B. Tech project report on

HYDRODYAMIC STUDY OF NEWTONIAN FLUID FLOW OVER A SPHERE USING CFD MODELS

For partial fulfilment of the requirements for the degree of

Bachelor of Technology
in
Chemical Engineering

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CERTIFICATE

This is to certify that the thesis entitled "**Hydrodyanmic Study of Newtonian Fluid Flow Over a Sphere Using CFD models**" submitted by **Sauvagya Behera (109CH0466)** in partial fulfilment of the requirements for the award of degree of Bachelor of Technology in Chemical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance.

To best of knowledge, the matter embodied in this thesis has not been submitted to any other university or institute for the award of any degree.

Date:

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I thank my family and friends for being constant support throughout my life.

Date:

Place: Rourkela

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ABSTRACT

The description of the motion of immersed bodies in fluids is present in several manufacturing processes. The objective of this project is modelling and simulation of a sphere rolling down an incline with constant angular velocity in an incompressible Newtonian media by using CFD techniques. Study on the hydrodynamics of the Newtonian fluid flow over the sphere has also been done. Comparison of velocity has been done for various types of fluids. Comparison of velocity has also been done for several angles of inclination and the angular velocity of the ball is also changed for each of these cases. Analysis and discussion of the motion of the sphere has been done using velocity contours.

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NOMENCLATURE

A	Projected area
Cd, Cx, Cw	Drag coefficient
D	Diameter of cylinder
F_d	Drag force
L	Length of cylinder
Re	Reynolds number
v	Velocity
y^+	the wall coordinate ; the distance y to the wall.
u^+	dimensionless velocity ; the velocity u parallel to the wall as a function y, divided by friction velocity u_T.
T_w	wall shear stress.
u_t	friction velocity or shear velocity
k	Von – Kraman constant

1.INTRODUCTION

A Newtonian fluid is one in which at a given temperature and pressure, the shear rate increases linearly with shear stress for a wide range of shear rates. As the shear stress tends to reduce the fluid flow near the centre of the pipe and accelerates the slow moving fluid towards the walls, for some radius within the pipe it is acting simultaneously in the negative direction on the fast moving fluid and in the positive direction on the slow moving fluid. There are several forces which affect the hydrodynamics of a Newtonian fluid among which drag force and wall effect are prominent. Whenever a difference in velocity exists between a particle and its surrounding fluid, the fluid will exert a resistive force on the particle. Either the gas may be at rest and the particle moving through it or the particle may be at rest and the fluid flowing by it. It is generally immaterial as to which phase is assumed to be at rest and which is assumed to be in motion; it is the relative velocity between the two that is important. The resistive force exerted by the fluid on the particle is called drag.

The drag coefficient (commonly denoted as C_d ,C_x or C_w) is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment. The drag coefficient is always associated with a particular surface area.

The drag coefficient C_d is defined as: $(2 f_d A / \rho v^2)$ (1.1)

From dimensional analysis, the drag coefficient of a smooth solid in an incompressible fluid depends on Reynolds number and necessary shape ratios.

Drag is generally divided into following types:

i. <u>Parasitic drag (also called skin friction drag):</u> It is the drag caused by moving a solid object through a fluid medium .Parasitic drag is made up of many components, the most important being form drag. Skin friction and interference drag are also major components of parasitic drag.

ii. <u>Lift-induced drag</u>: It is a drag force that occurs whenever a moving object redirects the airflow coming at it.

iii. Wave drag: It is a component of the drag on aircraft blade tips and projectiles moving at transonic and supersonic speeds, caused by the formation of shock waves around the body.

The effect of a wall on the flow of a fluid is quite pronounced in fluid dynamics, the law of the wall states that the average velocity of a turbulent flow at a certain point is proportional to the logarithm of the distance from that point to the boundary of the fluid region.

The law of the wall was first published by Robert von Karman. Technically it is only applicable to parts of the flow that are close to the wall.

The logarithimic law of the wall is a similar solution for the mean velocity parallel to the wall and is valid foe flows at high Reynolds number – in an overlap region with approximately conatant shear stress and far enough from the wall for (direct)viscous effects to be negligible.

Formulae:-

$$u^+ = 1/k * \ln(y^+) + C^+ \quad (1.2)$$

$$y^+ = yu_t / u \quad (1.3)$$

$$u^+ = u / u_t \quad (1.4)$$

$$u_t = \sqrt{Tw}/\sqrt{\rho} \quad (1.5)$$

where

y^+ is the wall coordinate ; the distance y to the wall.

u^+ is the dimensionless velocity ; the velocity u parallel to the wall as a function of y , divided by friction velocity u_T.

T_w is the wall shear stress.

ρ is the fluid density.

u_t is called the friction velocity or shear velocity.

k is the Von – Kraman constant.

Viscosity is due to friction between neighbouring layers of the fluid that are moving at different velocities. When fluid moves through a tube, the fluid generally moves faster near the axis and very slowly near the walls, therefore some stress (such as a pressure difference between the two ends of the tube) is needed to overcome the friction between layers and keep the fluid moving. For the same velocity pattern, the stress required is proportional to the fluid's viscosity. A liquid's viscosity depends on the size and shape of its particles and the attractions between the particles.

A fluid that has no resistance to shear stress is known as an ideal fluid or inviscid fluid. Zero viscosity is observed only at very low temperatures, in superfluids. Otherwise all fluids have positive viscosity. If the viscosity is very high, for instance in pitch, the fluid will appear to be a solid in a short term. A liquid whose viscosity is less than that of water is sometimes known as a mobile liquid, while a substance with a viscosity greater than water is called a viscous liquid.

2.LITERATURE REVIEW

The description of the motion of immersed bodies in fluids is present in several manufacturing processes, e.g. sediment transport and deposition in pipelines, alluvial channels, chemical engineering and powder process. Several works could be found in technical literature which investigated the spherical particles in low and high concentrations.

A particle falling or rolling down a plane in a fluid under the influence of gravity will accelerate until the gravitational force is balanced by the resistance forces that include buoyancy and drag. The constant velocity reached at that stage is called the “terminal velocity” or “settling velocity”. Knowledge of the terminal velocity of solids falling in liquids is required in many industrial applications. Typical examples include hydraulic transport slurry systems for coal and ore transportation, thickeners, mineral processing, solid–liquid mixing, fluidization equipment, drilling for oil and gas, geothermal drilling.

The resistive drag force depends upon drag coefficient. Drag coefficient and terminal velocities of particles are most important design parameters in engineering applications. There have been several attempts to relate the drag coefficient to the Reynolds number. Most of mentioned applications involve the description of the particle position, velocity and acceleration during time e.g. classification, centrifugal and gravity collection or separation, where it is often necessary to determine the trajectories of particle accelerating in a fluid for proposes of design or improved operation . For some industrial problems such as flow in the rolling ball viscometer which entails the measurement of the rolling velocity of a tightly fitting sphere in an inclined tube, transport of solid particles in inclined pipelines or sedimentation of solid particles in inclined open channels, we need information about the motion of particles rolling down an inclined plane.(Jalaal M et al .2009)

2.1 NECESSITY OF STUDY OF HYDRODYANMICS :

Study of Hydrodynamics of a particle placed in moving fluid streams is necessary in wide range of applications like chemical, mineral and process industries. Typical examples include process design calculation for continuous processing of large food particles, fixed and fluidized bed reactors, pneumatic and hydraulic conveying of coarse particles, liquid solid separation and classification technique etc. (Chhabra R.P. et al. 1998)

The settling behaviour for variously shaped particles is of fundamental importance. Irregularly shaped particles are met in many applications, such as sedimentation and flocculation of aggregates of fine particles in rivers and lakes, chemical blending, mineral processing, powder sintering, manufacturing with phase change and solidification processes. In most of these applications, the determination of the falling velocity of the particle is of interest for the design and optimization of processes and equipment. (Tran-Cong Sabine et al. 2003)

Many processes for the separation of particles of different sizes and shapes depend upon variations in the behaviour of the particles when subjected to the action of a moving fluid. A particle falling in an infinite fluid under the influence of gravity will accelerate until the gravitational force is exactly balanced by the resistance force that includes buoyancy and drag. The constant velocity reached at that stage is called the terminal velocity. The resistive drag force depends upon an experimentally determined drag coefficient. Drag coefficients along with terminal velocities is important design parameters in many separation processes (Gabitto J. 2007).

