angle between the liquid and solid surface .

In this part we are showing the effect of variation of these parameters on the movement of liquid drop:

4.1Inclination angle: To know the effect of inclination angle on the movement of liquid drop we have taken three different planes with different angle of inclination i.e 30˚,45˚ and 60˚ .To know the effect of inclination angle on the movement of liquid drop we have taken the same drop with same radius(3 mm) for all three cases. Apart from this we have taken other variables like surface tension(.0736N/m),contact angle(90°),density of water drop(998 kg/m3) etc. same for all the three cases. In all the three cases first we have calculated the maximum velocity which is attained by the drop and then we have compare the other velocity with reference to the maximum velocity.

i)Water drop over an inclined plane with 30° angle of inclination: :-First of all simulation has been started with inclination angle of 30°. A fixed volume of hemispherical model has been developed as an initial approximation of the shape, contact angle was specified a constant value of 90° and was placed at the midpoint of the plane as shown in fig. Under the influence of external forces gravity and friction force the model has been iterated over 2000 time steps with step size of 0.0001s and results have been recorded after every 50 time steps. Due to the effect of gravity and surface tension the velocity of the liquid changes continuously,

. The shapes acquired by the drop over different time steps are shown in Figure below:



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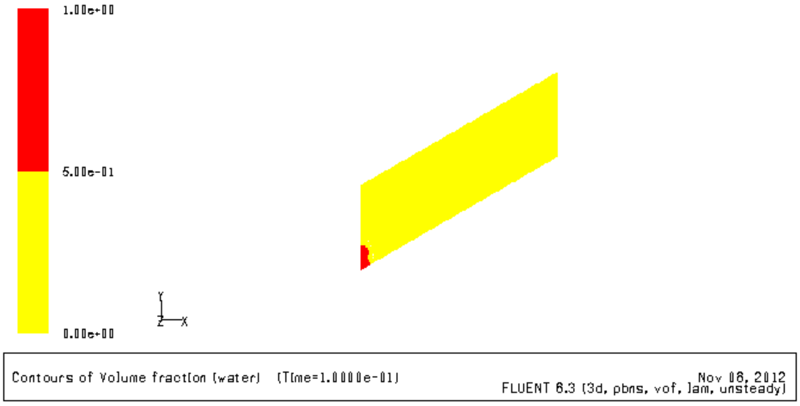

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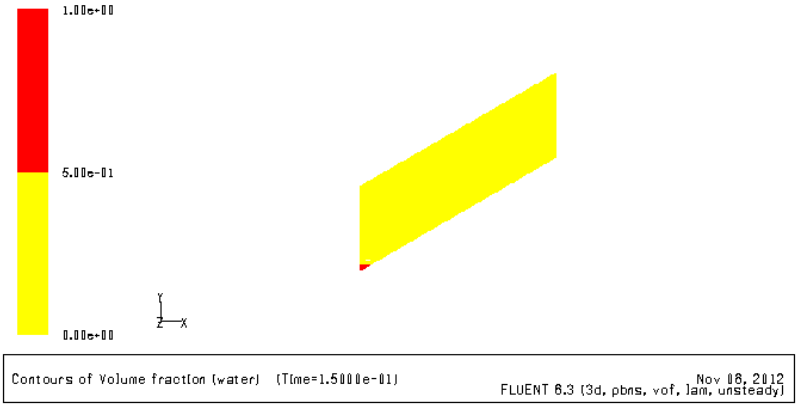

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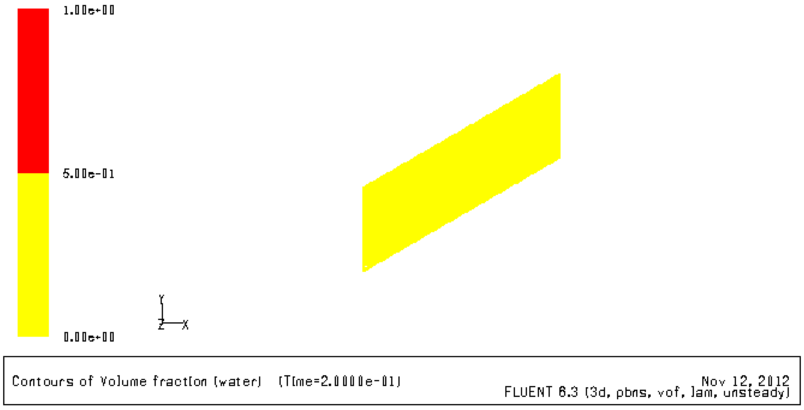

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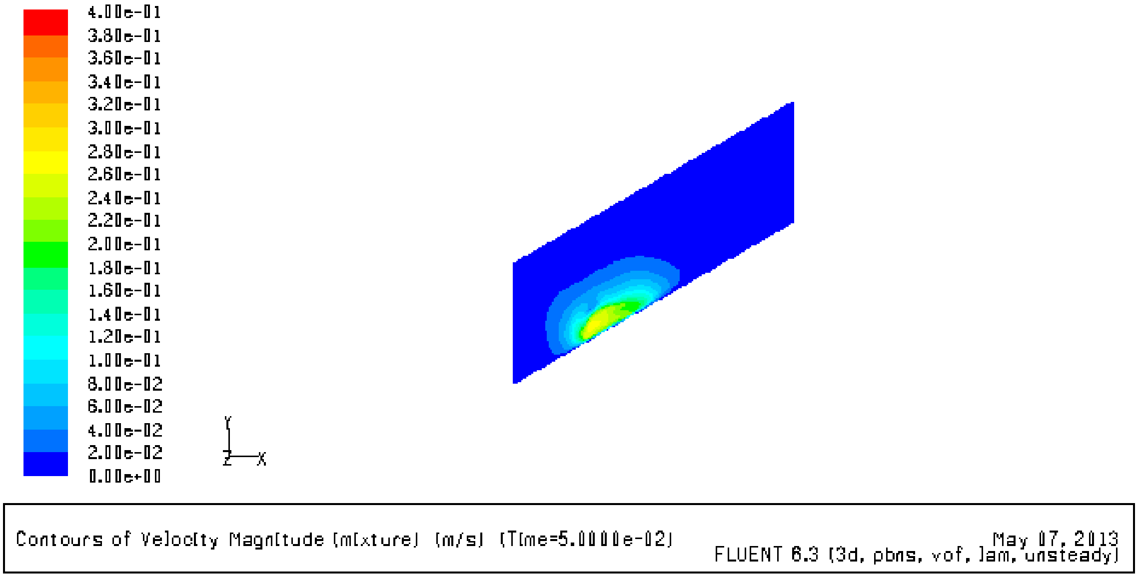
The figure below shows the velocity contour for the liquid drop at different time interval.



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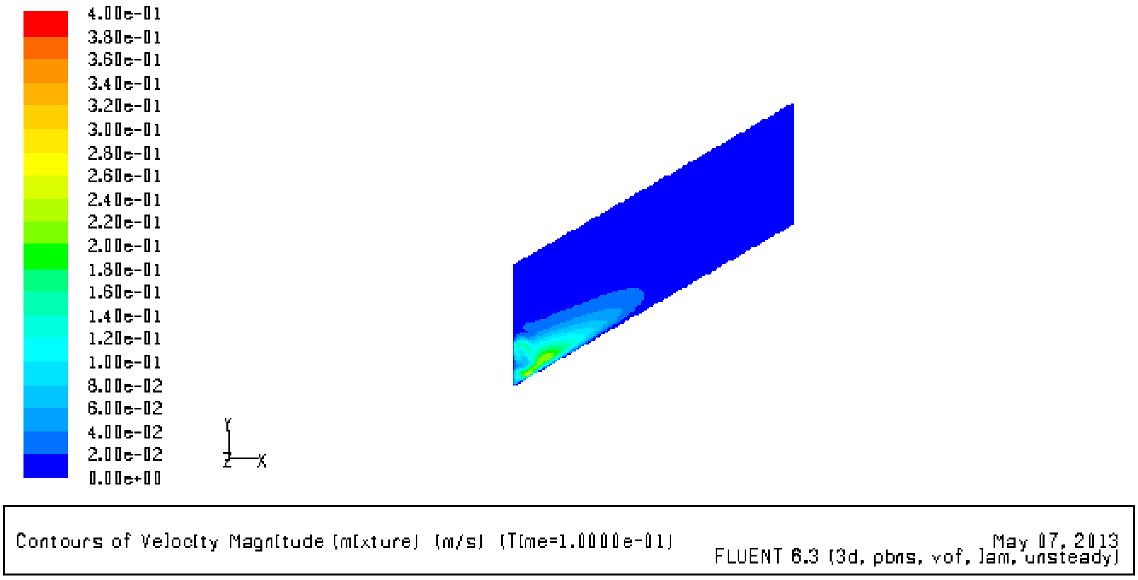

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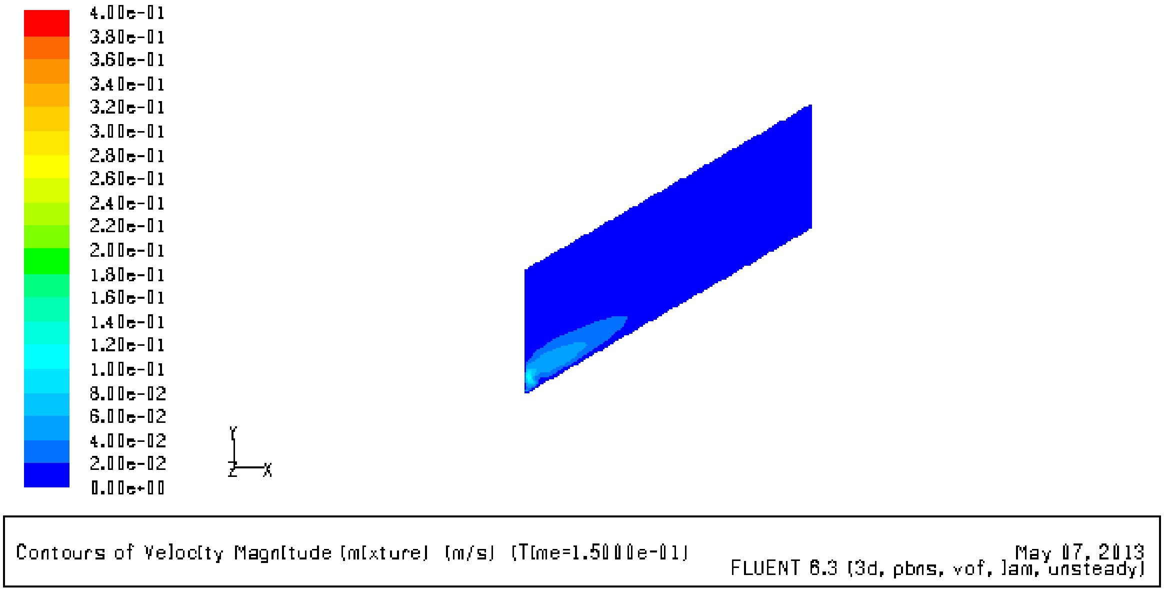

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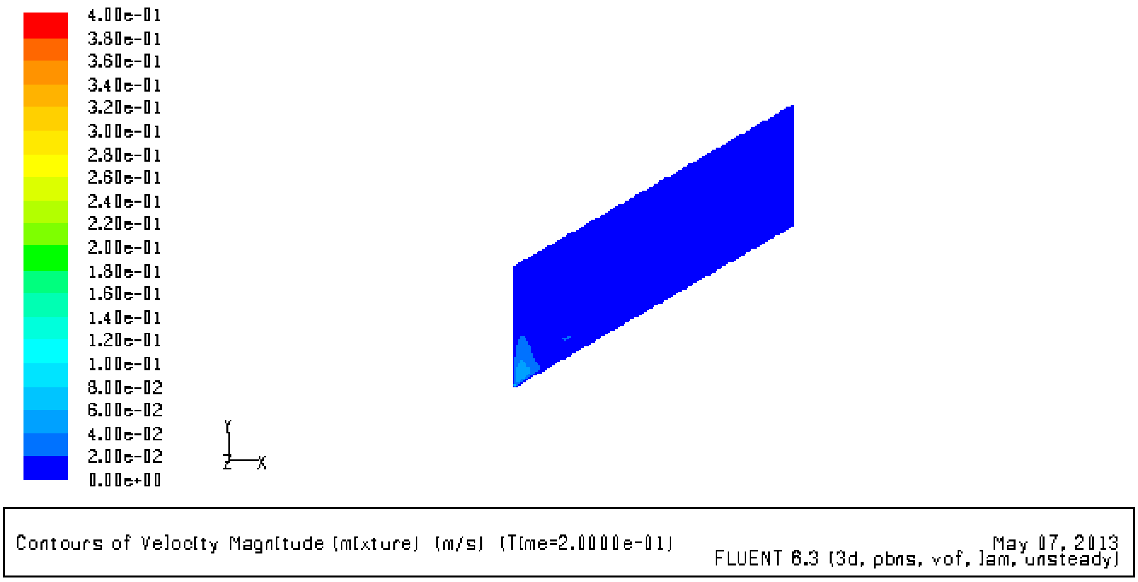
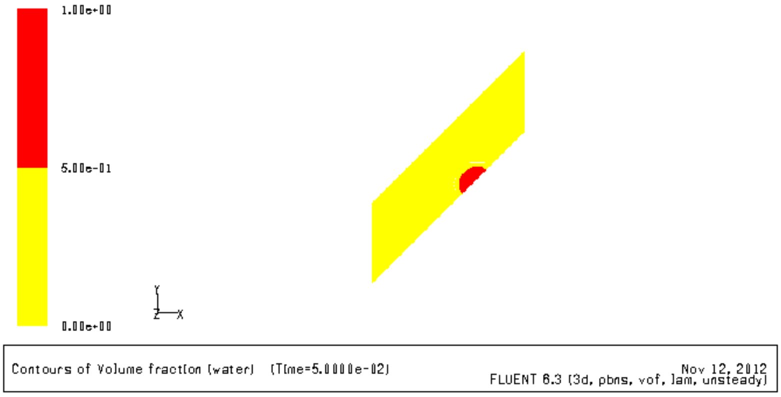


Time=.2 sec

ii) Water drop over an inclined plane with 45°angle of inclination:- Next iteration was done for inclination angle of 45 ° with all other parameter remains the same. Water drop was placed at top of the inclined plane. The drop was allowed to slide over the inclined surface and the movement of the drop at different time interval was captured as shown in Figure :



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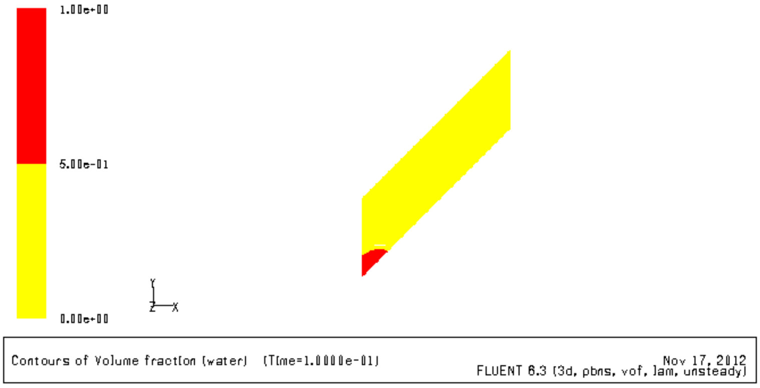

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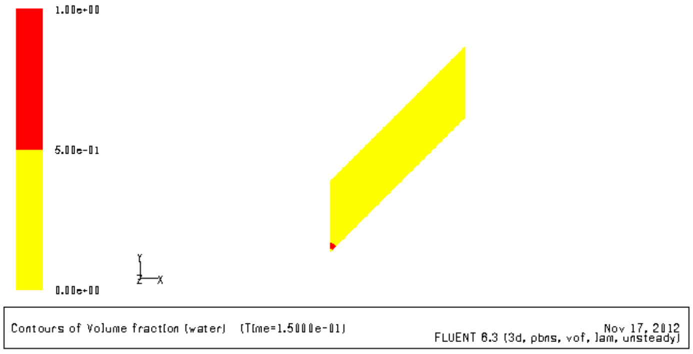