2.2 COMPUTATIONAL FLUID DYNAMICS (CFD):

CFD is the analysis of systems involving fluid flow, heat transfer, mass transfer, chemical reactions and related phenomena by solving mathematical equations which govern the processes using a numerical method. By means of computer based simulations. CFD is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyse problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of fluids and gases with the complex surfaces defined by boundary condition used in engineering. However, even with simplified equations and high speed supercomputers, only approximate solutions can be achieved in many cases. More accurate codes that can accurately and quickly simulate even complex scenarios such as supersonic or turbulent flows are an on-going area of research.

The fundamental basis of any CFD problem is the Navier-Stokes equations, which define any single-phase fluid flow. These equations can be simplified by removing terms describing viscosity to yield the Euler equations. Further simplification, by removing terms describing vorticity yields the Full Potential equations. Finally, these equations can be linearized to yield the Linearized Potential equations

2.3 APPLICATIONS OF CFD:

i. CFD can be used to simulate the flow over a vehicle. For instance, it can be used to study the interaction of propellers or rotors with the aircraft fuselage.

ii. Bio-medical engineering is a rapidly growing field and uses CFD to study the circulatory and respiratory systems.

iii. CFD is attractive to industry since it is more cost-effective than physical testing. However, one must note that complex flow simulations are challenging and error-prone and it takes a lot of engineering expertise to obtain validated solutions.

iv. Meteorology: weather prediction

v. Electrical and electronics engineering: cooling of equipment including microcircuits

vi. Chemical process engineering: mixing and separation, polymer moulding

2.4 PRACTICAL ADVANTAGES OF EMPLOYING CFD:

CFD predicts performance before modifying or installing systems: Without modifying and/or installing actual systems or a prototype, CFD can predict which design changes are most crucial to enhance performance.

CFD Saves Cost and Time: CFD costs much less than experiments because physical modifications are not necessary.

CFD is Reliable: The numerical schemes and methods upon which CFD is based are improving rapidly, so CFD results are increasingly reliable. CFD is a dependable tool for design and analyses.

2.5 LIMITATIONS OF CFD:

Despite advantages, there are few shortcomings of it as follows (Bakker., 2002)

i. CFD solutions rely upon physical models of real world processes.

ii. Solving equations on a computer invariably introduces numerical errors.

iii. Truncation errors due to approximation in the numerical models.

iv. Round-off errors due to finite word size available on the computer.

v. The accuracy of the CFD solution depends heavily upon the initial or boundary conditions provided to numerical model.

2.6 ANSYS:

ANSYS is a finite element analysis (FAE) code widely used in computer-aided engineering (CAE) field. ANSYS software helps to construct computer models of structures, machine components or systems; apply operating loads and other design criteria; and study physical responses such as stress levels, temperature distributions, pressure etc.

In the above software the following basic procedure is followed:

1. During preprocessing the geometry (physical bounds) of the problem is defined. The volume occupied by the fluid is divided into the discrete cells (the mesh). The mesh may be uniform or non-uniform. The physical modelling is defined, for example, the equations of motion + enthalpy + radiation + species conversion Boundary conditions are defined. This involves specifying the fluid behaviour of the problem. For transient problems, boundary conditions are also defined.

2. The simulation is started and the equations are solved iteratively as a steady-state or transient.

3. Finally a post-processor is used for the analysis and visualisation of the resulting problem.

2.7 USER DEFINED FUNCTION:-

A user-defined function, or UDF, is a function that one can program and which can be dynamically loaded in the FLUENT solver to increase the features of the code.
One can use a UDF to define one's own boundary conditions, material properties, and source terms for one's own regime, as well as specify customized model parameters initialize a solution or enhance post-processing.

UDFs are written in the C programming language using any text editor and the source code is saved with a .c extension.

The salient features of UDF are

1. They are written in the C programming language.
2. They must have an include statement for the udf.h file.
3. They must be definned using DEFINE macros supplied by Fluent Inc.
4. They utilize predfined macros and functions supplied by Fluent Inc. to acccess FLUENT
5. They solve for data and perform other tasks.
6. They are executed as interpreted or compiled functions.

3. MODELLING AND SIMULATION

3.1 PROBLEM DESCRIPTION :-

Consider a small, spherical, non-deformable particle of diameter D, mass m and density ρs rolling down a smooth plane in an infinite extent of an incompressible Newtonian fluid of density ρ and viscosity μ. Let u represent the velocity of the particle at any instant time, t, and g the acceleration due to gravity. Fig 1 demonstrates a schematic figure of current problem. Neglecting lift force and sphere tube friction, the equation of motion is gained as follows .

$$m(1.4+ 2\ \rho/\rho_s)du/dt = mg(1- \rho/\rho_s)\sin(\theta) - 1/8\pi D^2\rho C_D u^2 \qquad (3.1)$$

where C_D represents the drag coefficient. In the right hand side of the Eq. the first term represents the buoyancy affect and the second one corresponds to resistance, drag, and force. The main difficulty in solution of Eq. lies in the non-linear terms which are generated due to non-linearity nature of the drag coefficient, CD. Substituting in Eq. and by rearranging parameters, Eq. could be rewritten as follows

$$adu/dt + bu + cu^2 - d = 0\ ,\ u(0)=0 \qquad (3.2)$$

where ,

$$a=m(1.4 + 2\ \rho/\rho_s) \qquad (3.3)$$

$$b= \beta\pi D\mu/ 8 \qquad (3.4)$$

$$c=\alpha\pi D^2\rho/ 8 \qquad (3.5)$$

$$d=mg(1- \rho/\rho_s) \sin(\theta) \qquad (3.6)$$

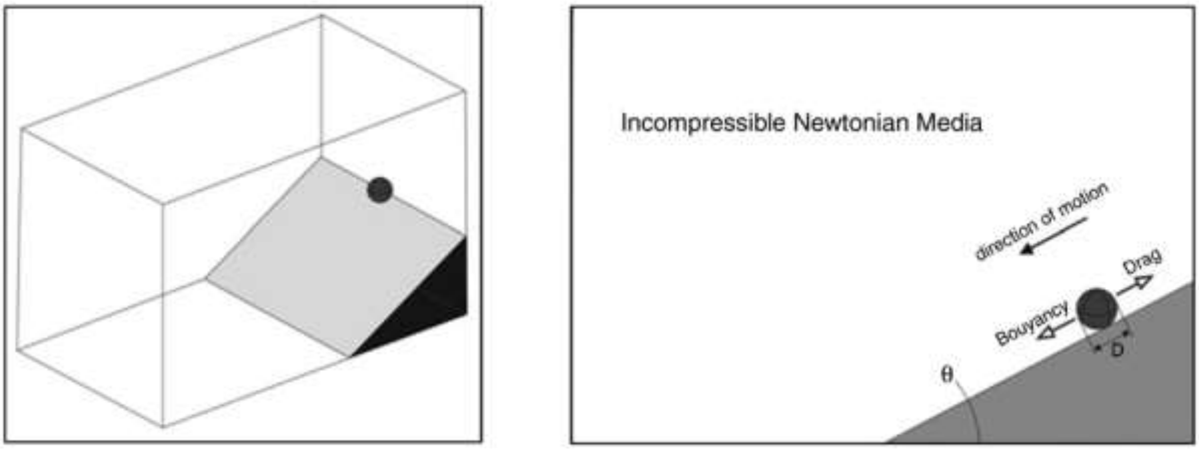

Figure 1 Schematic picture of a spherical particle rolling down a smooth inclined plane in a Newtonian media (Jalaal M et al .2009)

3.2 CFD SIMULATION

3.2.1 Geometry and Mesh:

Geometrical modeling is one of the most critical stages in CFD simulation; correct definition of the geometry provides a more realistic scenario for the simulation, and the technique used for constructing the geometry will ensure the feasibility of generating a mesh good enough to capture all of the phenomena involved in the problem (Salari D.et al, 2007).

The present problem involves the design of an inclined plane in an incompressible Newtonian media where a spherical particle rolls down the plane. The rolling sphere thus involves the problem of a moving mesh for which a user defined function or (UDF) is defined and this is imported into fluent for the above said simulation. The angular velocity of the ball is kept constant for each case and that of the slope is varying with each simulation. The media in which the sphere rolls is also changed from time to time for a comparison among the various medias used.

ANSYS FLUENT 13 was used for making 3D geometry of the sphere present on the incline. The diameter of the sphere was 3mm. The length of the inclined plane was 200mm. Then fine meshing was done in order to have 15691 nodes for the whole geometry. Then named selection was done for the entire geometry.

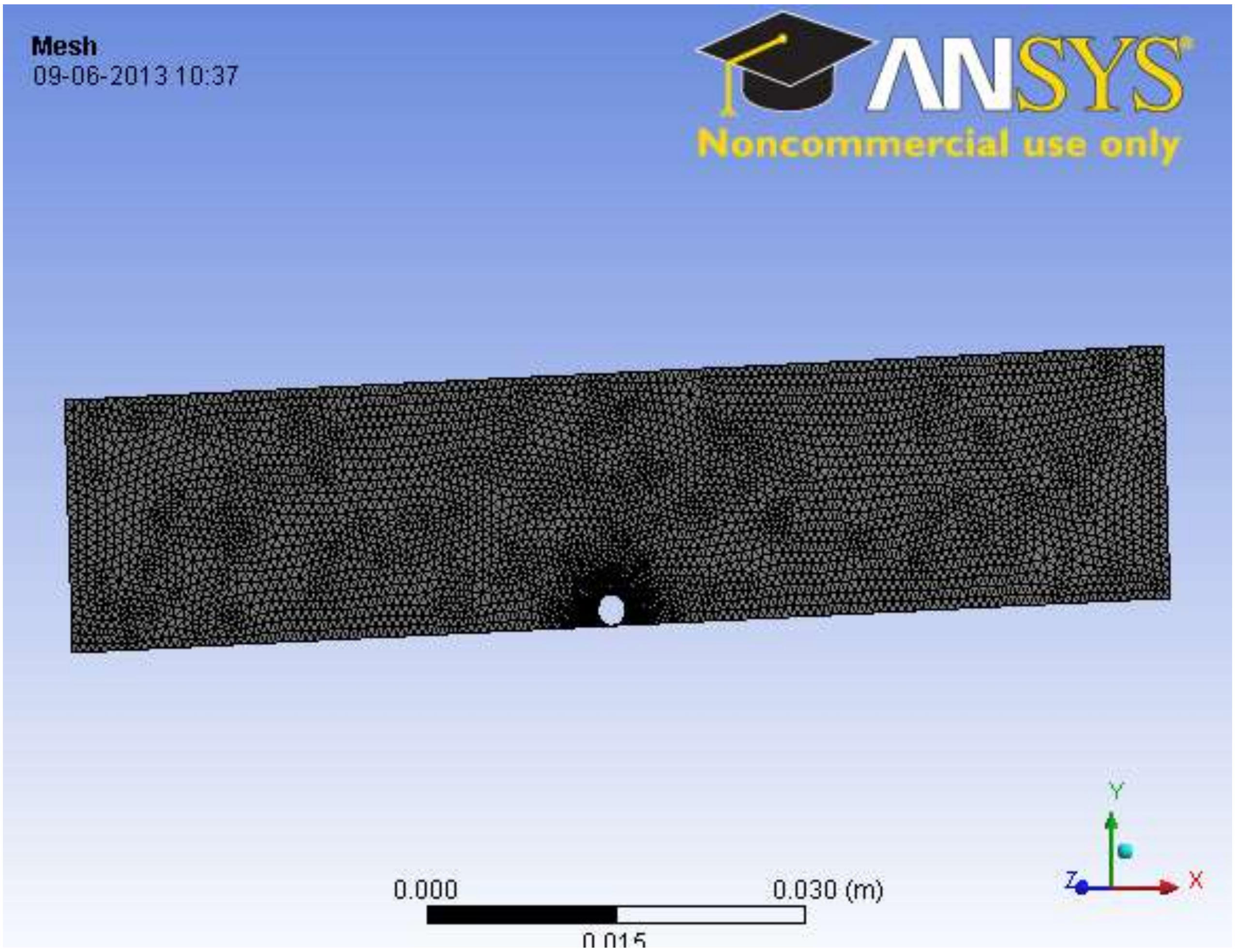

Figure 2 mesh for θ=2°

Table 1 Physical properties of media at 298K

Material	Density kg/m^3	Viscosity kg/m.sec
Olive oil	913.0	.0840
75% Glycerine	1178.2	.0182
Water	998.0	.0010