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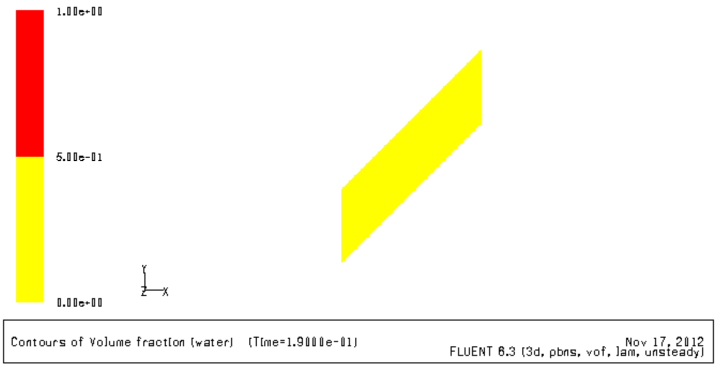
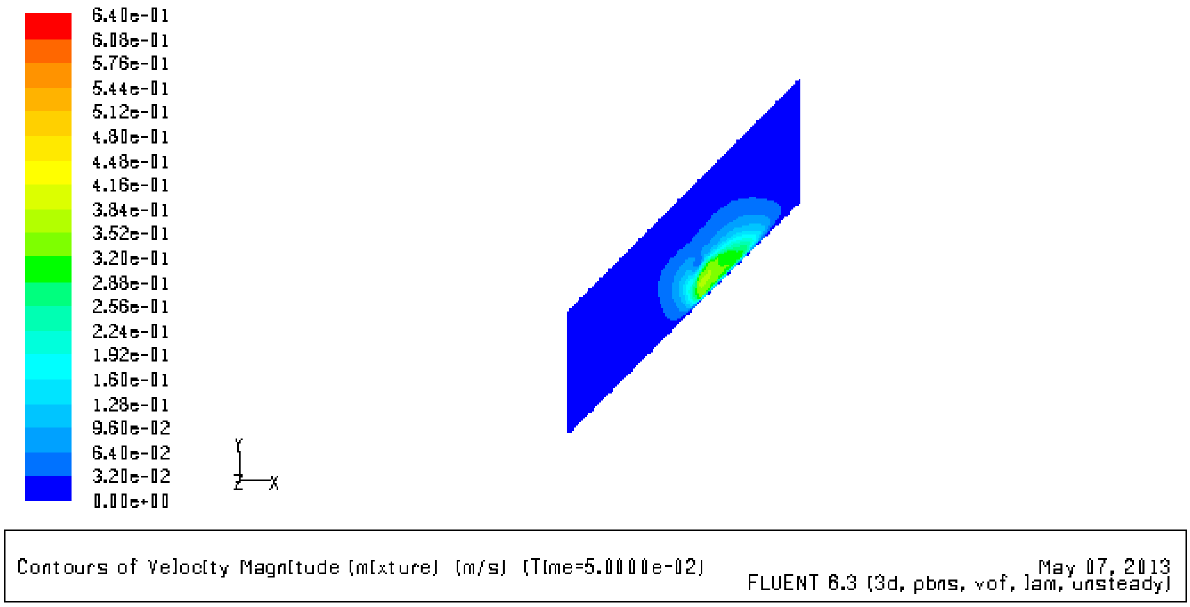
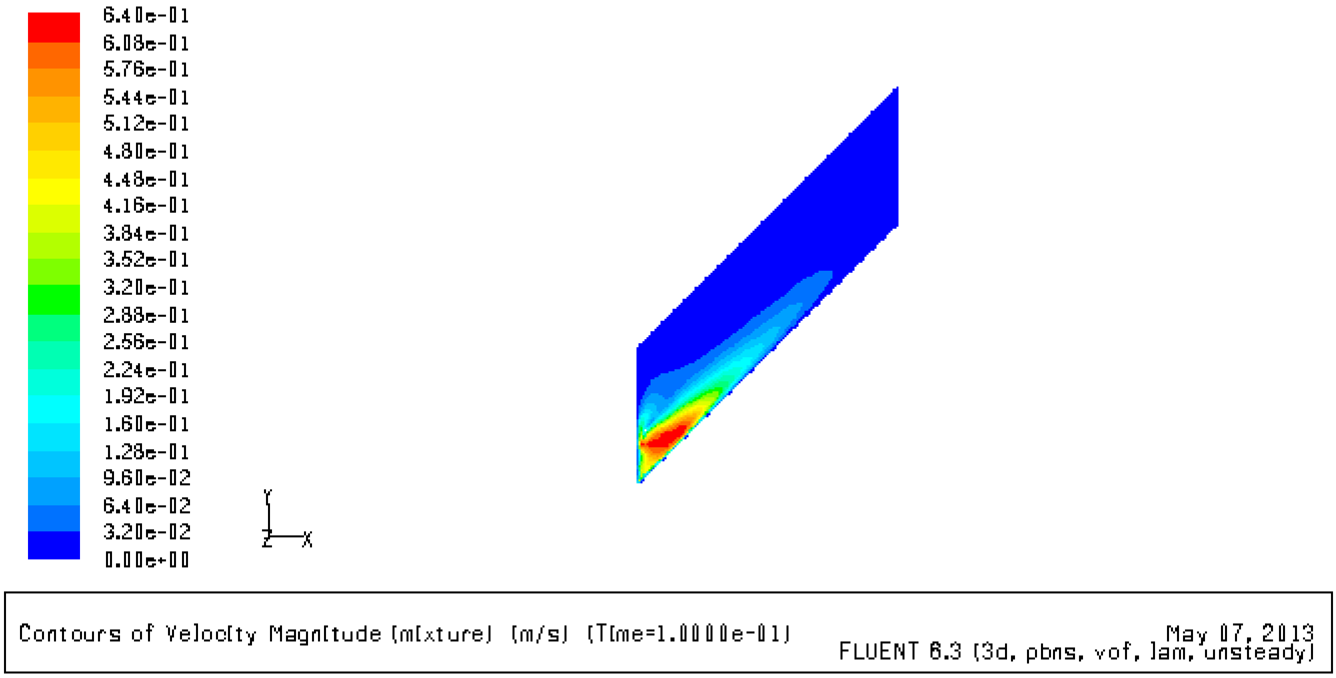


time=.2 sec

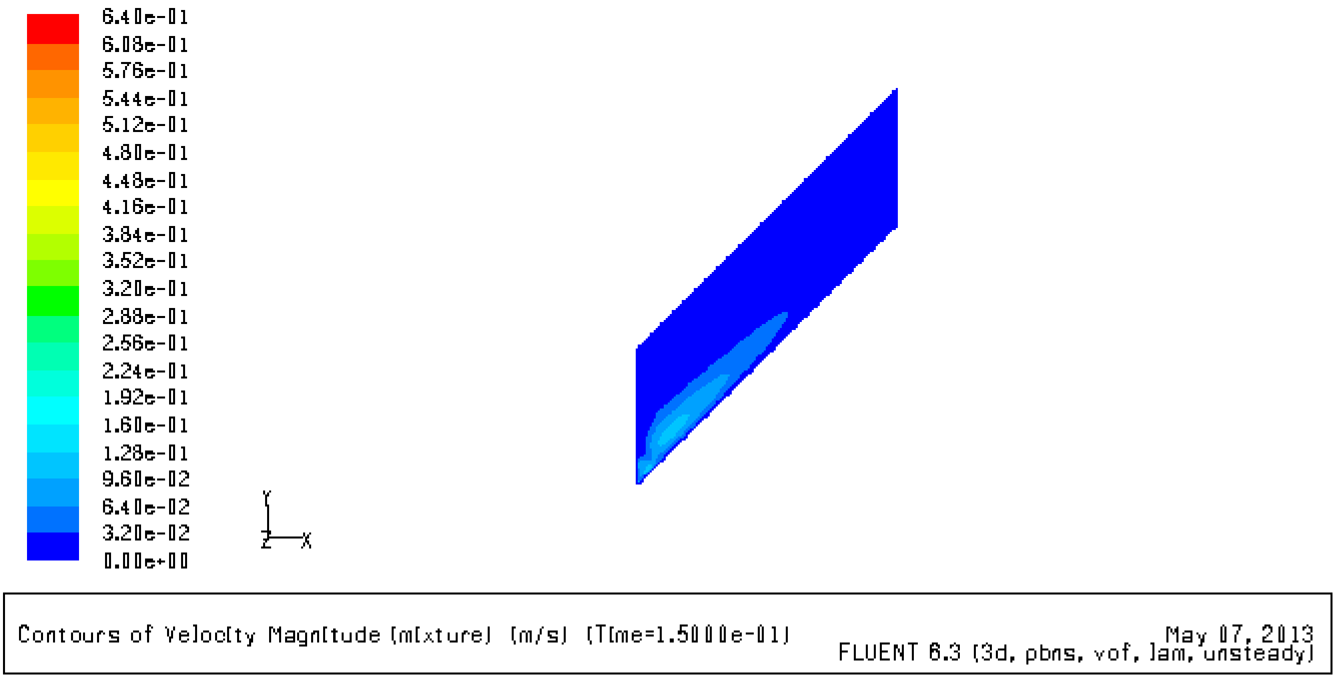
Velocity contour of the drop at different time interval is shown below:



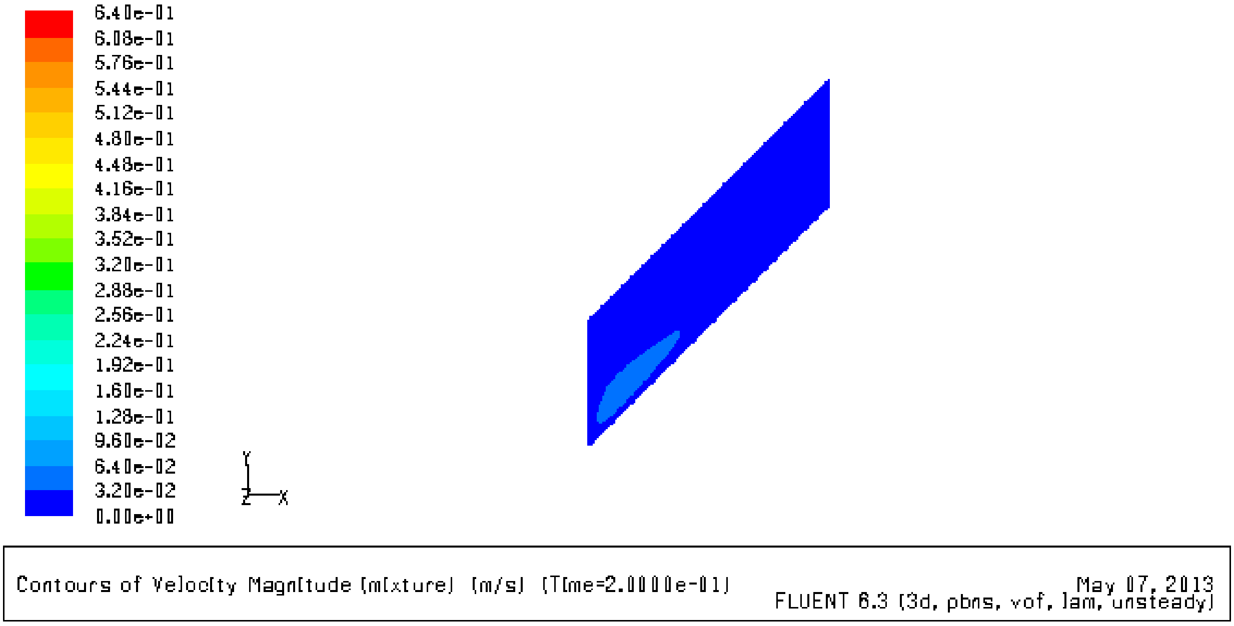
time=.05 sec



time=.1 sec



time=.15 sec

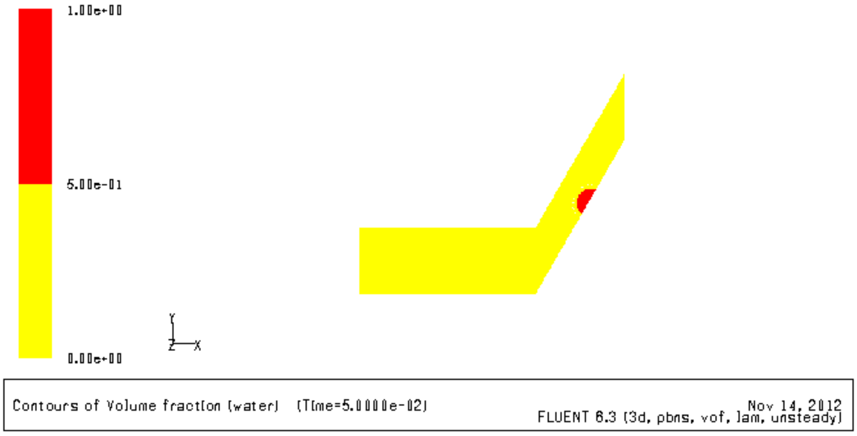


time=.2 sec

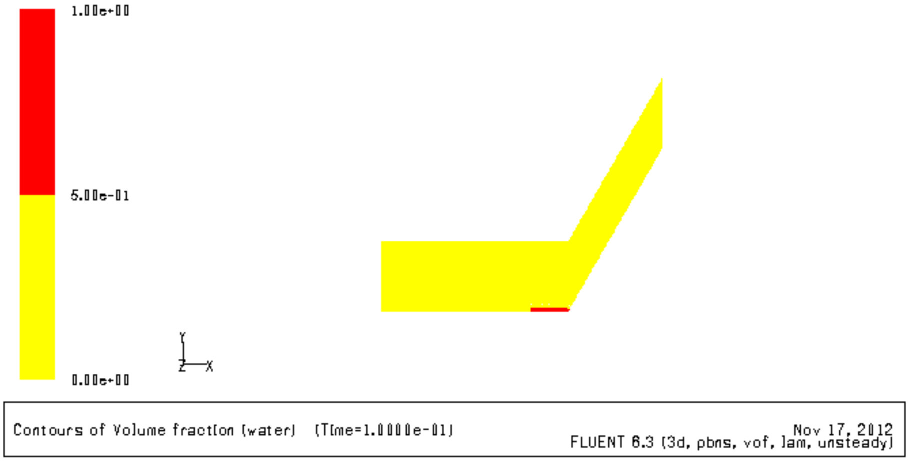
iii) Water drop over an inclined plane with 60 ° angle of inclination:- :- A horizontal inclined surface with inclination angle of 60 ° was taken for the simulation of the water drop.

At starting drop was kept on top of the surface and other variables remains same the shape acquired by the drop at different time interval is shown below:

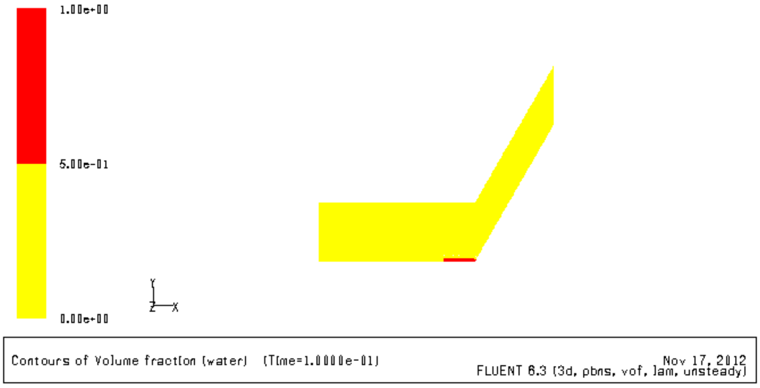
velocity contour of the drop was captured at different time interval as shown in Figure :



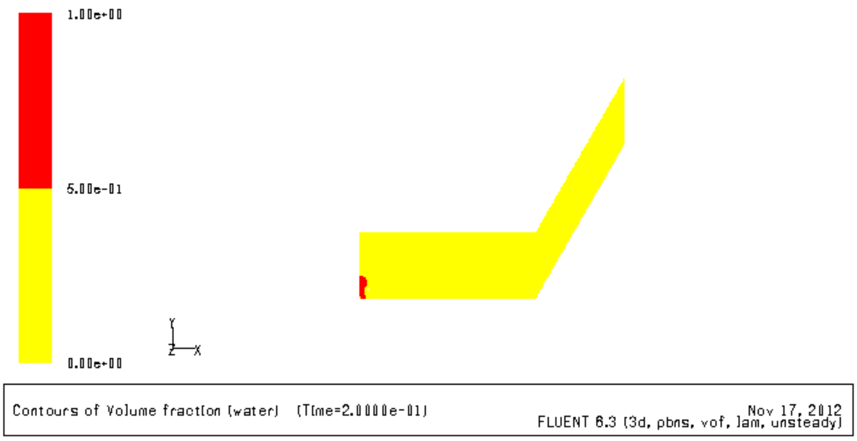
time=.05 sec



time=.1 sec

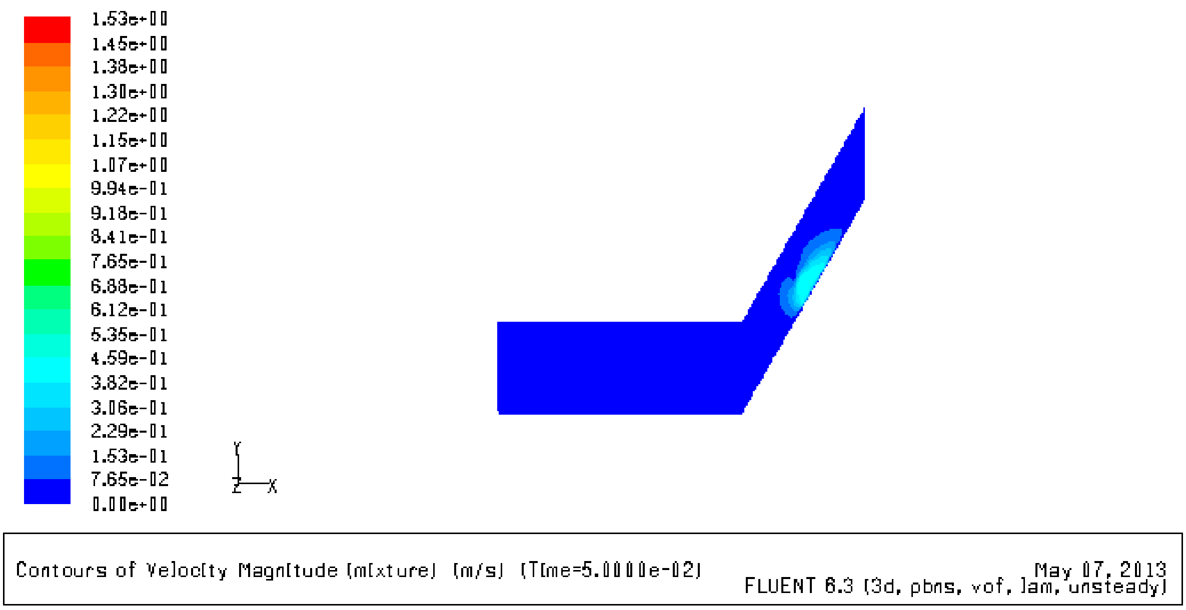


Time=.15 sec

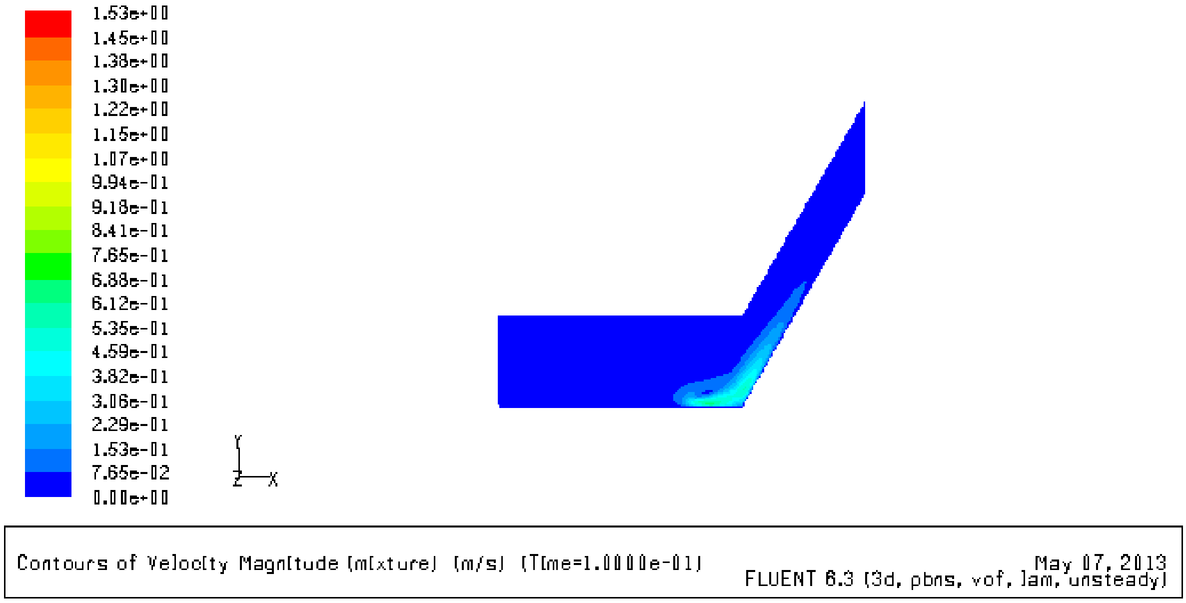


Time=.2 sec

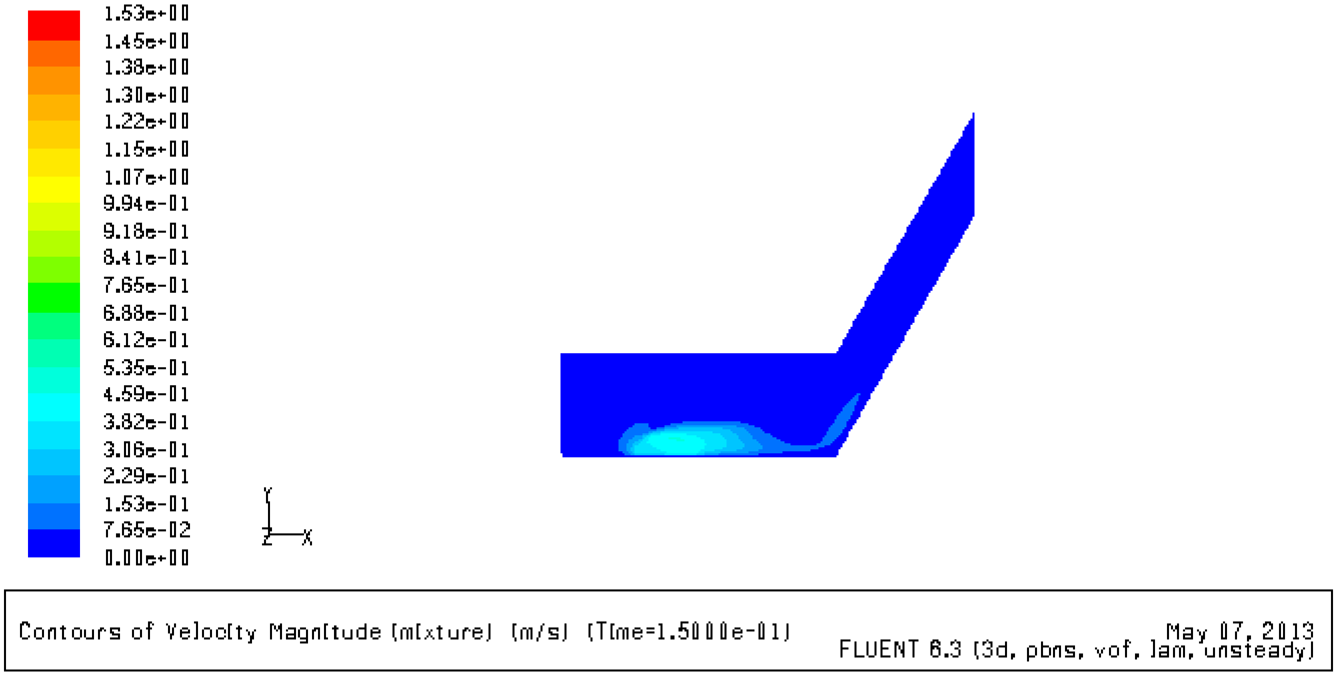
Fig. shows the velocity contour at different time interval:



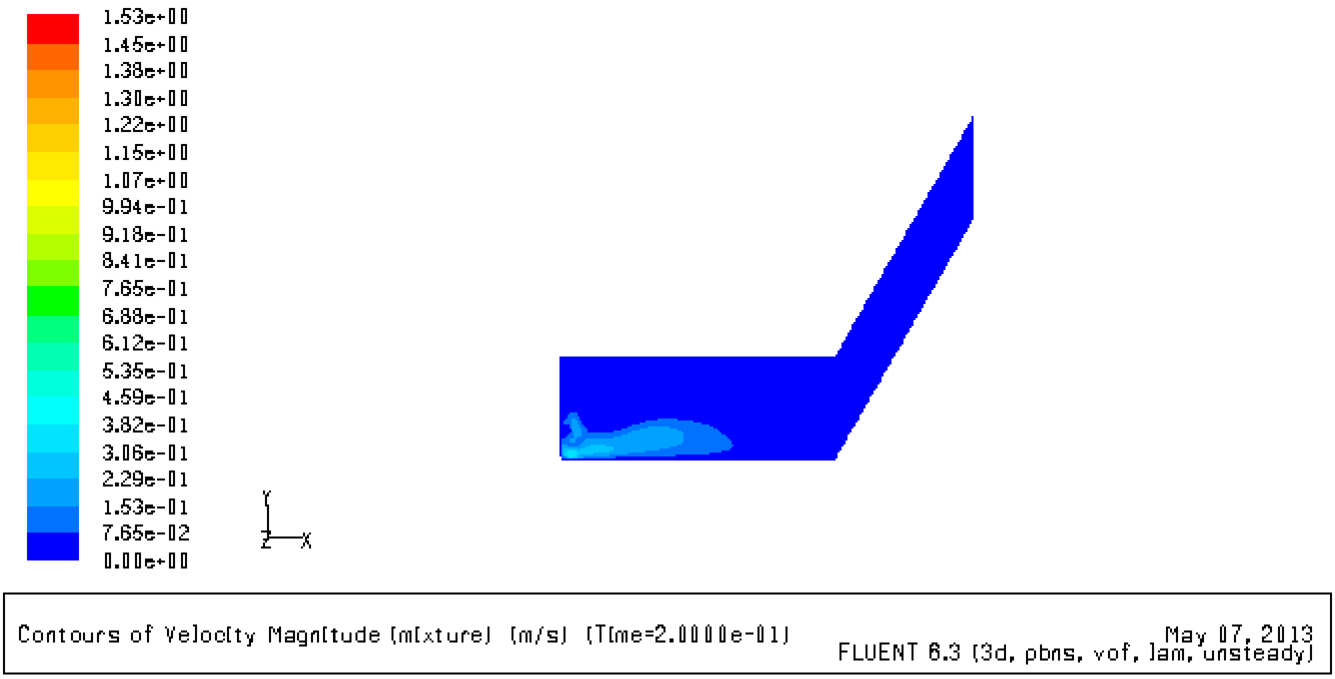
time-.05 sec



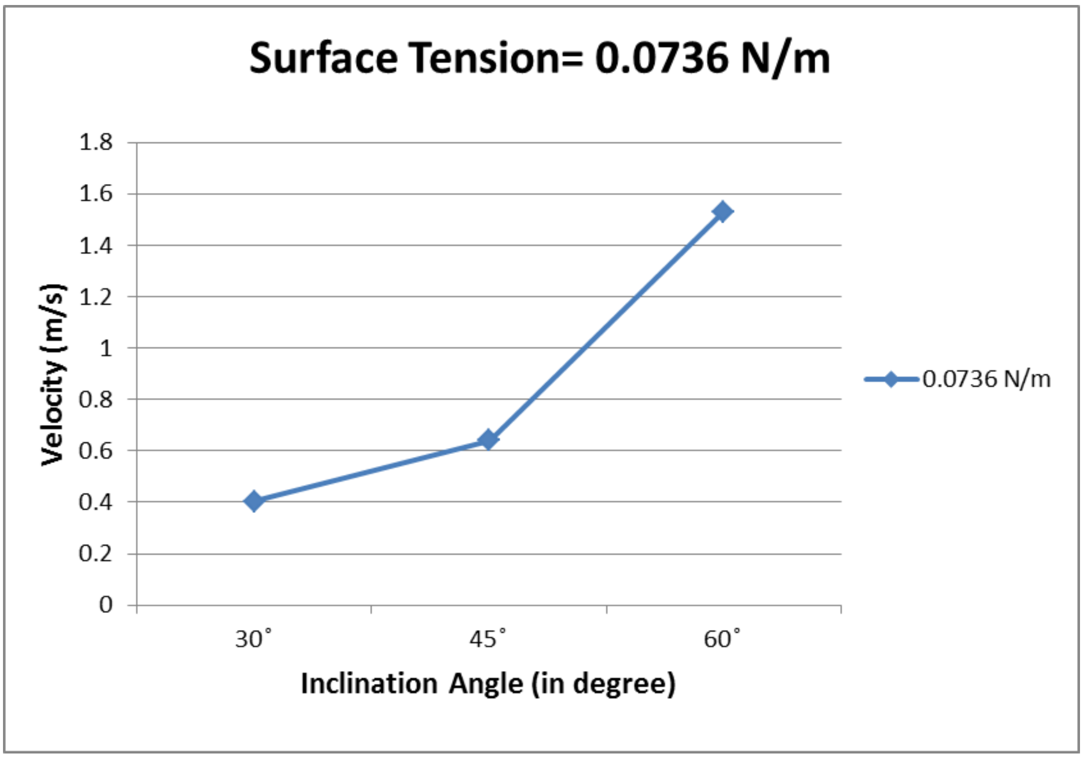
time=.1 sec



time=.15 sec



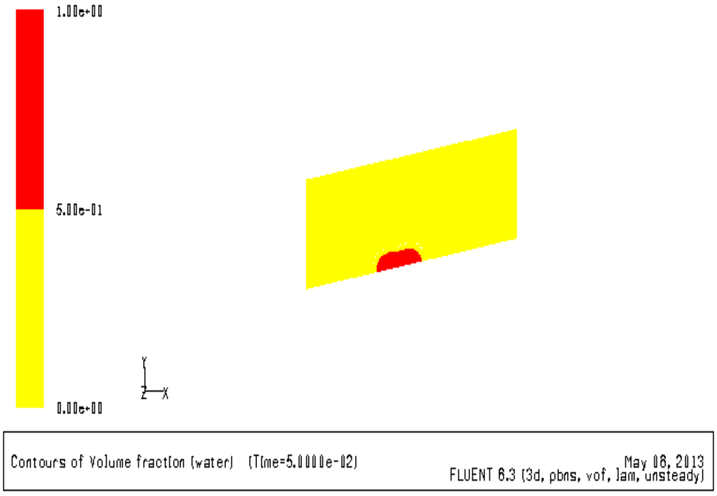
time=.2 sec



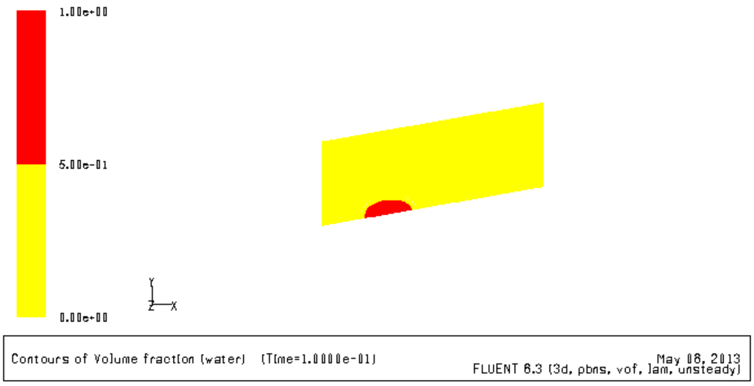
Above graph shows the effect of inclination angle on the maximum velocity attained by the drop.from graph we can see that with increase in inclination angle the velocity of the liquid drop also increase.This can be explained by taking the gravity force into account, as the inclination angle increases the component of the gravity force(gsinϴ)along the inclined plane also increases which cause the increase in velocity for the liquid drop.

4.2 surface tension: To visualize the effect of surface tension on the movement of liquid drop we have taken a water drop with radius(3 mm),here we have taken three different values of surface tension i.e surface tension=.059N/m,.0736 N/m amd .09 N/m.to know the effect of surface tension the other properties like contact angle(90˚),density of water(998 kg/m3),thermal conductivity() etc. is taken same for all the three cases.

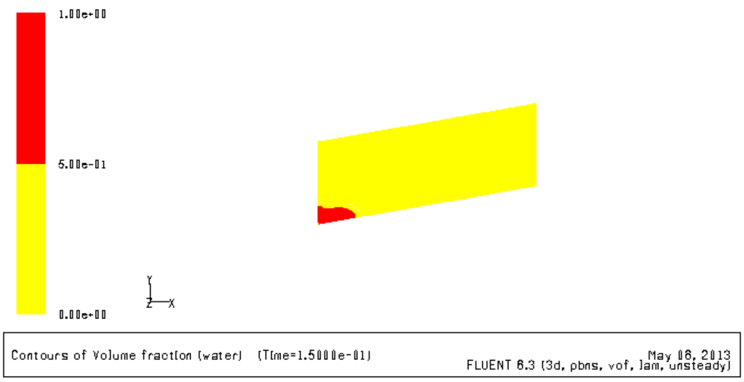
i)water drop over an inclined plane with surface tension .059N/m: First of all a water drop of hemispherical shape with radius 3 mm is taken on an inclined plane with 10˚ of inclination. initially the water drop is rested on the middle of the inclined plane now under the effect of external gravity force and frictional force the water drop start to move on the inclined plane and accordingly the velocity of the drop changes . this phenomenon is iterated over 2000 time steps with time step size of .0001 s. the result has been saved after every 50 time steps. The shapes acquired by the drop over different time steps are shown in figure