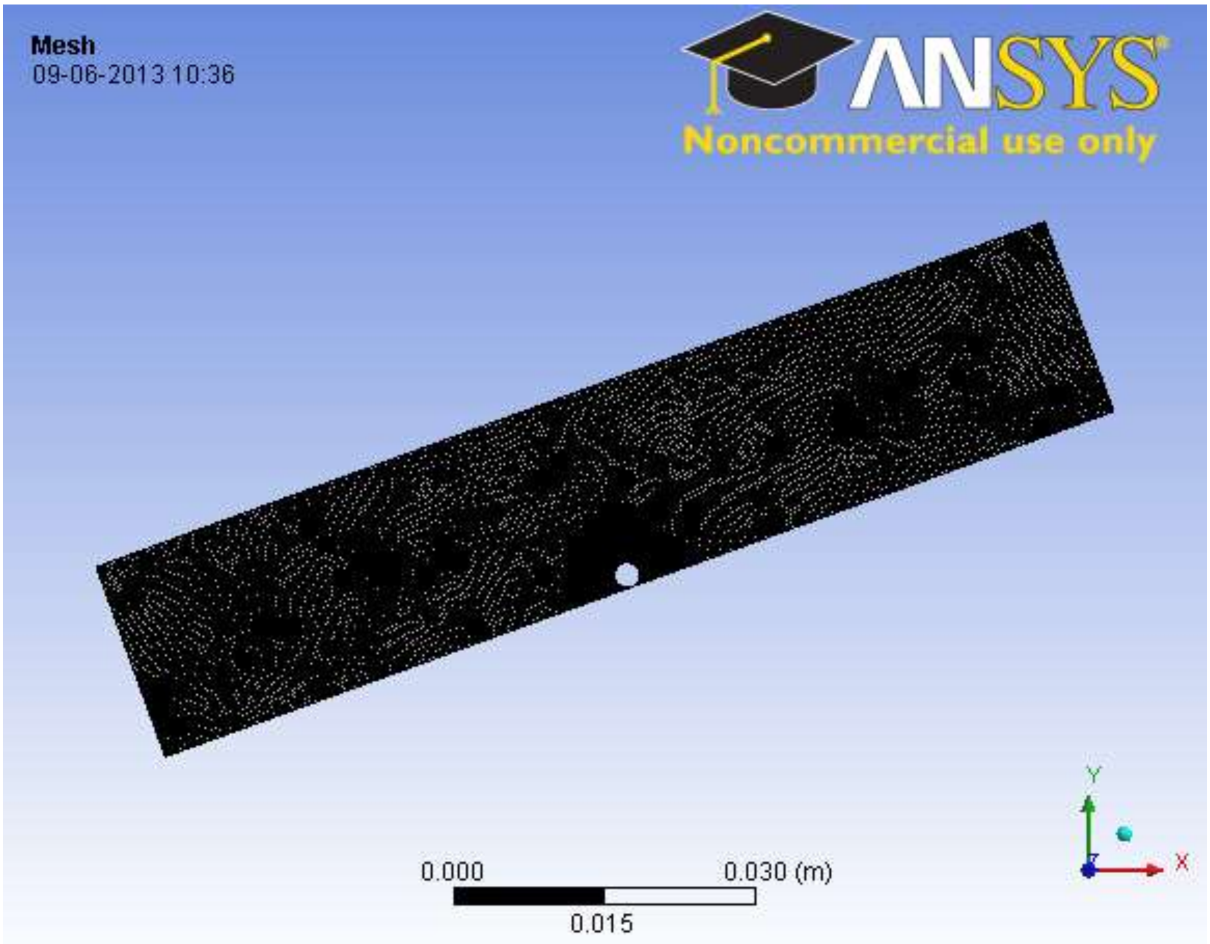

Figure 3 mesh for θ=20°

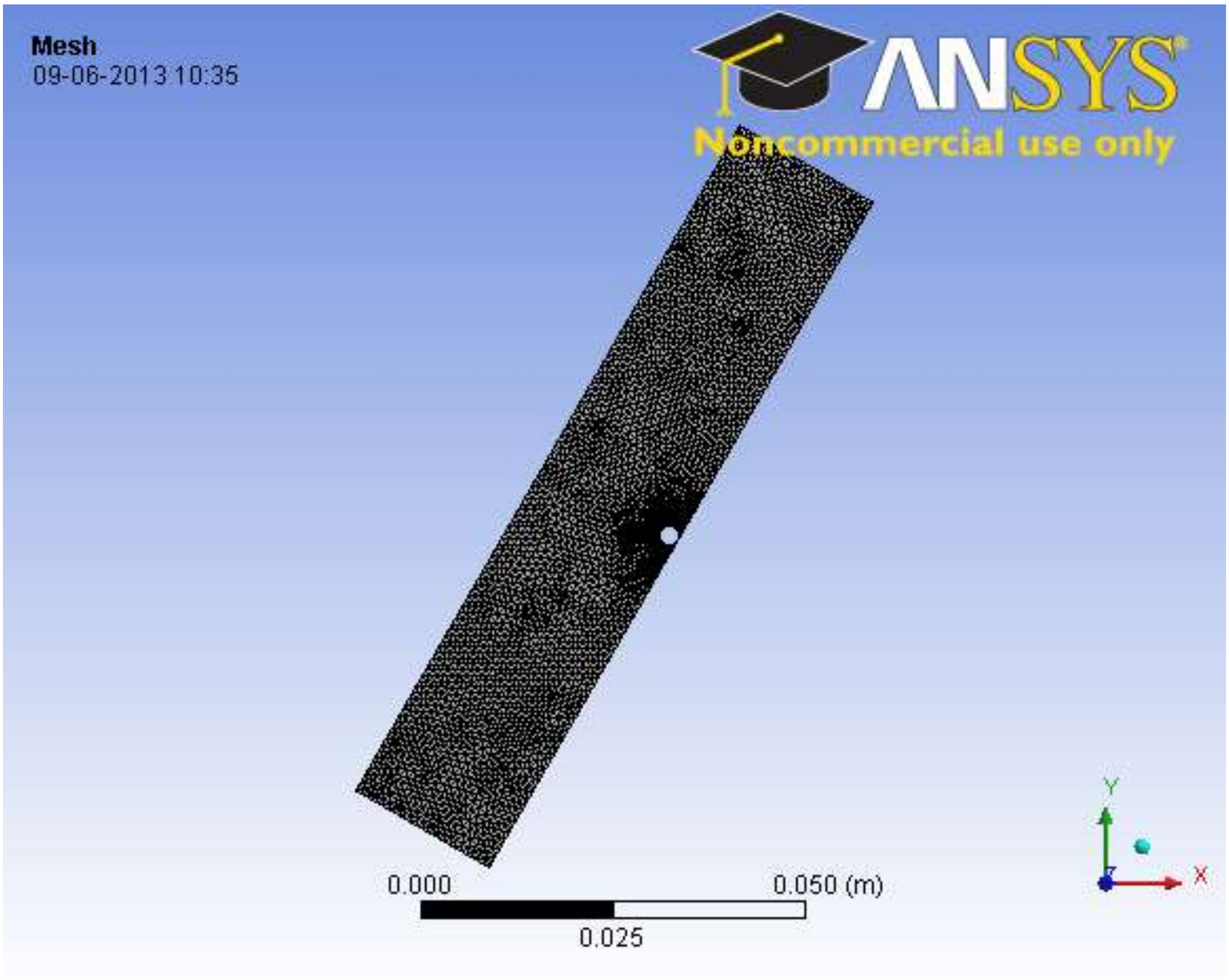

Figure 4 mesh for θ=60°

3.2.2 USER DEFINED FUNCTION

An udf (user defined function) used in each of the simulations (Appendix). The various MACROS used in this program are DEFINE_CG_MOTION, NV_S and DT_THREAD. Each of these MACROS has a special usage in the program. In each of these simulations a change in parameters in the UDF is done so as to accommodate the changes for varying conditions.