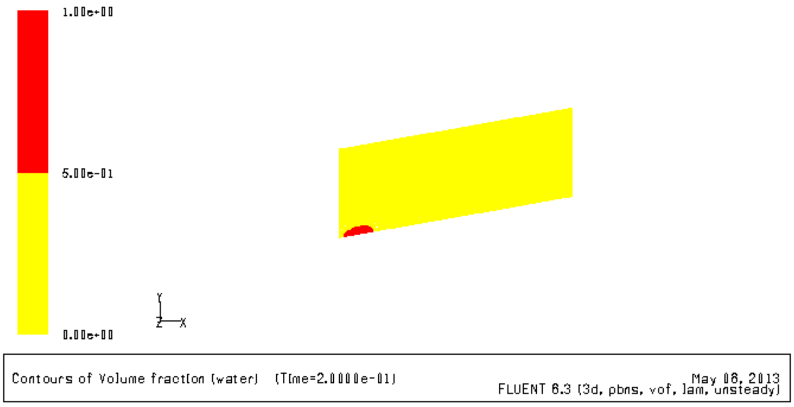
time=.05 sec



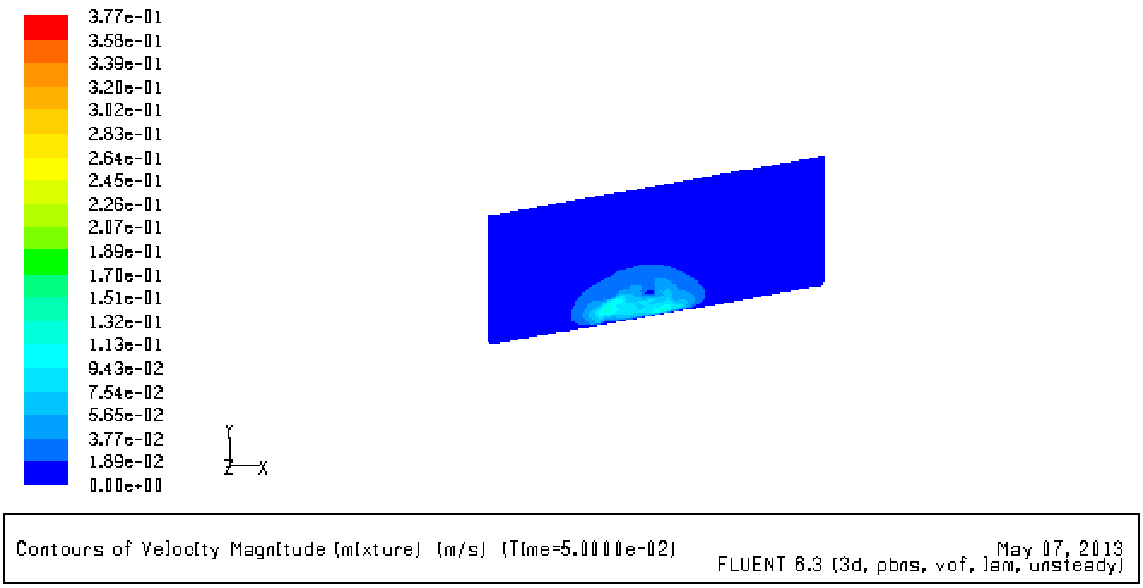
time=.1 sec



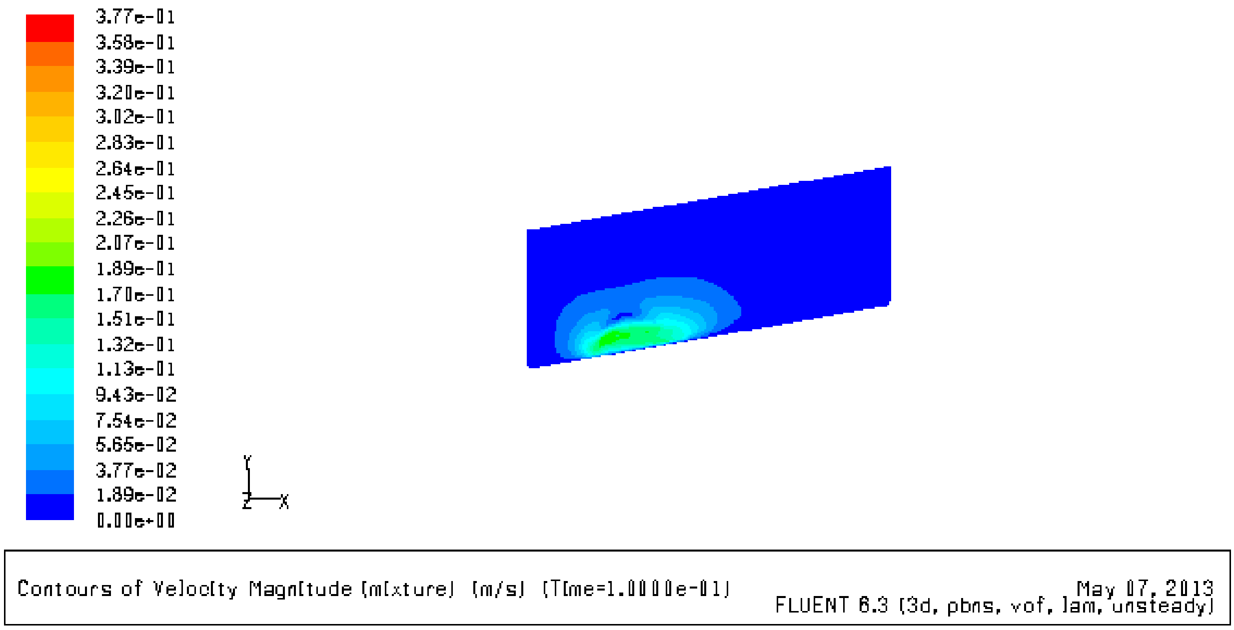
time=.15 sec



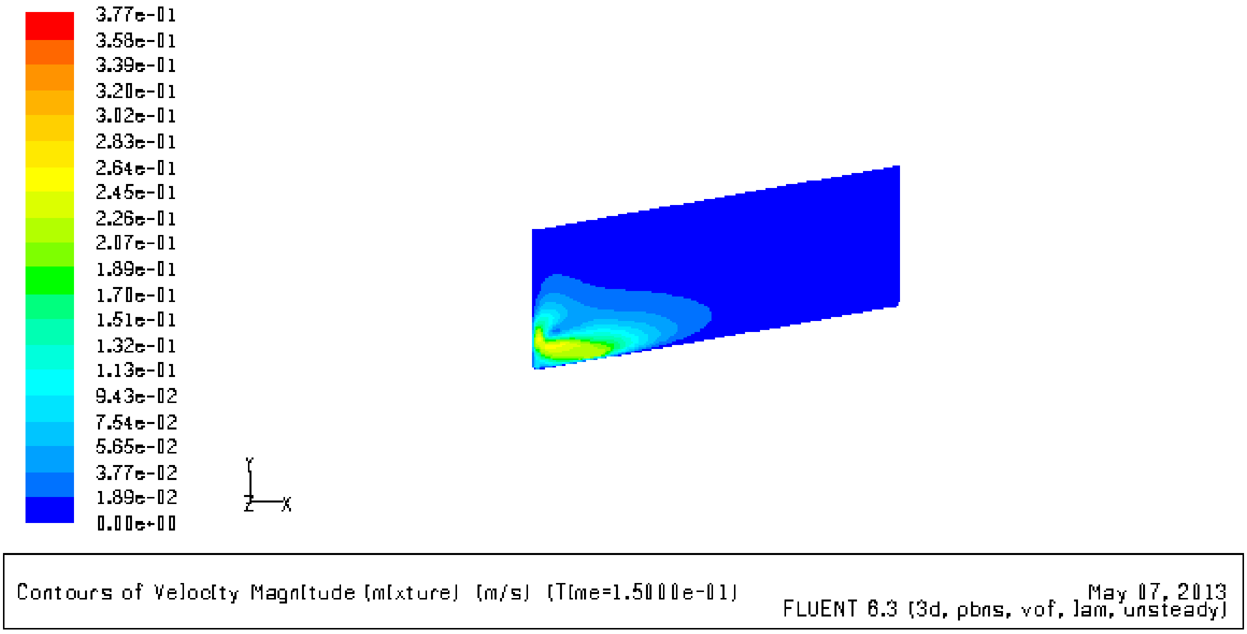
time=.2 sec



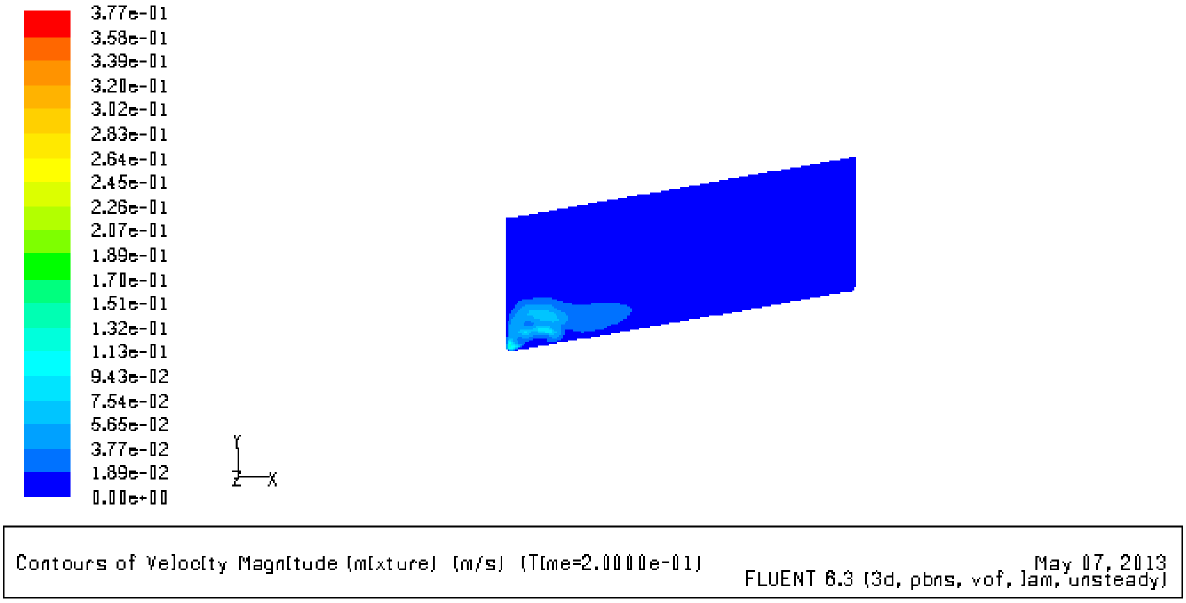
Time=.05 sec



Time =0.1 sec

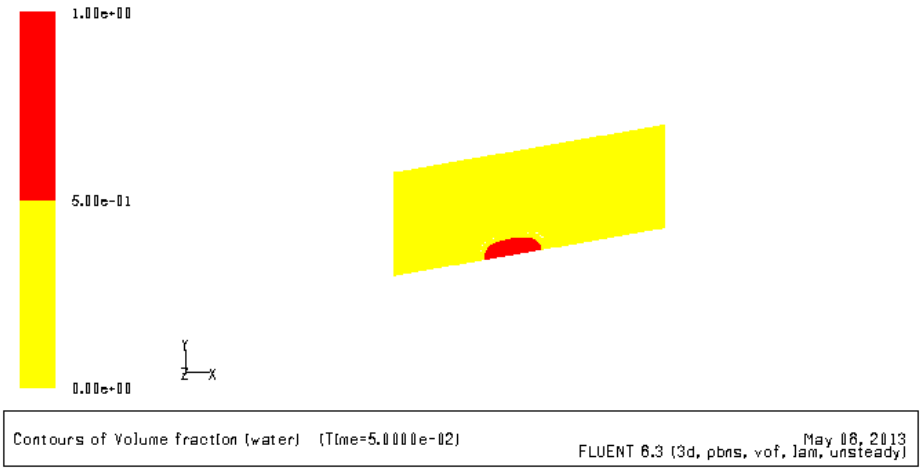


time=.15 sec

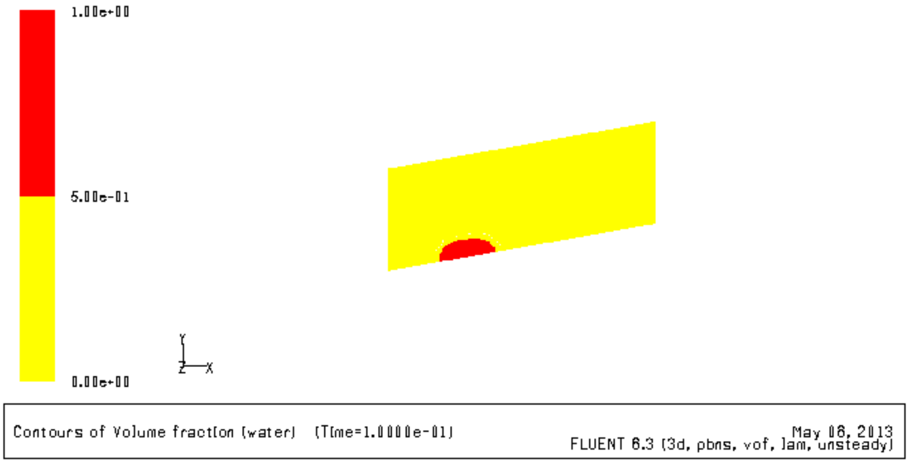


time =0.2 sec

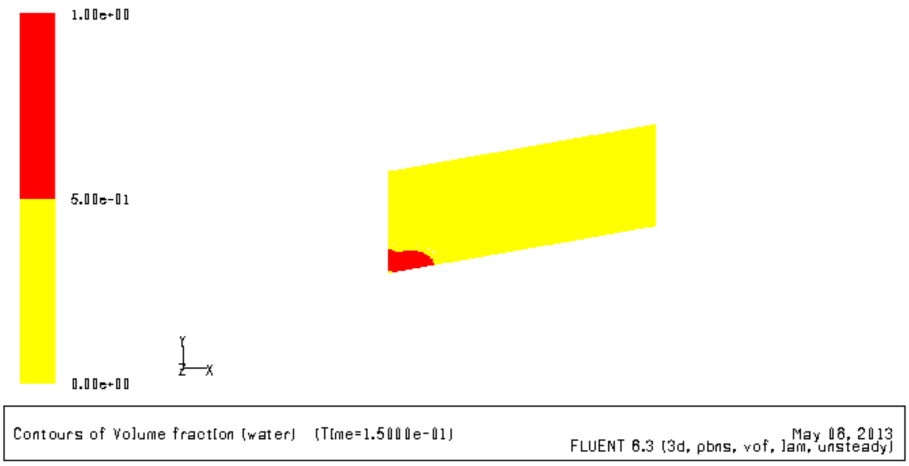
ii)water drop over an inclined plane with surface tension .0736N/m: Here the same water drop is taken on inclined plane with 10° inclination with same properties the only difference is with value of surface tension which is taken as .0736N/m .the movement of the water drop is iterated over 2000 steps with time interval of .0001 s and the data is recorded after every 50 time steps. The shape at different time interval is shown below:



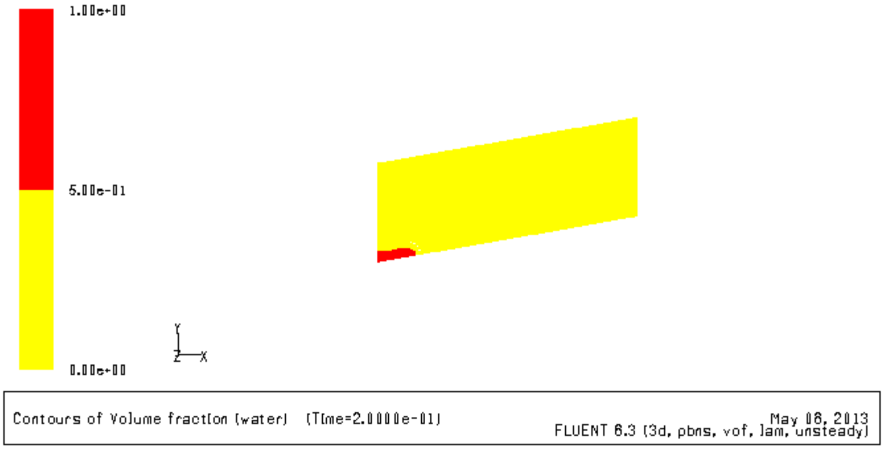
time=.05 sec



time=.1 sec

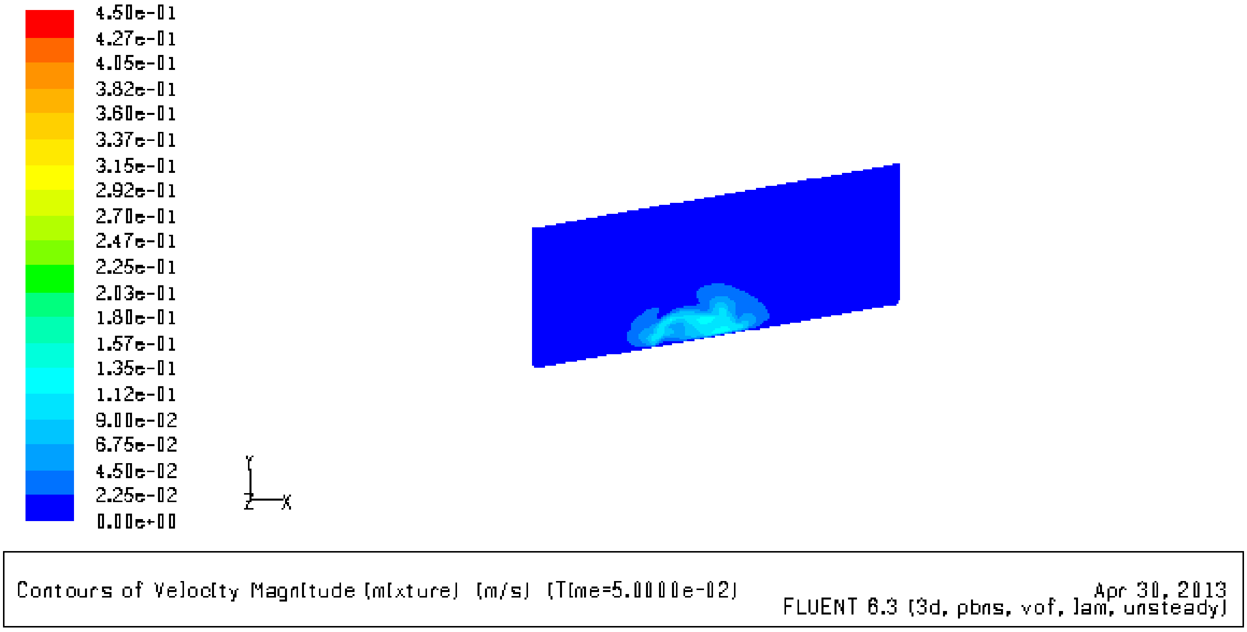


time=.15 sec

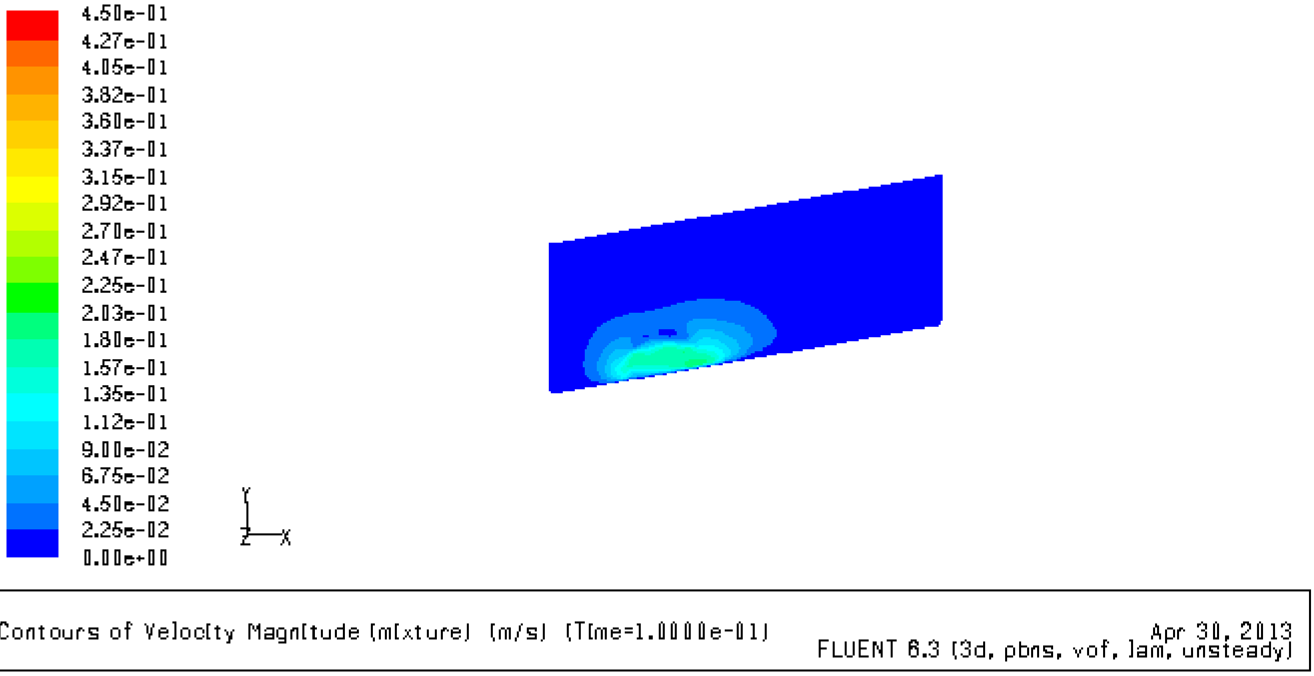


time=.2 sec

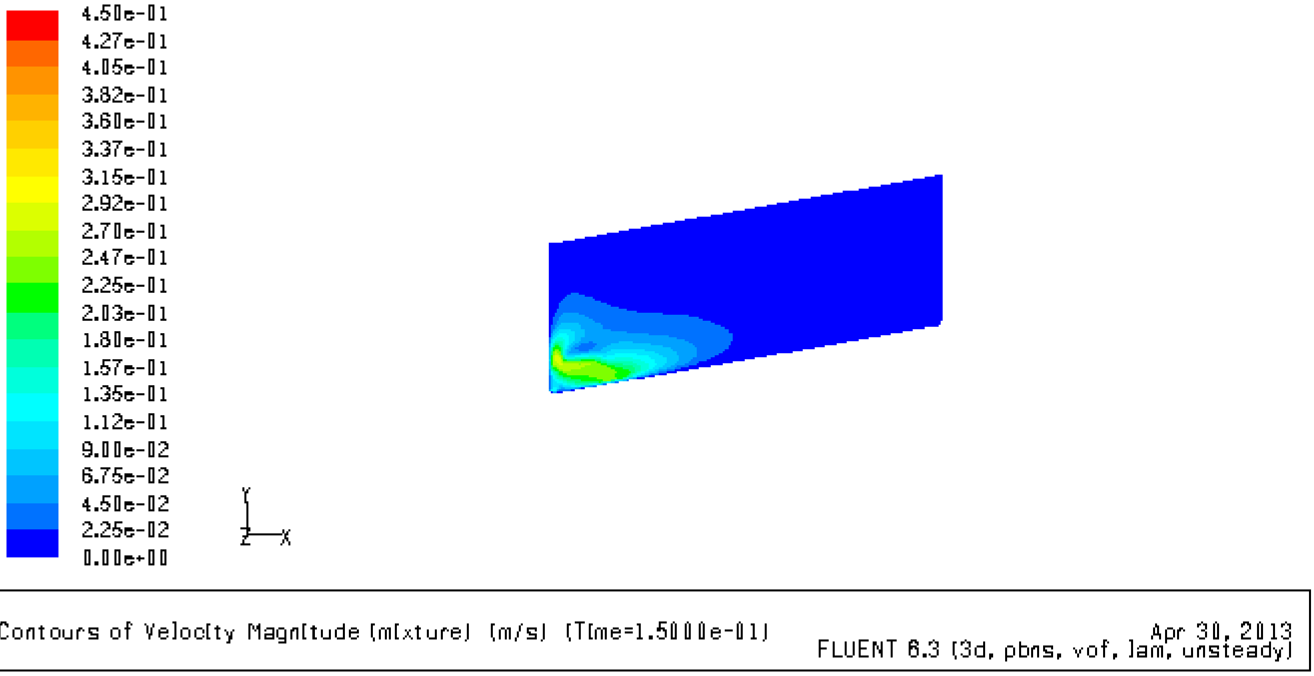
Velocity contour at different time interval:



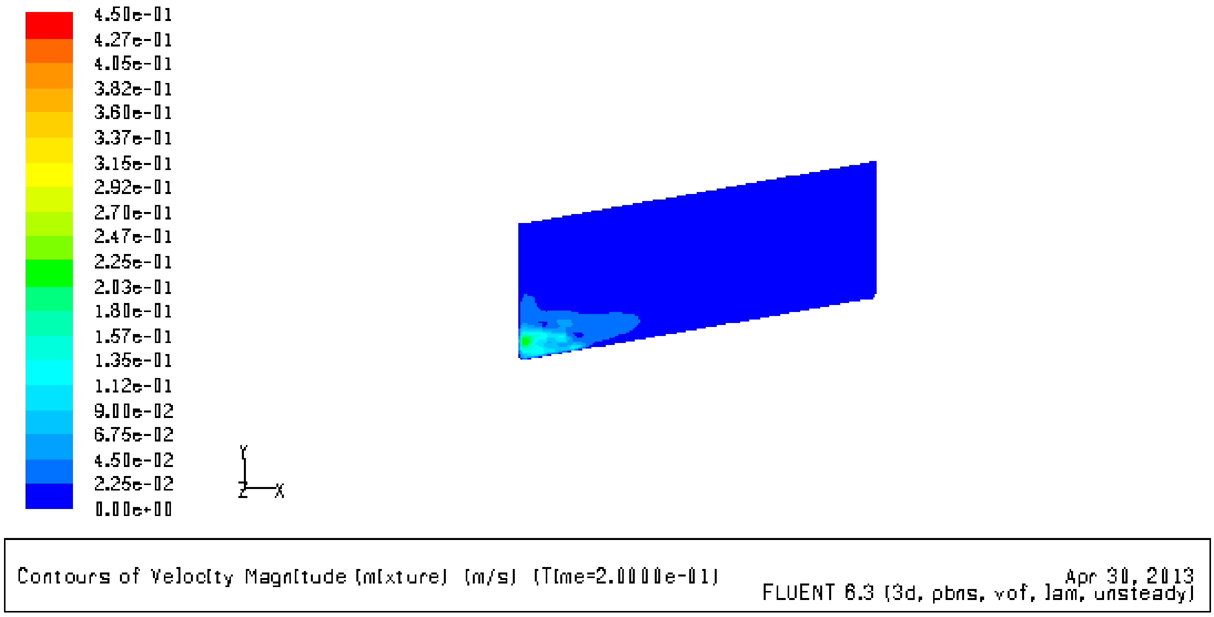
Time=.05 sec



Time =.1 sec

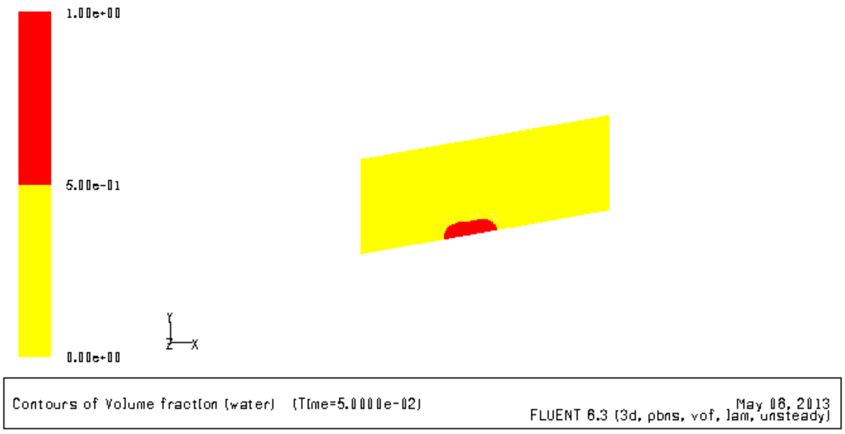


Time =.15 sec

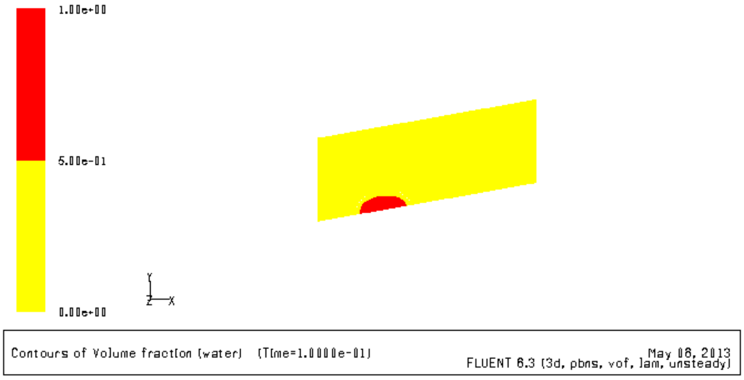


Time=.2 sec

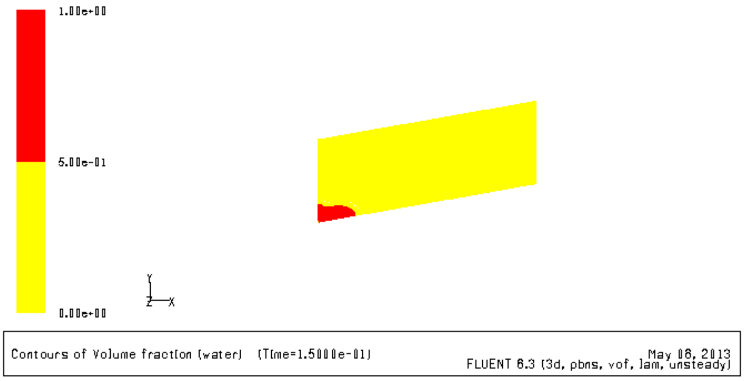
iii) **water drop over an inclined plane with surface tension .090N/m**: Next iteration is done with surface tensionis .09 N/m,all other parameters are taken as same to visualize the effect of surface tension the iteration was done and the data was recorded for every 50 iteration.the shape at different time interval is shown below:



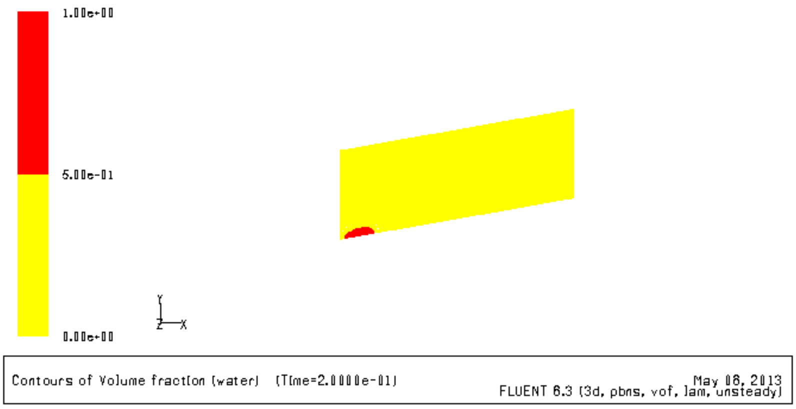
time=.05 sec



time=.1 sec

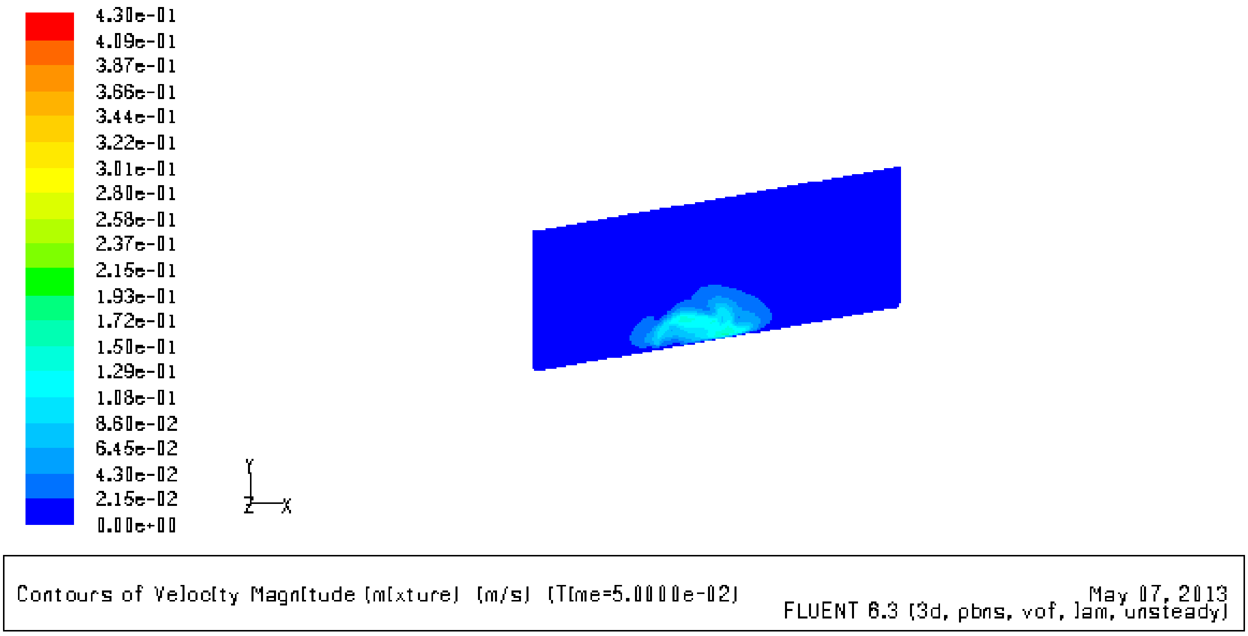


time=.15 sec

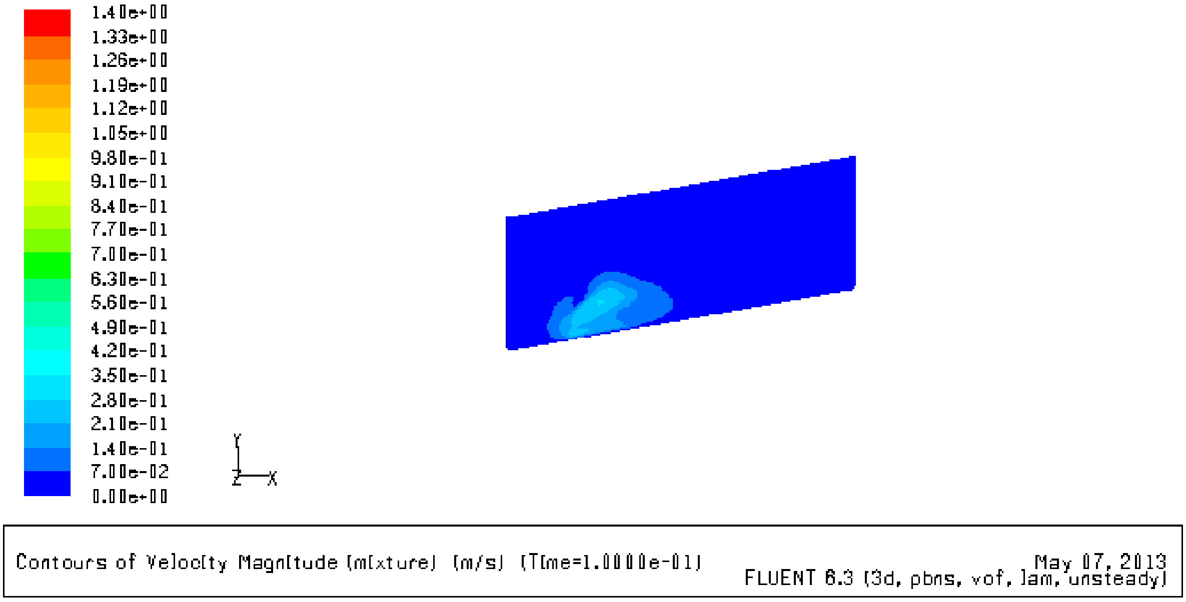


time=.2 sec

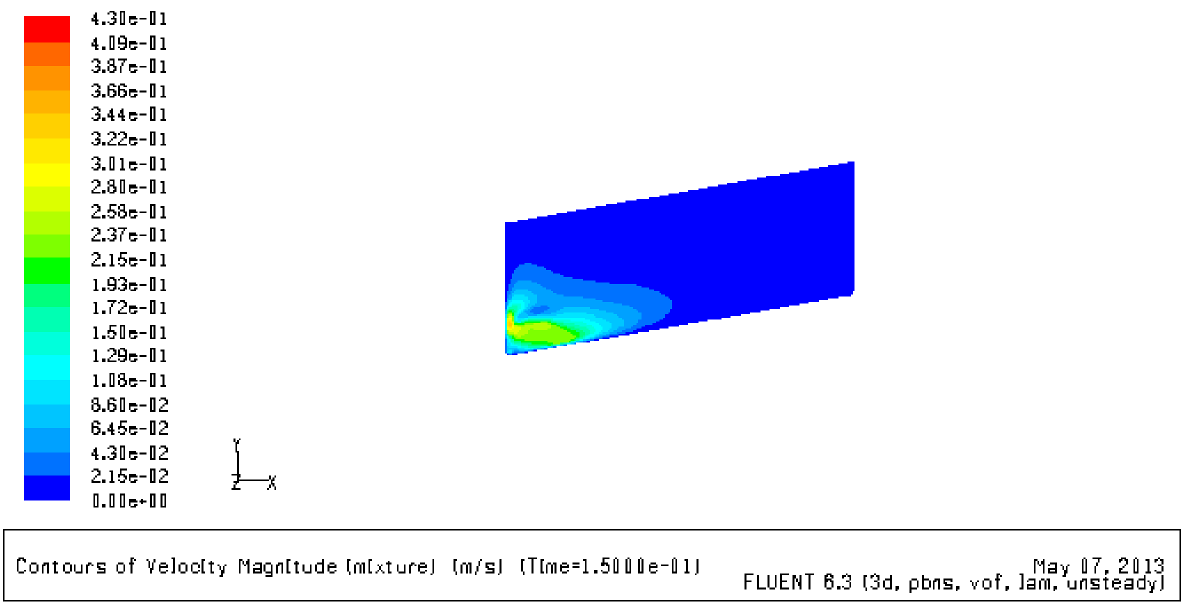
velocity contour is shown below for different time interval.



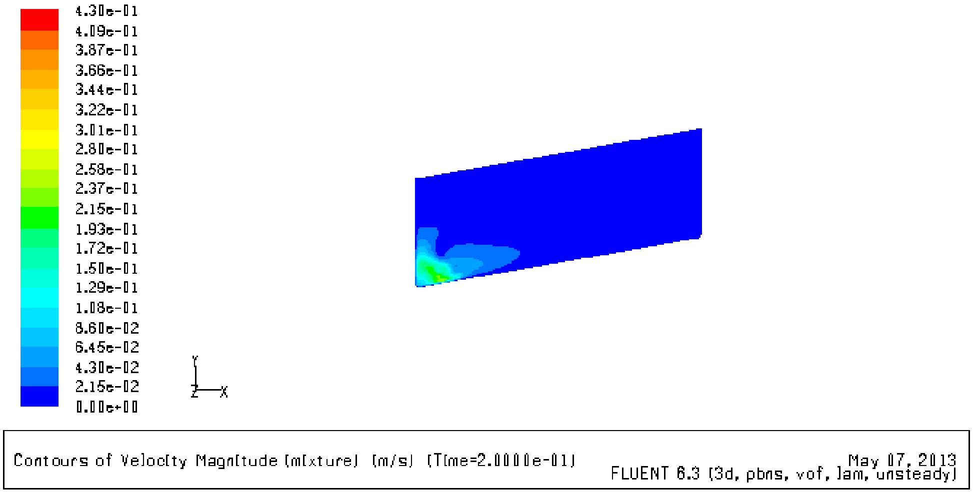
Time=.05 sec



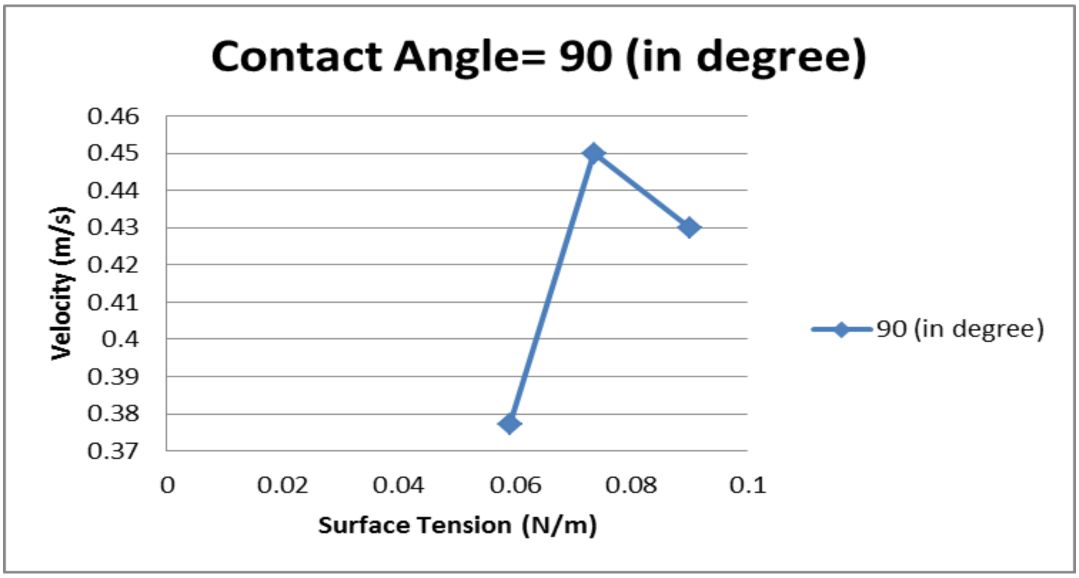
Time=.1 sec



Time=.15 sec



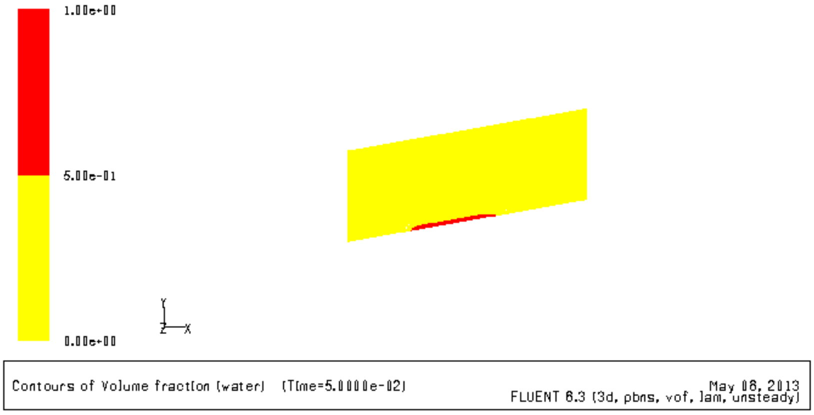
Time=.2 sec



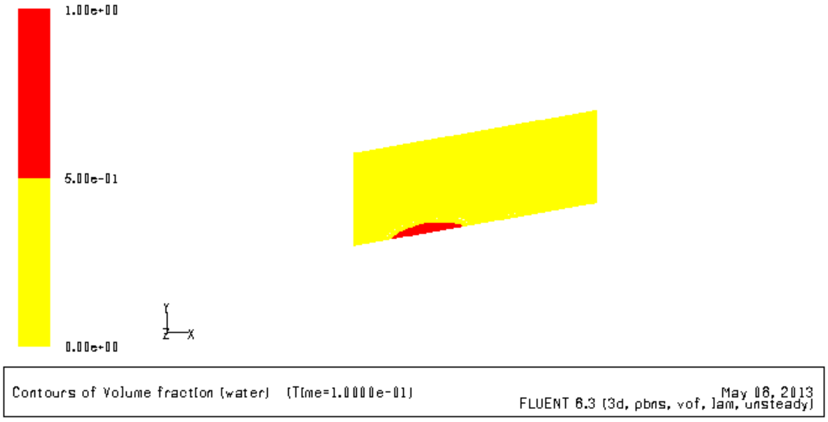
Above graph shows the effect of surface tension on the velocity of liquid drop when contact angle is 90˚. Here we can see that when the surface tension is changing from .059N/m to .0736 N/m then the velocity increase but on the other jand when surface tension is changing from .0736 N/m to .09 N/m then the velocity decrease from .45 m/s to .43 m/s.i.e velocity of the liquid drop is fluctuating in nature.