3. RESULTS AND DISCUSSIONS

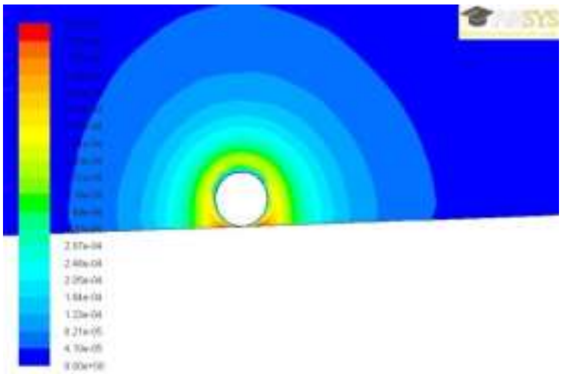

Figure 5 velocity contour for media water θ=2°, t= 0.15 sec & ω=5 rad/sec

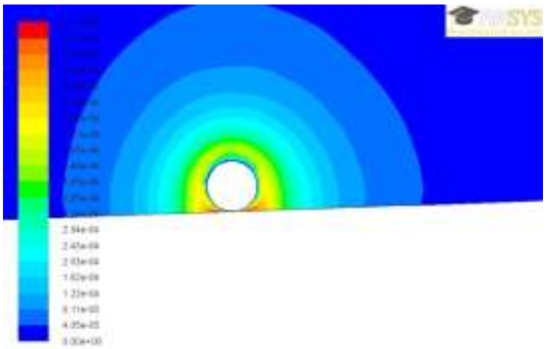

Figure 6 velocity contour for media water θ=2°, t= 0.2 sec & ω=5 rad/sec

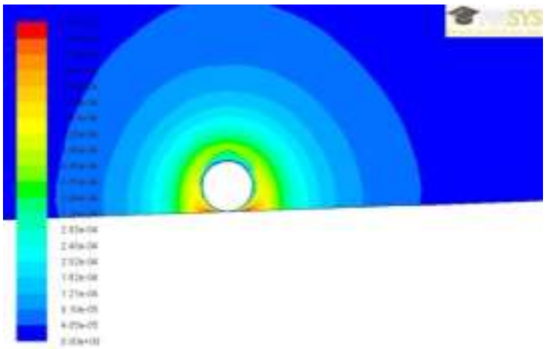

Figure 7 velocity contour for media water θ=2°, t= 0.3 sec & ω=5 rad/sec

Table 2 Values of velocity for media water , θ= 2° and ω= 5 rad/sec

Media	Angle	Time	Angular velocity	Velocity
water	2°	.15sec	5 rad/sec	.0512 m /sec
water	2°	.2sec	5 rad/sec	.01122 m /sec
water	2°	.3sec	5 rad/sec	.007 m/sec

The velocity of a sphere having a constant angular velocity of 5 rad/sec rolling down an inclined plane of inclination 2° in a water media decreases until it reaches a terminal velocity. Initially it has high velocity because at t=0sec it is given an angular velocity of 5 rad/sec.

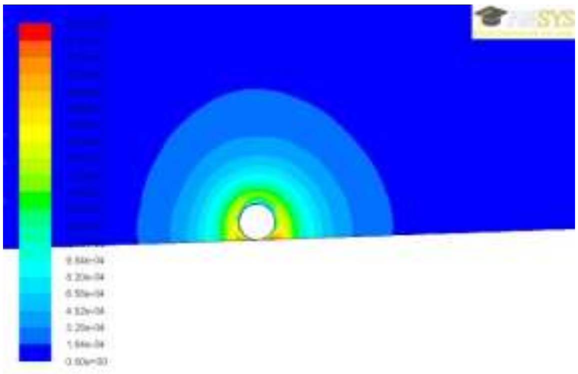

Figure 8 velocity contour for media water θ=2°, t= 0.15 sec & ω=10 rad/sec

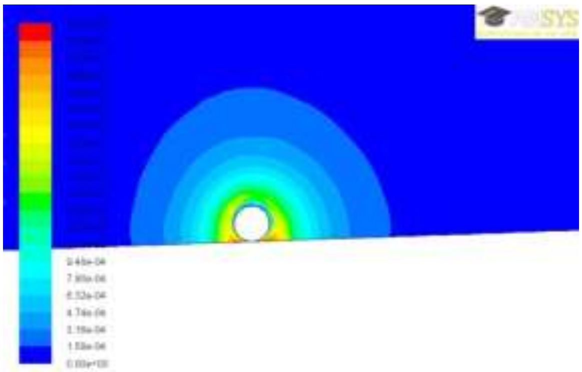

Figure 9 velocity contour for media water θ=2°, t= 0.2 sec & ω=10 rad/sec

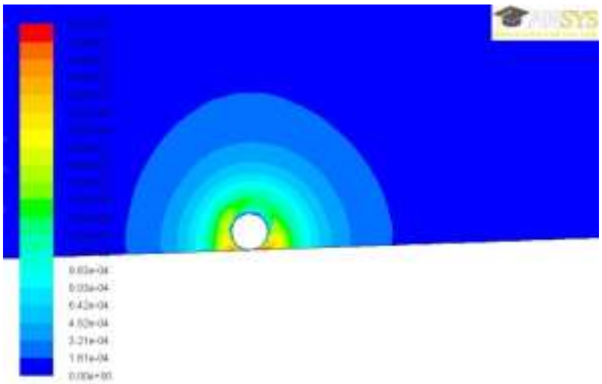

Figure 10 velocity contour for media water θ=2°, t= 0.3 sec & ω=10 rad/sec

Table 3 Values of velocity for media water , θ= 2° and ω= 10 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
water	2°	.15sec	10 rad/sec	.01526 m/sec
water	2°	.2sec	10 rad/sec	.01129 m/sec
water	2°	.3sec	10 rad/sec	.00738 m/sec

The velocity of a sphere having a constant angular velocity of 10 rad/sec rolling down an inclined plane of inclination 2° in a water media decreases until it reaches a terminal velocity. The higher velocity at the beginning persists but the velocity increases mildly because of higher angular velocity.

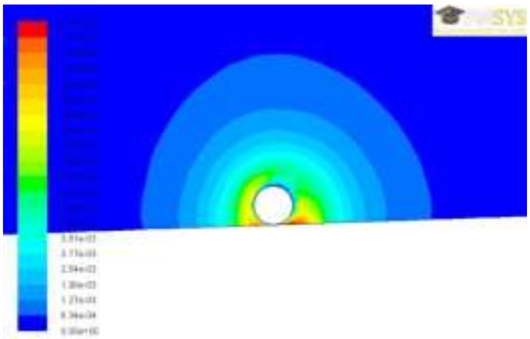

Figure 11 velocity contour for media water θ=2°, t= 0.15 sec & ω=20 rad/sec

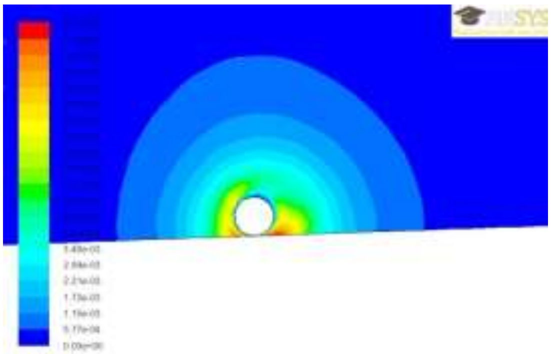

Figure 12 velocity contour for media water θ=2°, t= 0.2 sec & ω=20 rad/sec

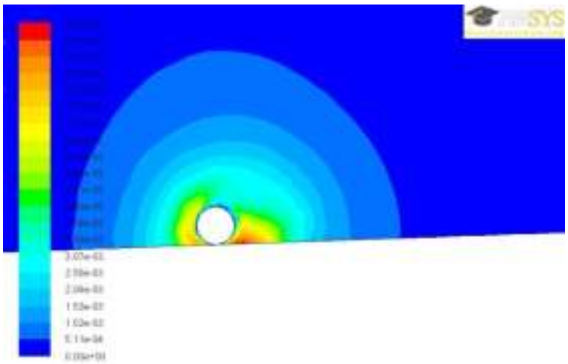

Figure 13 velocity contour for media water θ=2°, t= 0.3 sec & ω=20 rad/sec

Table 4 Values of velocity for media water , θ= 2° and ω= 20 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
water	2°	.15sec	20 rad/sec	.01537 m/sec
water	2°	.2 sec	20 rad/sec	.01197 m/sec
water	2°	.3 sec	20 rad/sec	.00749 m/sec

The velocity of a sphere having a constant angular velocity of 20 rad/sec rolling down an inclined plane of inclination 2° in a water media decreases until it reaches a terminal velocity. The increase in velocity for higher angular velocity is still seen along with the mild increase in overall velocity with respect to other angular velocities.

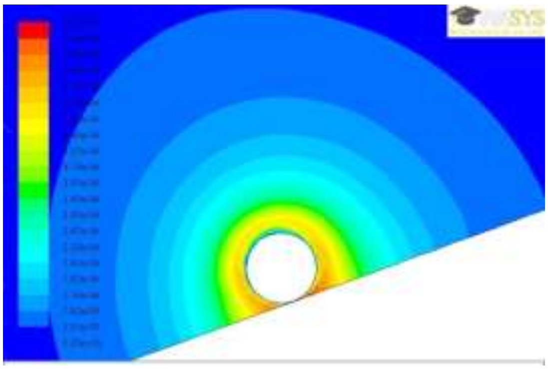

Figure 14 velocity contour for media water θ=20°, t= 0.15 sec & ω=5 rad/sec

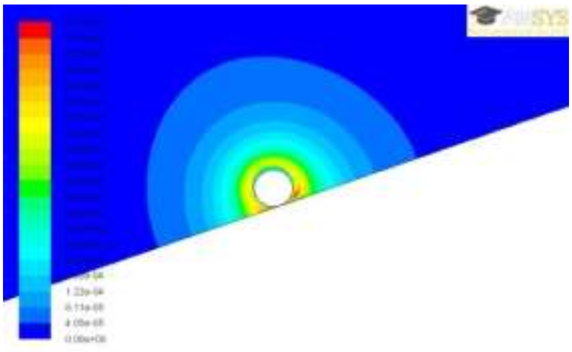

Figure 15 velocity contour for media water θ=20°, t= 0.2 sec & ω=5 rad/sec

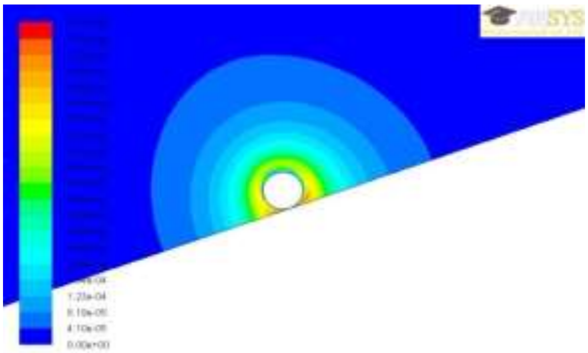

Figure 16 velocity contour for media water θ=20°, t= 0.3 sec & ω=5 rad/sec

Table 5 Values of velocity for media water , θ= 20° and ω= 5 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
water	20°	.15sec	5 rad/sec	.01651 m/sec
water	20°	.2 sec	5 rad/sec	.01235 m/sec
water	20°	.3 sec	5 rad/sec	.00821 m/sec

The velocity of a sphere having a constant angular velocity of 5 rad/sec rolling down an inclined plane of inclination 20° in a water media decreases until it reaches a terminal velocity. There is an increase in velocity by .001 m/sec for each case with respect to 2° angle for the same conditions. Thus showing the effect of change in angle on the velocity of the sphere .

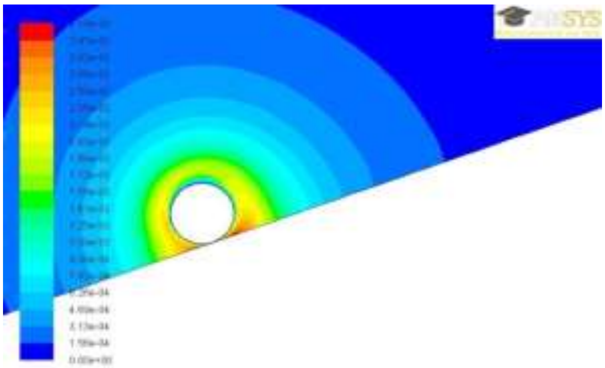

Figure 17 velocity contour for media water θ=20°, t= 0.15 sec & ω=10 rad/sec

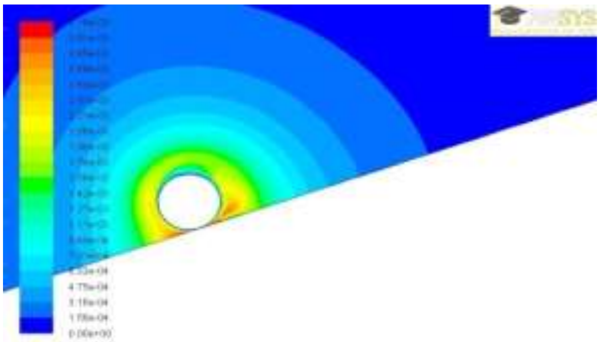

Figure 18 velocity contour for media water θ=20°, t= 0.2 sec & ω=10 rad/sec

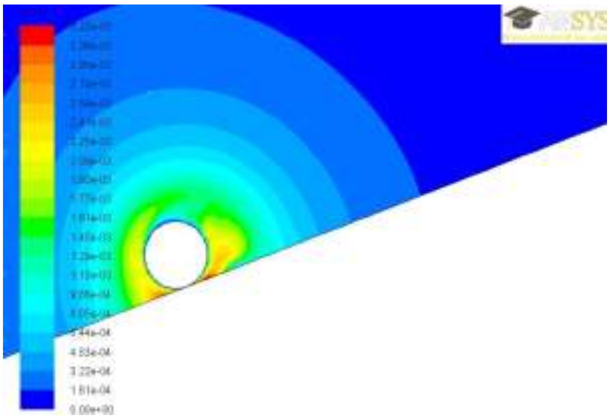

Figure 19 velocity contour for media water θ=20°, t= 0.3 sec & ω=10 rad/sec

Table 6 Values of velocity for media water , θ= 20° and ω= 10 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
water	20°	.15sec	10 rad/sec	.01659 m/sec
water	20°	.2 sec	10 rad/sec	.01241 m/sec
water	20°	.3 sec	10 rad/sec	.00829 m/sec

The velocity of a sphere having a constant angular velocity of 10 rad/sec rolling down an inclined plane of inclination 20° in a water media decreases until it reaches a terminal velocity. There is a slight increase in velocity with respect to the previous case for the same angle, however the effect of angle can be seen for the same angular velocity where the velocity increases by .001 m/sec or more.