4.3contact angle: To know the effect of contact angle on the movement of the liquid drop we have taken a water drop on an inclined plane with an inclination angle of 10˚and we changed the contact value by keeping other parameters like surface tension(.0736 N/m),density(998 Kg/m3),inclination angle (10˚) etc. as constant. Here we have taken three contact angle values i.e 30˚,90˚and 150˚and trying to study the effect of these contact angles on the velocity of water drop.

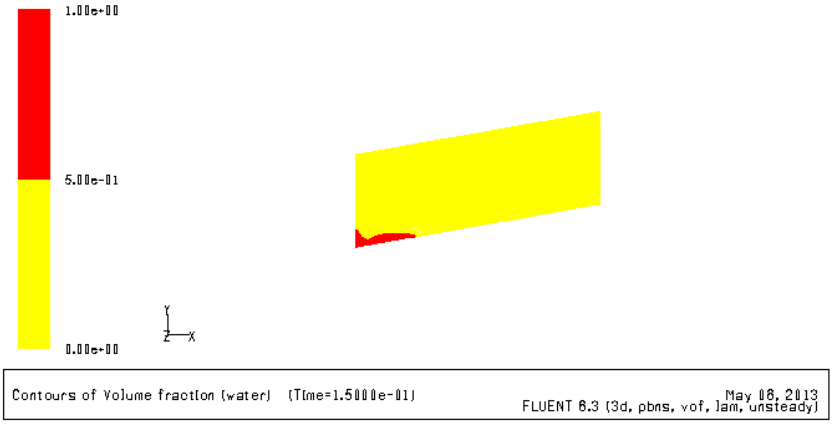
i)Water drop movement when contact angle is 30˚: The hemispherical water drop with radius 3 mm is taken at the middle point of an inclined plane with inclination angle of 10˚.now to capture the movement the iteration was started and it was iterated for 2000 with time step of .0001 s.due to the effect of gravity and frictional force the drop start to move on the inclined plane the movement of the drop is saved at a time step of 50.shap of the drop at different time interval is shown below:



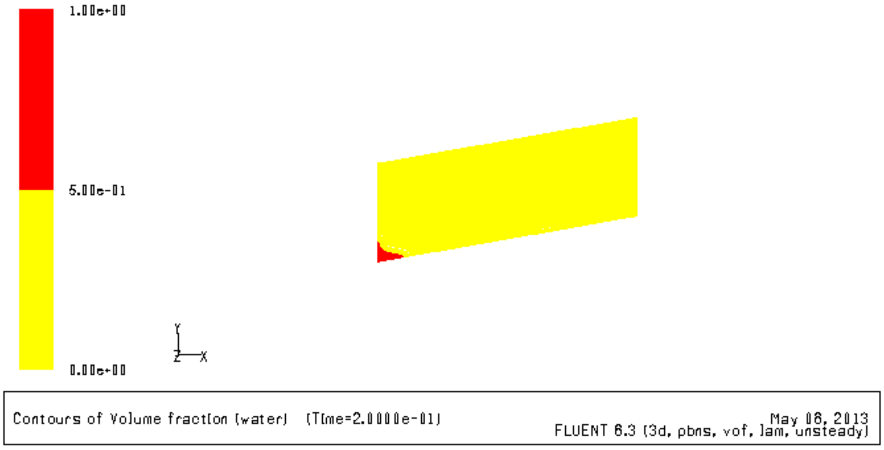
time =.05 sec



time=.1 sec

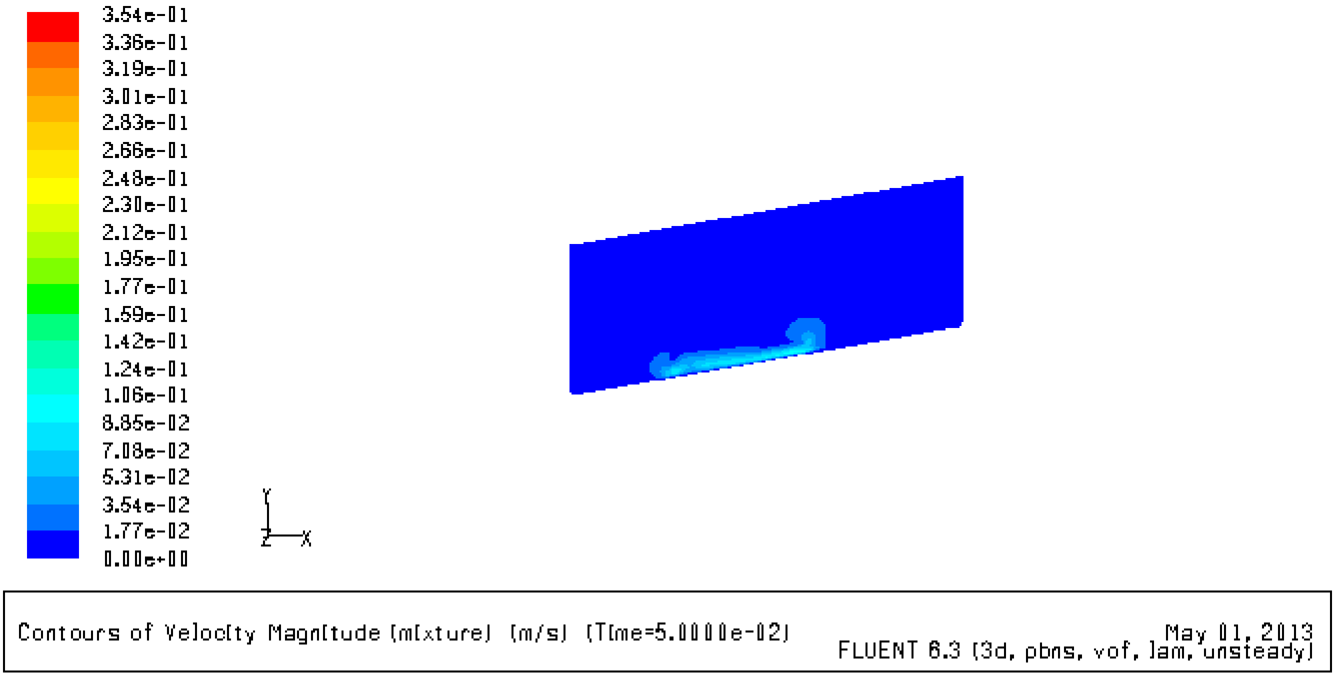


time=.15 sec

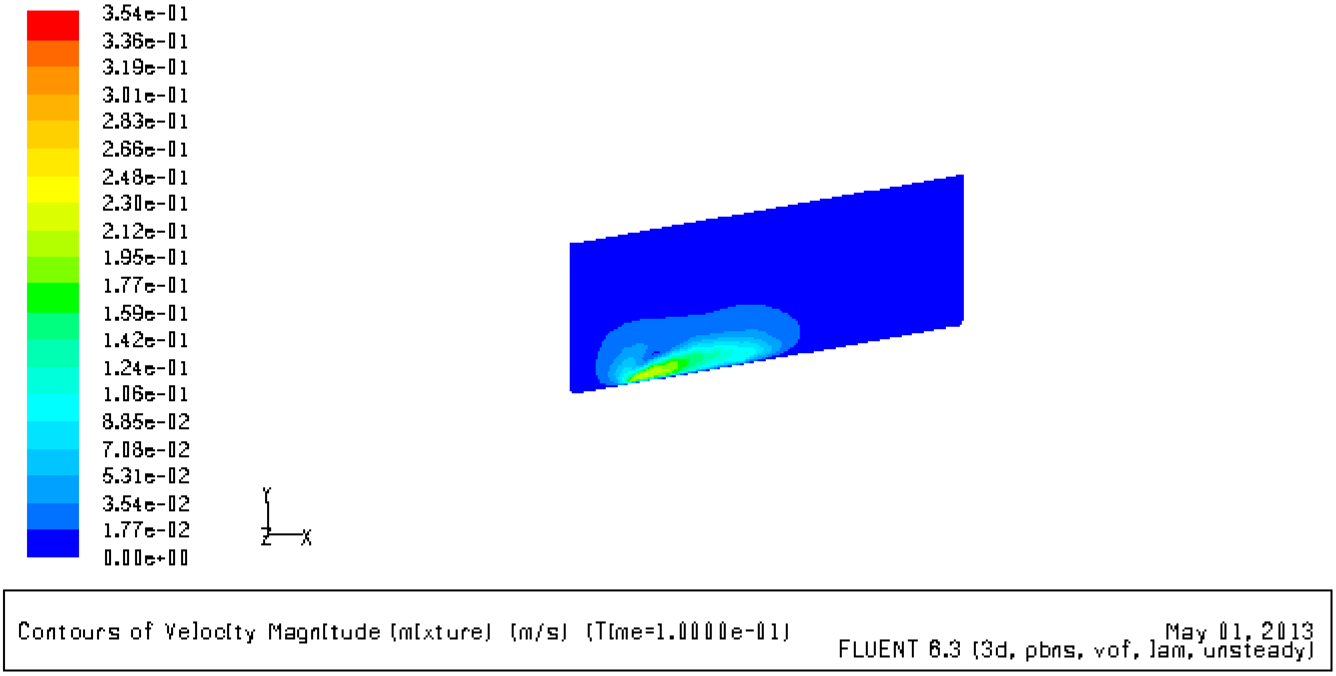


time=.2 sec

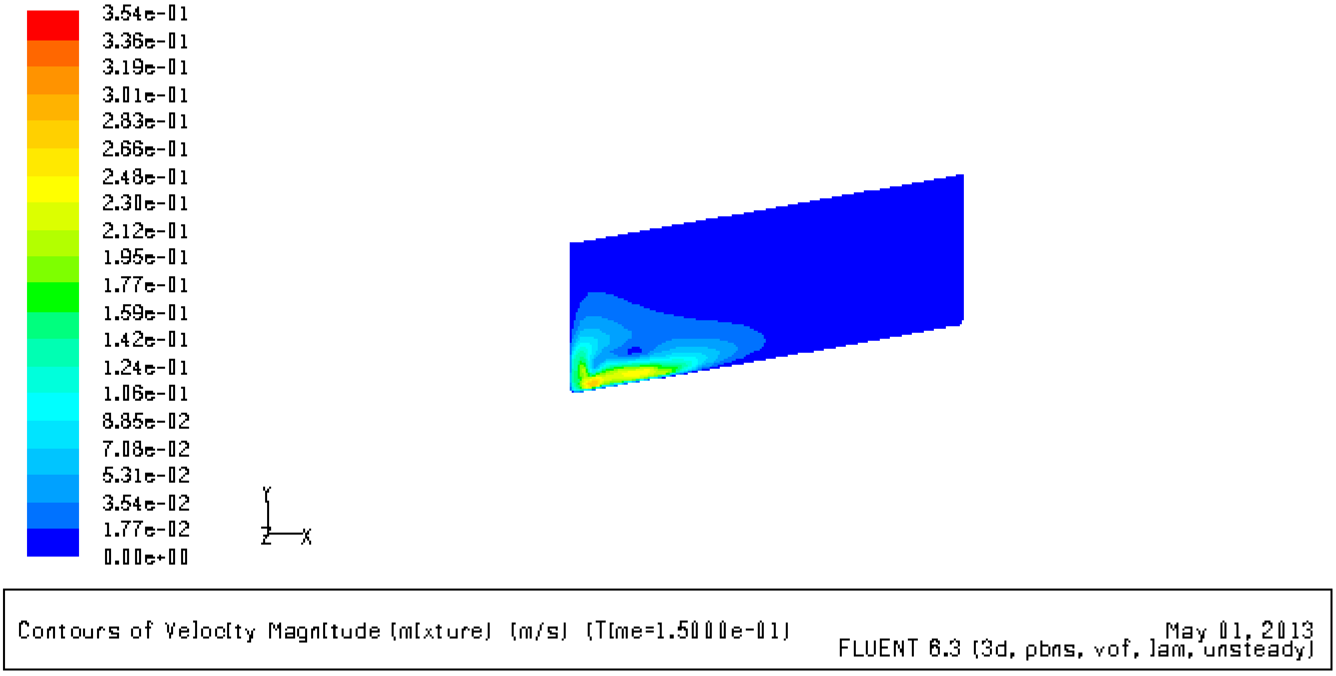
the velocity contour for the drop at different time interval is shown in the figure.



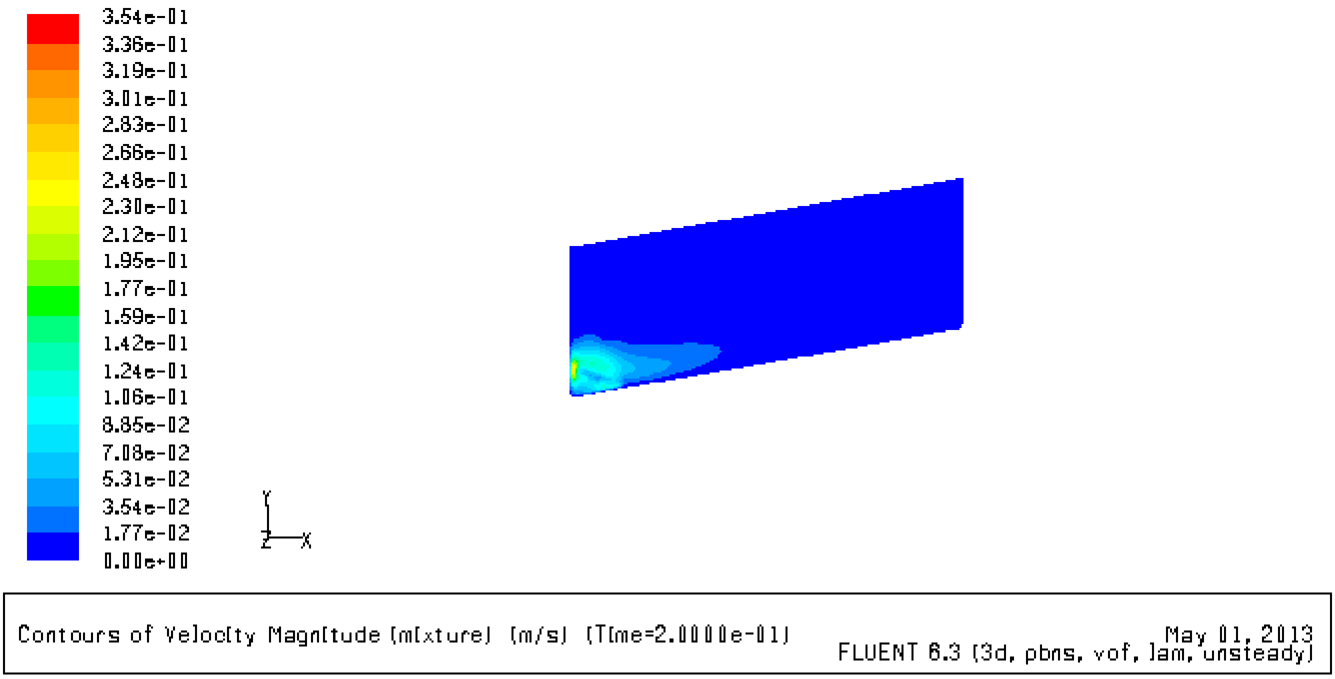
Time=.05 sec



Time =.1 sec

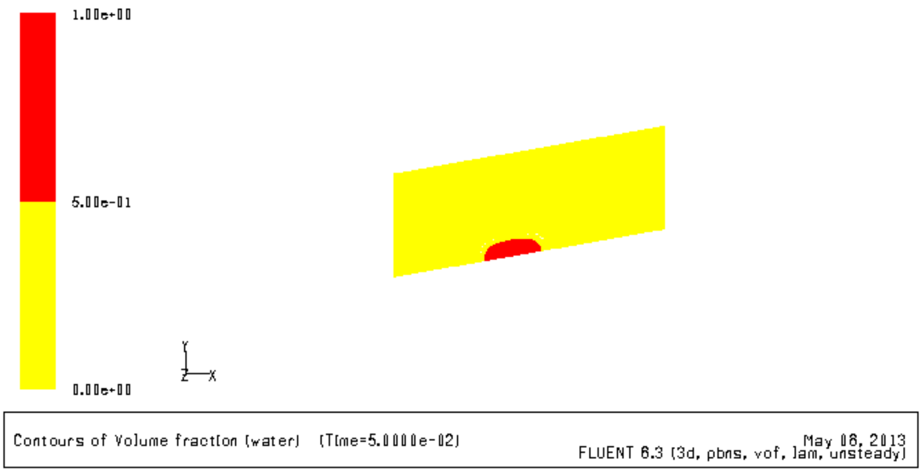


Time=.15 sec

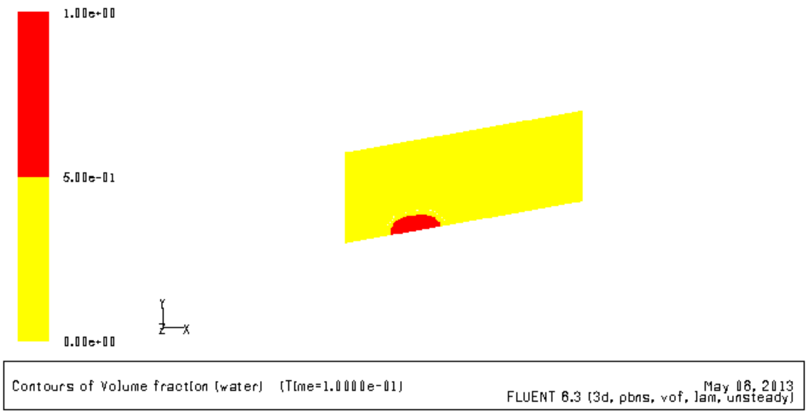


Time =.2 sec

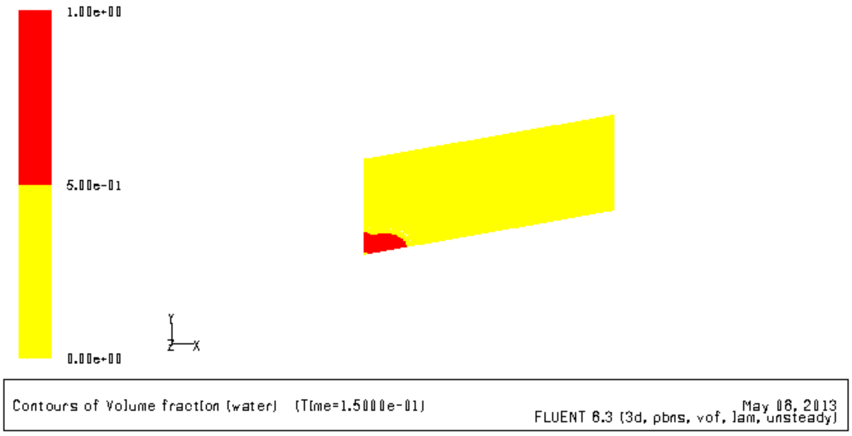
ii)Water drop movement when contact angle is 90˚: Next iteration was done when contact angle is taken as 90˚.Here the other parameters remains constant .The iteration was started and continue upto 2000 time step with time step size .0001 s and the saved after every 50 time step. The position of the drop at different time interval is shown below:



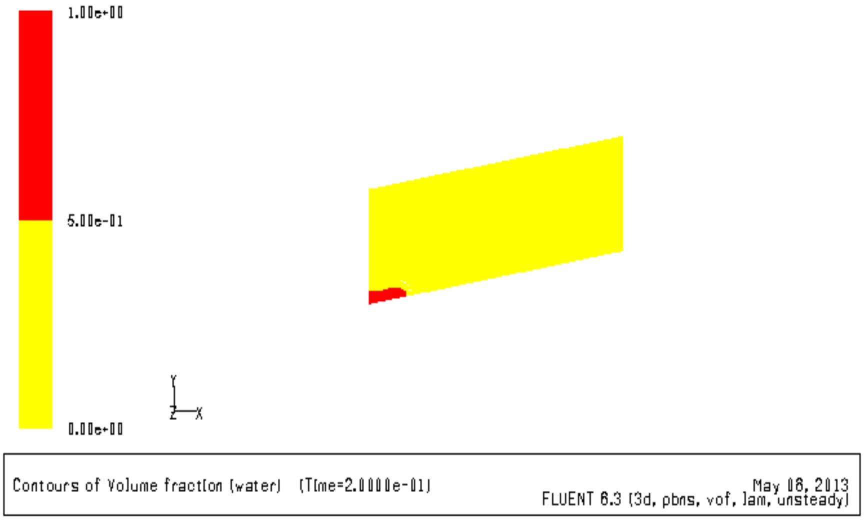
time=.05 sec



time=.1 sec

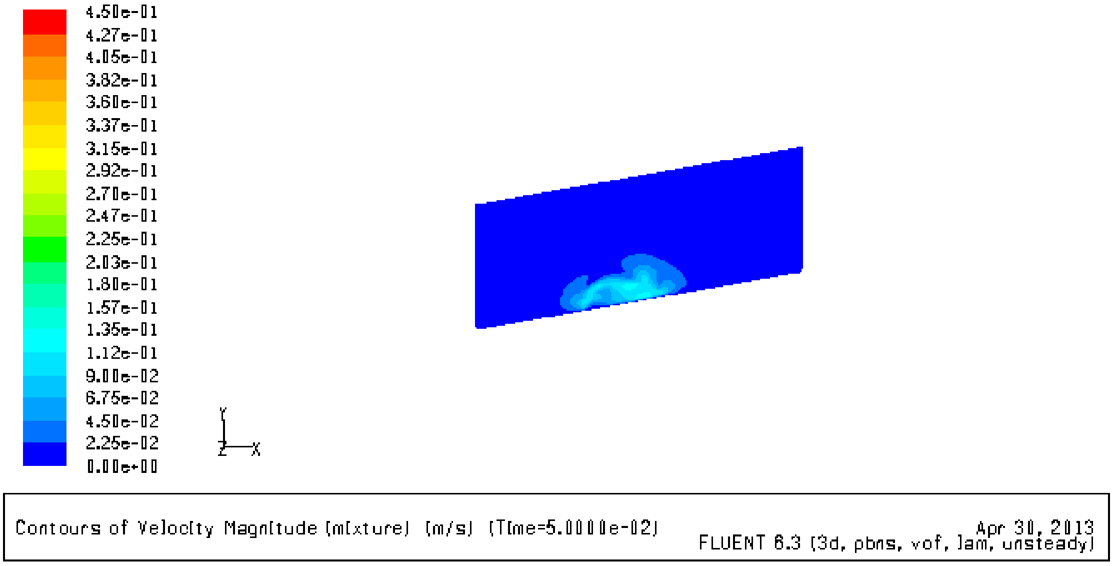


time=.15 sec

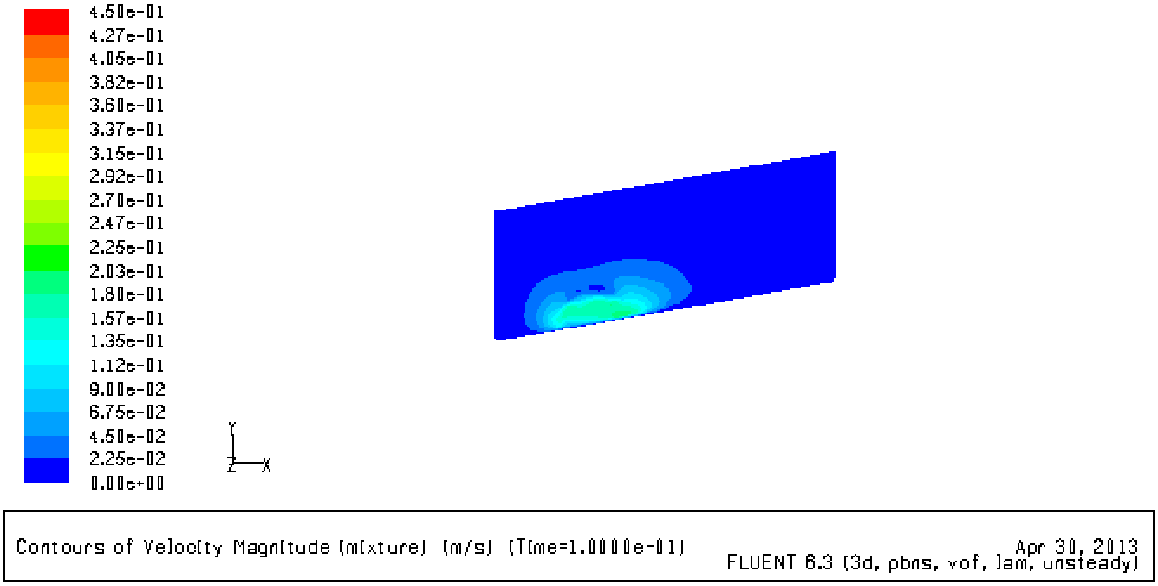


time=.2 sec

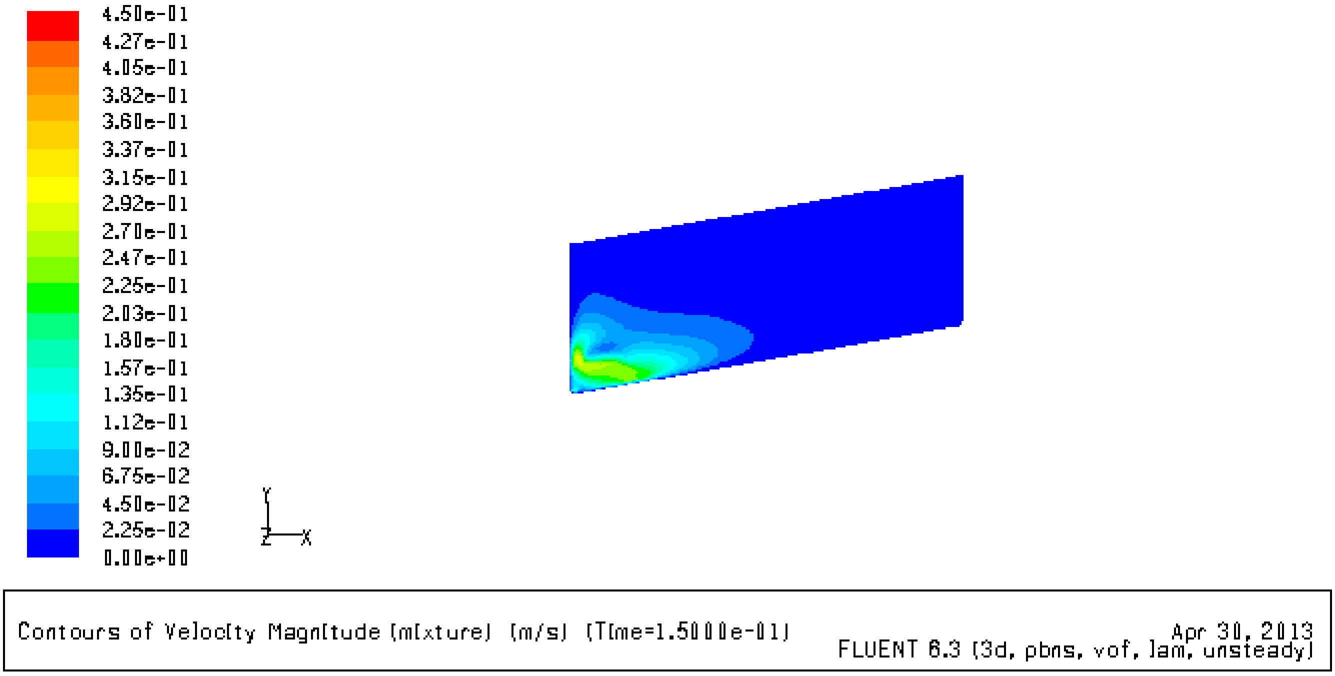
Velocity contour at different time interval:



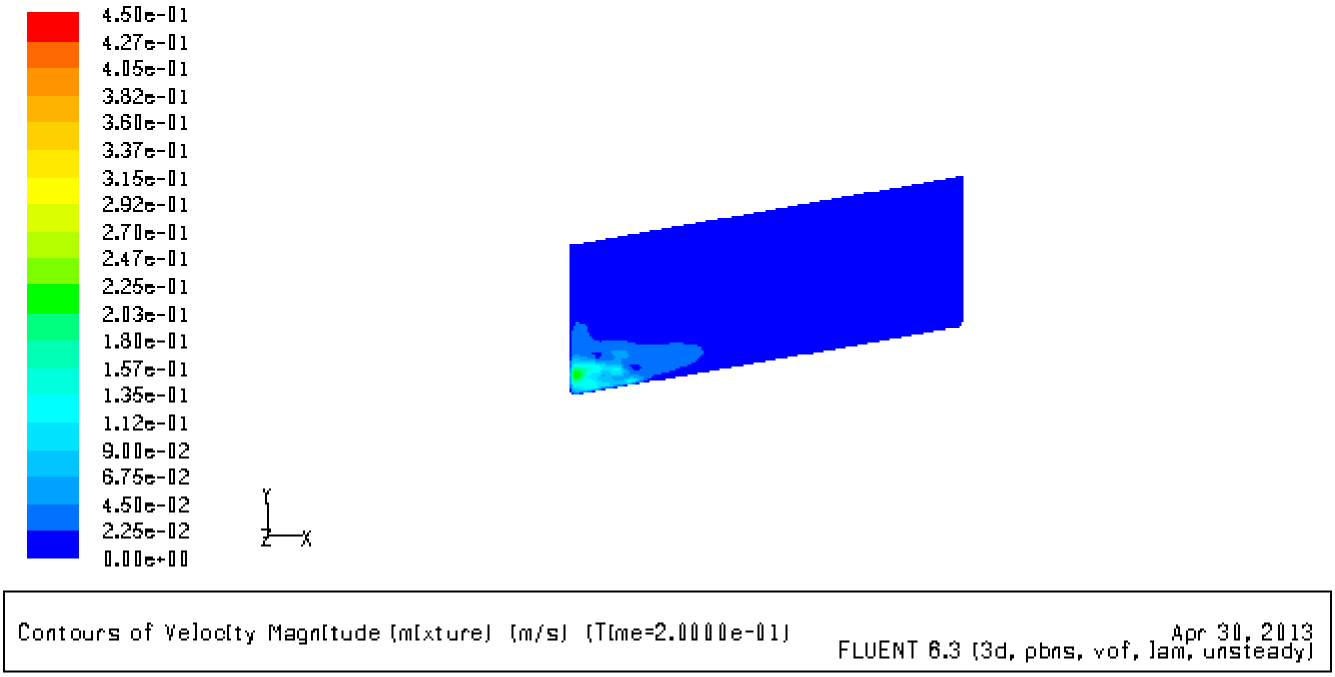
Time =.o5 sec



Time =.1 sec



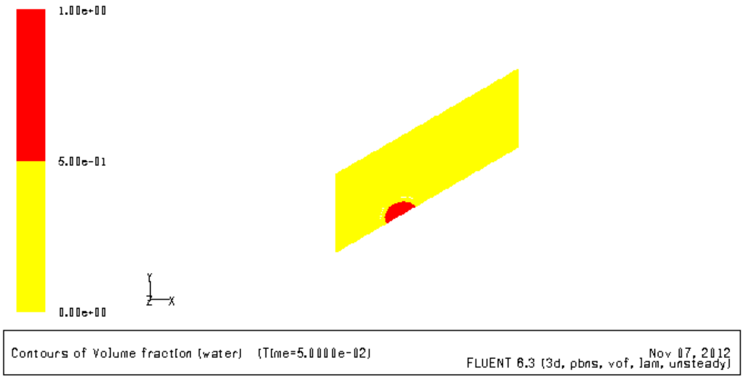
Time =.15 sec



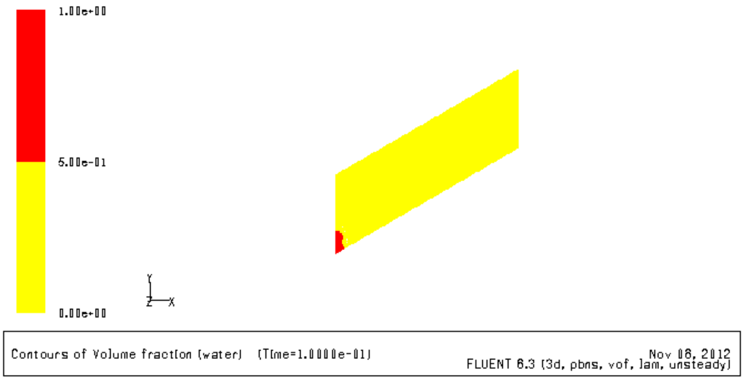
Time =.2 sec

iii)Water drop movement when contact angle is 150°: Here the surface is taken as superhydrophobic surfaces such as the leaves of the lotus plan these are the surfaces which are difficult to wet.the liquid drop is taken at the middle of inclined plane and iteration started and it continues upto 2000 time step and the necessary data was recorded in every 50 time step.

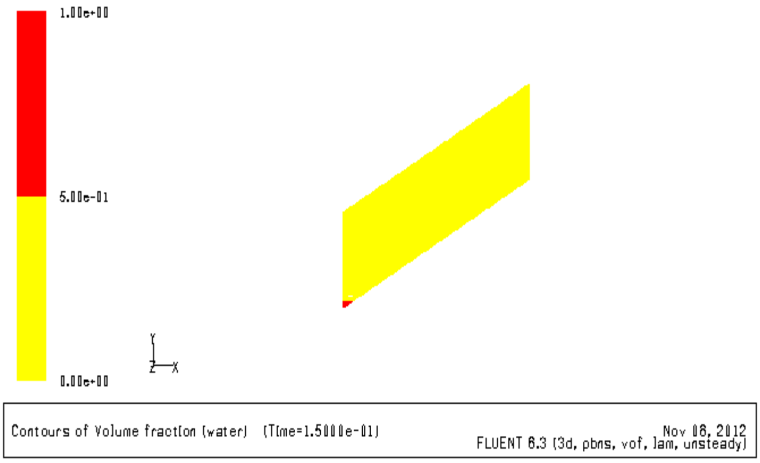
Position of the drop at different time interval shown below:



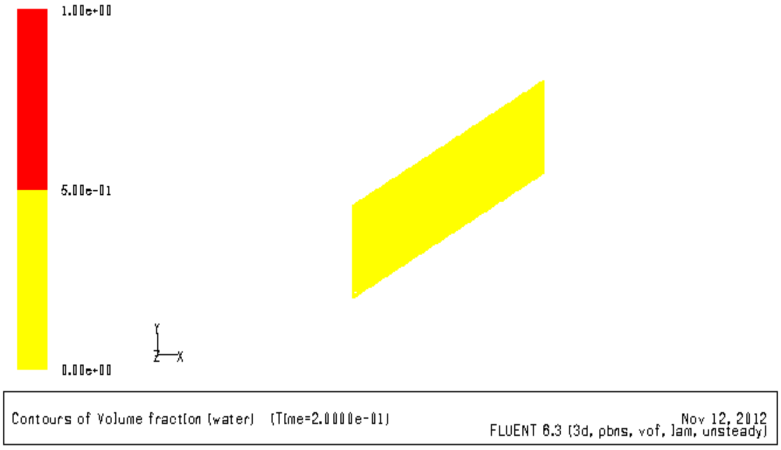
time=.05 sec



time=.1 sec

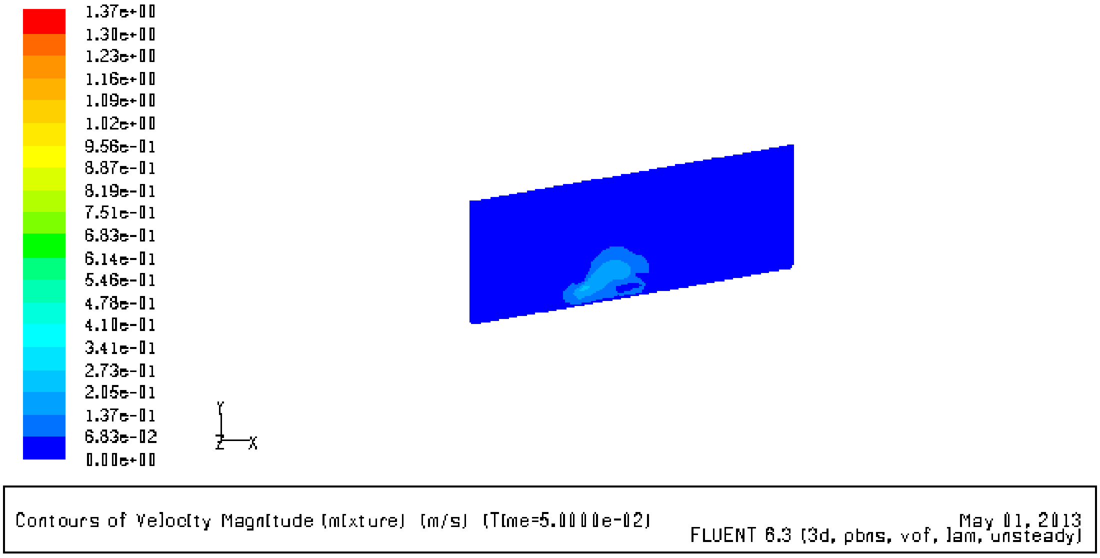


time=.15 sec

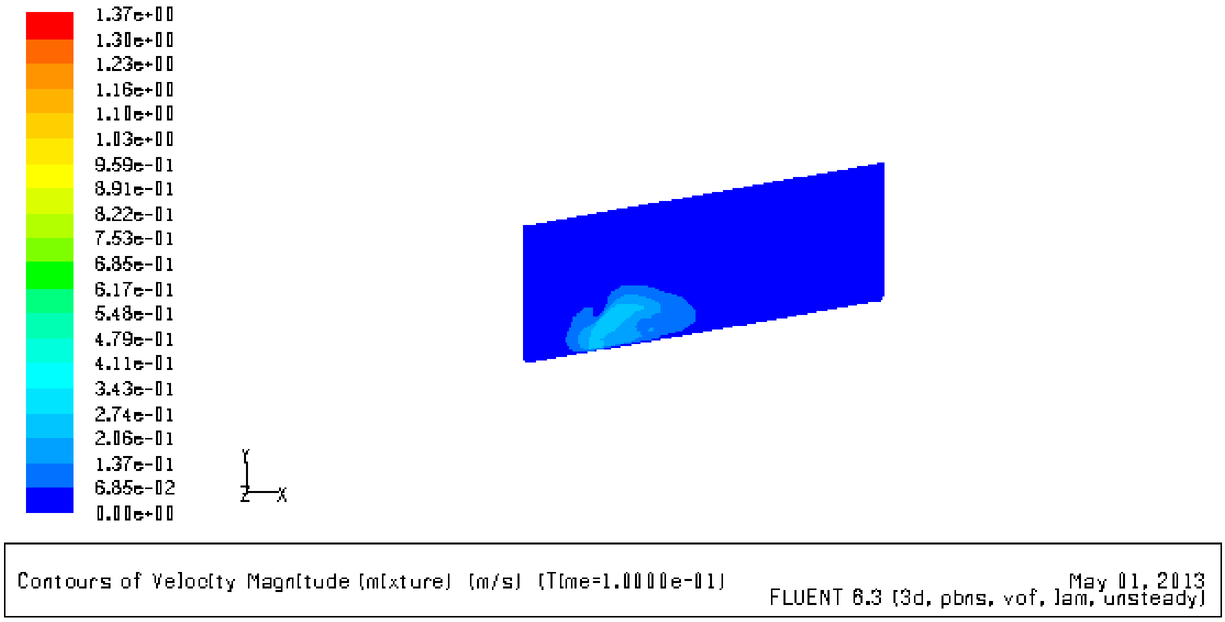


time=.2 sec

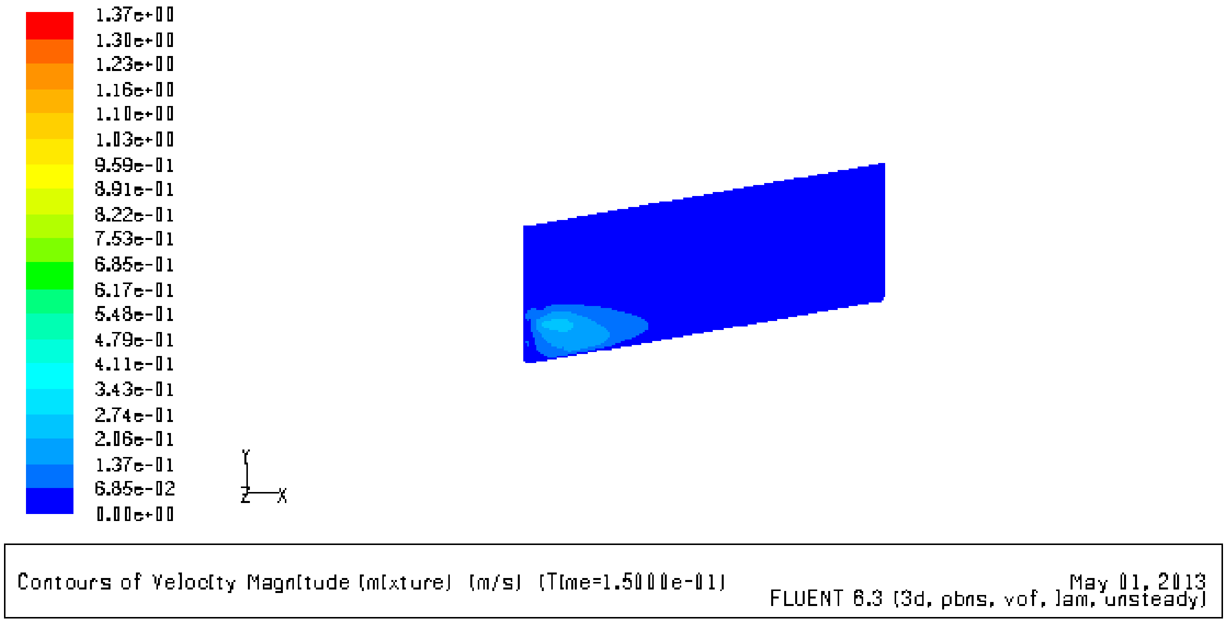
Velocity contour at different time interval:



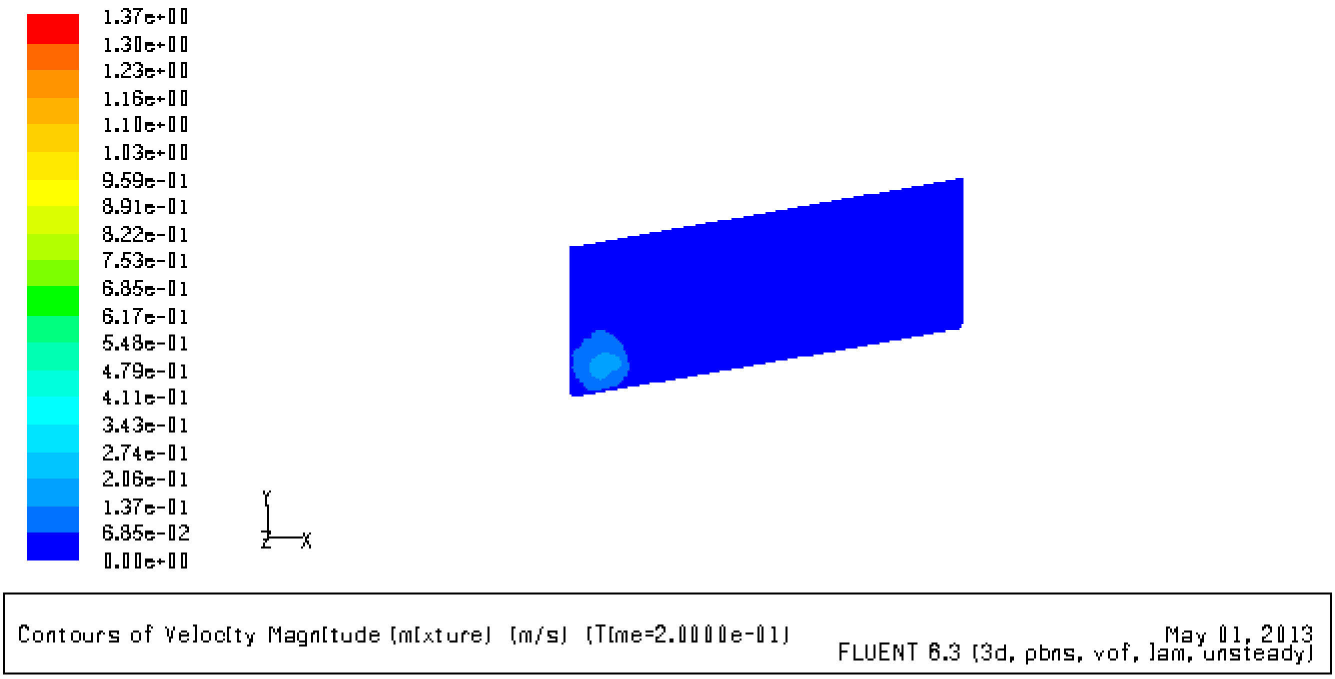
Time=.05 sec



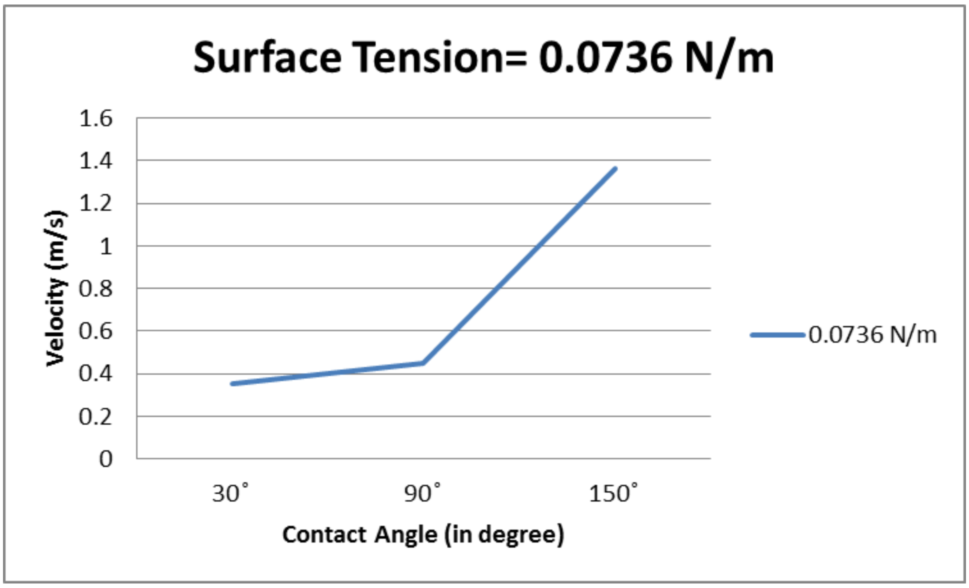
Time=0.1 sec



Time=0.15 sec



Time=0.2 sec



Above graph shows the effect of contact angle on velocity of the liquid drop.from graph we can see that the velocity of drop increases with increase in contact angle,but the effect of contact angle on the velocity of the liquid drop is large when the solid surface is hydrophobic.i.e when the liquid drop does not wet the solid surface.

5. Conclusion:

The equilibrium shape and the velocity attained by a liquid drop is depend upon a number of factors like surface tension, volume of the drop, surrounding atmosphere, material properties, external forces, contamination of the liquid and surface gradient.

The important findings from the above analysis can be summarized as :

i)The velocity of the liquid drop is directly proportional to the angle of inclination(other parameters remain constant) i.e with increase in angle of inclination the velocity of liquid drop is also increases, the reason behind this is the effect of gravity which will increase with increase in inclination angle. But the effect of gravity is not linearly related with inclination angle as we can see from above observation that when the angle of inclination is changes from 30˚ to 45˚ the velocity increase by a factor of 1.58(.64/.404=1.58) but when angle of increase from 45˚ to 60˚ the velocity increases by a factor of 2.39(1.53/.64=2.39) i.e with increase in inclination angle the increase in frictional force is less than the increase in gravity force .

ii)The velocity of liquid drop does not follow a definite relationship with surface tension.as we can see that with incrase in surface tension the velocity first increases than it start to decrease.

iii)With increase in contact angle (other parameters remains constant) the velocity of the liquid drop increases but this change in velocity is not linear in nature as we can see this from above observation when the contact angle increases from 30˚ to 90˚ velocity increases by a factor of 1.28(.45/.35=1.28)but when contact angle increases from 90˚ to 150˚ the velocity increases by a factor of 3.03(1.365/.45).

This suggest that with increase in contact angle(i.e for hydrophobic surface) the type of motion changes from sliding to rolling as suggested by Yarnold (1938) and later verified by

Alle and Benson(1975).due to rolling motion the friction acting is rolling friction as we know that rolling friction is less than sliding friction so the velocity of the drop increases.

6. FUTURE WORK:

The present research work can be extended by other investigators to explore many other aspects liquid drop movement. Some recommendations for future research include:

i)Study the dynamics of movement of liquid other than water.

ii)To find out a mathematical expression which will correlate the velocity with contact angle.

iii)To study the effect of surface tension or contact angle by user defined function.

7. REFERENCES:

Alle R.F., Benson P.R.,1975. Rolling drops on an inclined plane, J. Coll. Interface Sci. 50, 250–253.

Attinger, D., Zhao, Z., and Poulikakos, D.,2000.An experimental study of molten microdroplet surface deposition and solidification: transient behavior and wetting angle dynamics,"Journal of Heat Transfer 122, 544–546

Bartolo D, Boudaoud A, Narcy G. & Bonn D.,2007.Dynamics of non-Newtonian droplets, Phys. Rev. Lett. 99, 174502.

Beltrame P, Hanggi P, Knobloch E Thiele U., 2001. Depinning of 2d and 3d droplets blocked by a hydrophobic defect.

Brochard F., 1988. Motions of Droplets on Solid Surfaces Induced by Chemical or Thermal Gradients

Burns, S. E., Cain, P., Mills, J., Wang, J., and Sirringhaus, H.,2003. Inkjet printing of polymer
thin-film transistor circuits, MRS Bulletin 28, 829–834.

Calvert, P.,2001.Inkjet printing for materials and devices, Chemistry of Materials 13, 3299–3305.

Chaudhury K. M,Whitesides M.G.,1992. How to make water Run uphill, Science, 256,1539-1541.

Das A.K, Das P. K., 2010. Multimode Dynamics of a Liquid Drop over an Inclined Surface with a Wettability Gradient, Langmuir, 26, 9547–9555.

Daniel S, Chaudhury M.K, Chen J.C., 2001. Fast drop movements resulting from the phase change on a gradient surface, Science, 291(5504),633-636.

Dantel S, Chaudhury K.M., 2002. Rectified Motion of Liquid Drops on Gradient Surfaces Induced by Vibration, 18, 3404-3407.

Denis Bartolo, Arezki Boudaoud, Gregoire Narcy, and Daniel Bonn.,2007. Dynamics of Non-Newtonian Droplets, 99, 174502-1, 174502-4.

Derby, B.,2010. Inkjet printing of functional and structural materials: Fluid property requirements, feature stability and resolution, Annual Review of Materials Research 40, 395–414

.Ding, H. & Spelt, P. D. M., 2007. Inertial effects in droplet spreading: a comparison between disuse interface and level-set simulations, J. Fluid Mech., 576, 287-296

Dussan V.E.B,Chow R.T.,1983. ability of drops or bubbles to stick to non-horizontal surfaces of solids,journal of fluid mechanics,137,1-29.

Ford L. M, Nadim A., 1994. Thermo capillary migration of an attached drop on a solid surface, American Institute of Physics.

Gallardo, B.S., Gupta, V.K., Eagerton,F.D., Jong, L.I., Craig, V.S,Shah, R.R. & Abbot, N.L.,1983.Electrochemical principles for active control of liquids on sub millimeter scales, Science ,283, 57-60.

Gao.L, McCarthy J.T., 2006. Contact Angle Hysteresis Explained, Langmuir, 22, 6234-6237.

Gingold R.A,Monaghan J.J.,1977, Smoothed particle hydrodynamics - Theory and application to non-spherical stars,Mon.Not.R.astr.Soc,181,375-389.

Gau H, Herminghaus .S, Lenz.P,Lipowsky.R.,1999. Liquid Morphologies on Structured Surfaces, From Micro channels to Microchips, Science journal,283,46-49.

Greenspan H.P, 1978. On the motion of a small viscous droplet that wets a surface, Journal of Fluid Mechanics,84,125-143.

Grissom, W. M. and Wierum, F. A.,1981 Liquid spray cooling of a heated surface,International Journal of Heat and Mass Transfer 24, 261–271

Holmes W.H, Williams R.J, Tilke P., 2000. Smooth particle hydrodynamics simulations of low Reynolds number flows through porous media, Int. J. Numer. Anal. Meth. Geomech, 1.02, 1-6.

Hongwen R, 2010. Liquid crystal droplet array for non-contact electro-optic inspections, J . Phys. D: Appl. Phys, 43, 365103.

Huang J.J, Shu C, Chew Y.T, 2008. Numerical investigation of transporting droplets by spatiotemporally controlling substrate wettability. J Colloid Interface Sci., 328, 124-133.

Juncker, D., Schmid. H., Drechsler U., Wolf, H., Wolf, M., Michel, B., 2002**.** Autonomous Microfluidic Capillary System, Anal Chem,74,6139-6144.

Kusumaatmaja, H, Yeomans, J. M., 2007. Modeling contact angle hysteresis on chemically patterned and superhydrophobic surfaces, Langmuir, 23, 6019-6032.

Morris J.P, Fox P.J, Zhu Y.,1997. Modeling low Reynolds number incompressible °ows using SPH. Journal of Computational Physics, 136,214-226.

Moumen N, Subramanian S.R, McLaughlin B.J, 2006. Experiments on the Motion of Drops on a Horizontal Solid Surface Due to a Wettability Gradient, Langmuir, 22, 2682-2690.

Pismen L.M,Thiele U.,2006, Asymptotic theory for a moving droplet driven by a wettability gradient Phys. Fluids 18, 042104-14.

M. Sakai, J. Song, N. Yoshida, S. Suzuki, Y. Kameshima, A. Nakajima,2006. Direct observation of internal fluidity in a water droplet during sliding on hydrophobic surfaces, Langmuir 22, 4906–4909.

Shikhmurzaev D.Y.,1997. Moving contact lines in liquid/liquid/solid systems,J. of fluid mechanics,334,211-249.

Song F., 2008.PhD Thesis, Univ. of Akron.

Squires, T. M. and Quake, S. R.,2005. Microfluidics: Fluid physics at the nanoliter scale, Reviews of Modern Physics 77, 977–1026 .

Subramanian S.R., Moumen N., McLaughlin B.J., 2005. Motion of a Drop on a Solid Surface Due to a Wettability Gradient, Langmuir, 21, 11844-11849.

Wu X, Thien N.P, Fan X.J, and Ng T.N.,2003. A molecular dynamics study of drop spreading on a solid surface, Phys. of fluids,15,10.1063-10.1069.

Yarnold G.D.,1938. The motion of a mercury index in a capillary tube, Proc. Phys. Soc. 50, 540–552.