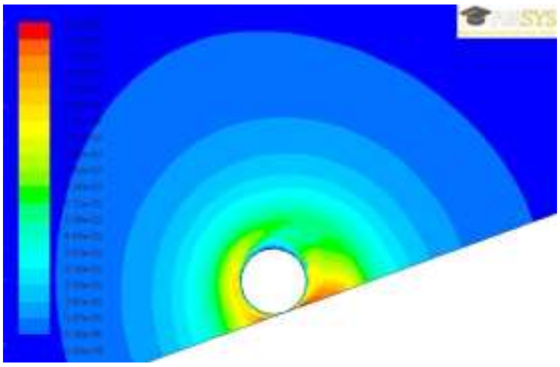

Figure 20 velocity contour for media water θ=20°, t= 0.15 sec & ω=20 rad/sec

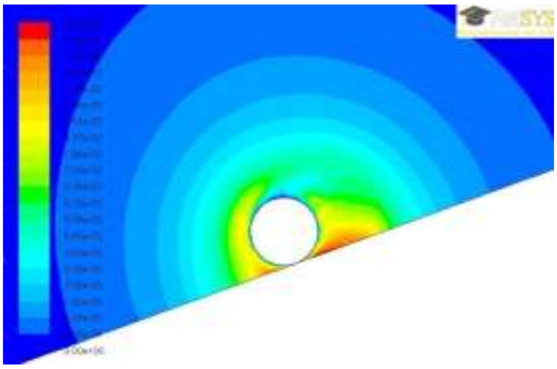

Figure 21 velocity contour for media water θ=20°, t= 0.2 sec & ω=20 rad/sec

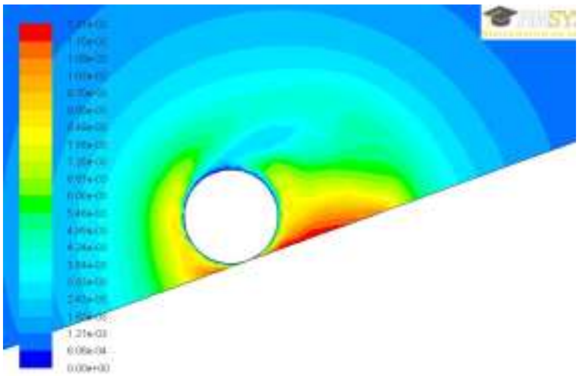

Figure 22 velocity contour for media water θ=20°, t= 0.3 sec & ω=20 rad/sec

Table 7 Values of velocity for media water , θ= 20° and ω= 20 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
water	20°	.15sec	20 rad/sec	.01668 m/sec
water	20°	.2 sec	20 rad/sec	.01261 m/sec
water	20°	.3 sec	20 rad/sec	.00831 m/sec

The velocity of a sphere having a constant angular velocity of 20 rad/sec rolling down an inclined plane of inclination 20° in a water media decreases until it reaches a terminal velocity. The velocity is found to be highest among all the cases simulated until now because it has the highest angular velocity and angle.

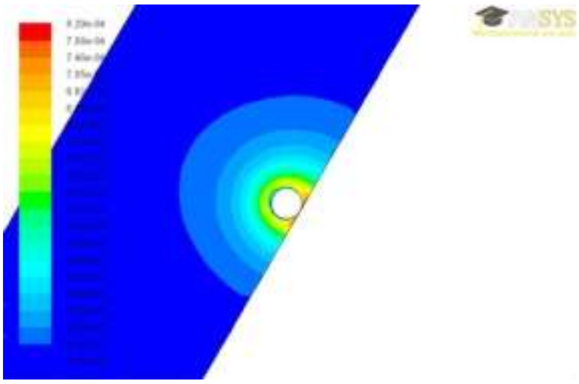

Figure 23 velocity contour for media water θ=60°, t= 0.15 sec & ω=5 rad/sec

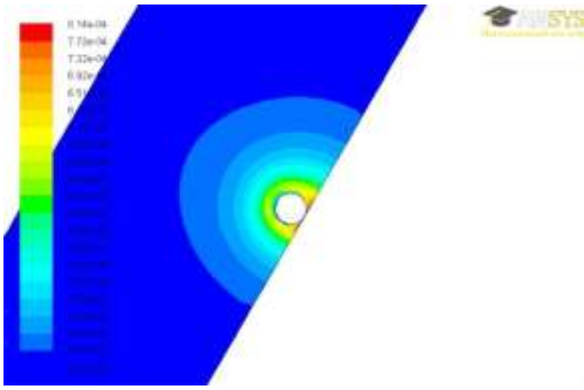

Figure 24 velocity contour for media water θ=60°, t= 0.2 sec & ω=5 rad/sec

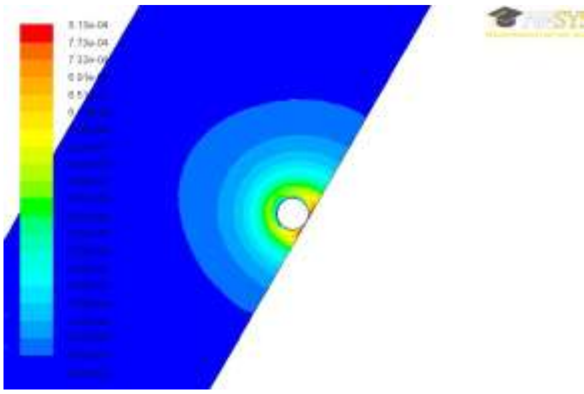

Figure 25 velocity contour for media water θ=60°, t= 0.3 sec & ω=5 rad/sec

Table 8 Values of velocity for media water , θ= 60° and ω= 5 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
water	60°	.15sec	5 rad/sec	.17524 m/sec
water	60°	.2 sec	5 rad/sec	.13188 m/sec
water	60°	.3 sec	5 rad/sec	.00880 m/sec

The velocity of a sphere having a constant angular velocity of 5 rad/sec rolling down an inclined plane of inclination 60° in a water media decreases until it reaches a terminal velocity. The effect of angle can be clearly seen as the velocity increases by as high as 11.5 times than for the previous cases with the same angular velocities.

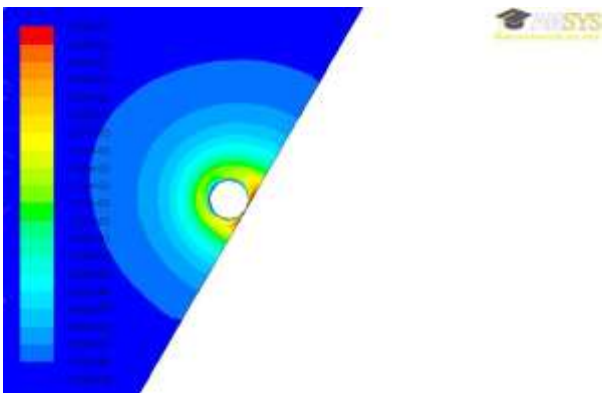

Figure 26 velocity contour for media water θ=60°, t= 0.15 sec & ω=10 rad/sec

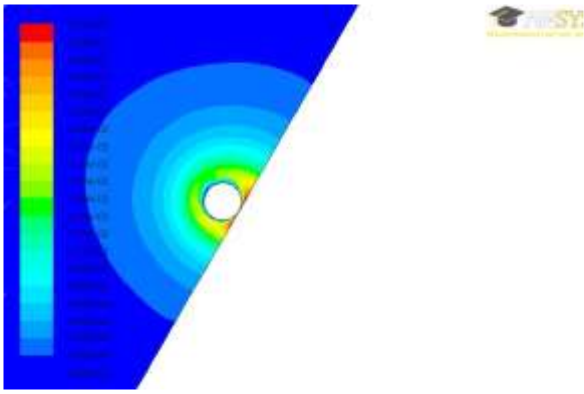

Figure 27 velocity contour for media water θ=60°, t= 0.2 sec & ω=10 rad/sec

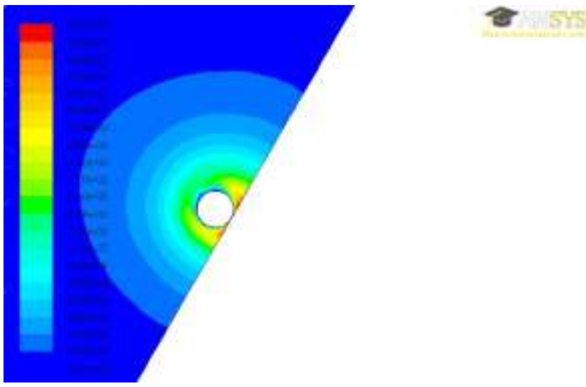

Figure 28 velocity contour for media water θ=60°, t= 0.3 sec & ω=10 rad/sec

Table 9 Values of velocity for media water , θ= 60° and ω= 10 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
water	60°	.15sec	10 rad/sec	.17947 m/sec
water	60°	.2 sec	10 rad/sec	.13279 m/sec
water	60°	.3 sec	10 rad/sec	.089 m/sec

The velocity of a sphere having a constant angular velocity of 10 rad/sec rolling down an inclined plane of inclination 60° in a water media decreases until it reaches a terminal velocity. The effect of angle in this case is more pronounced in this case and it has higher velocity than the previous case for the same angle owing to the higher angular velocity.

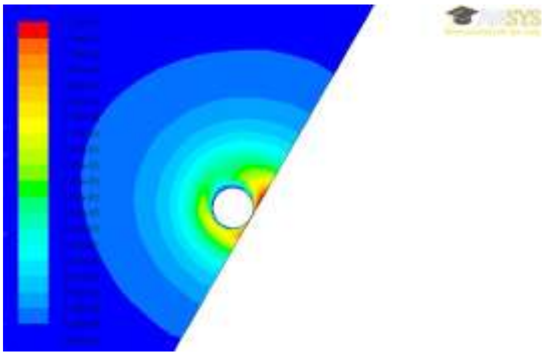

Figure 29 velocity contour for media water θ=60°, t= 0.15 sec & ω=20 rad/sec

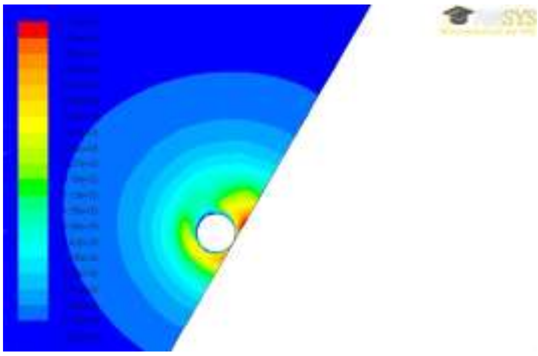

Figure 30 velocity contour for media water θ=60°, t= 0.2 sec & ω=20 rad/sec

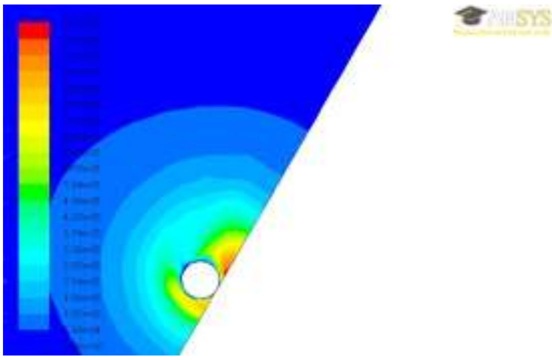

Figure 31 velocity contour for media water θ=60°, t= 0.3 sec & ω=20 rad/sec

Table 10 Values of velocity for media water , θ= 60° and ω= 20 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
water	60°	.15sec	20 rad/sec	.1796 m/sec
water	60°	.2 sec	20 rad/sec	.1388 m/sec
water	60°	.3 sec	20 rad/sec	.0968 m/sec

The velocity of a sphere having a constant angular velocity of 20 rad/sec rolling down an inclined plane of inclination 60° in a water media decreases until it reaches a terminal velocity. This case has the highest velocity among all the cases simulated for water media because of the higher angular velocity as well as the highest angle of inclination.

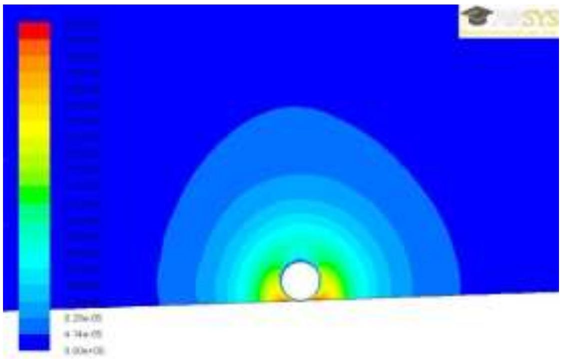

Figure 32 velocity contour for media glycerine θ=2°, t= 0.15 sec & ω=5 rad/sec

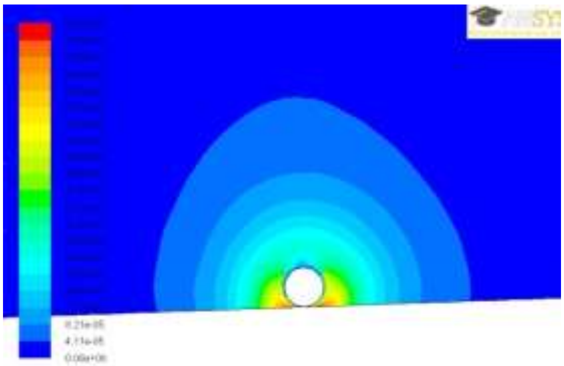

Figure 33 velocity contour for media glycerine θ=2°, t= 0.2 sec & ω=5 rad/sec

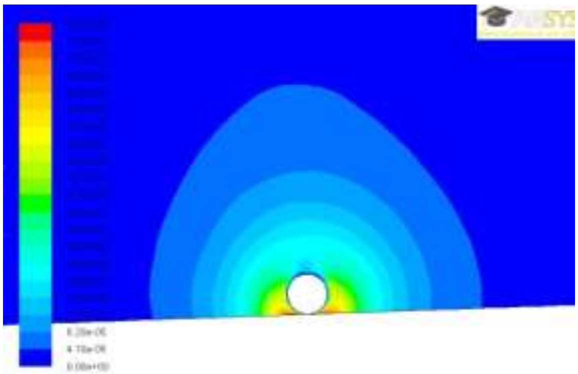

Figure 34 velocity contour for media glycerine θ=2°, t= 0.3 sec & ω=5 rad/sec

Table 11 Values of velocity for media glycerine , θ= 2° and ω= 5 rad/sec

Media	Angle	Time	Angular velocity	Velocity
Glycerine	2°	.15sec	5 rad/sec	.01507 m/sec
Glycerine	2°	.2sec	5 rad/sec	.01119 m/sec
Glycerine	2°	.3sec	5 rad/sec	.00696 m/sec

The velocity of a sphere having a constant angular velocity of 5 rad/sec rolling down an inclined plane of inclination 2° in a glycerine media decreases until it reaches a terminal velocity. The velocity in this case is lower than water for the same angular velocity and angle because of higher viscosity of .0182 kg/m.sec than water which has a density of .0010 kg/m.sec.

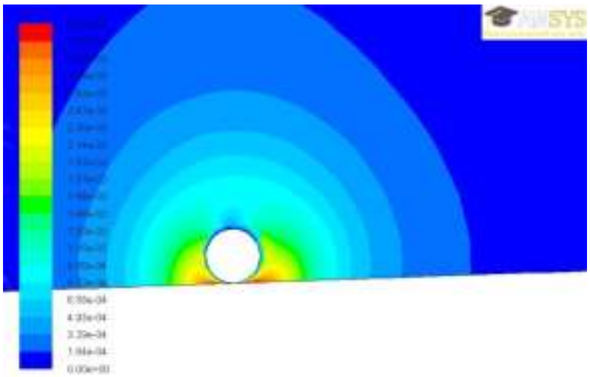

Figure 35 velocity contour for media glycerine θ=2°, t= 0.15 sec & ω=10 rad/sec

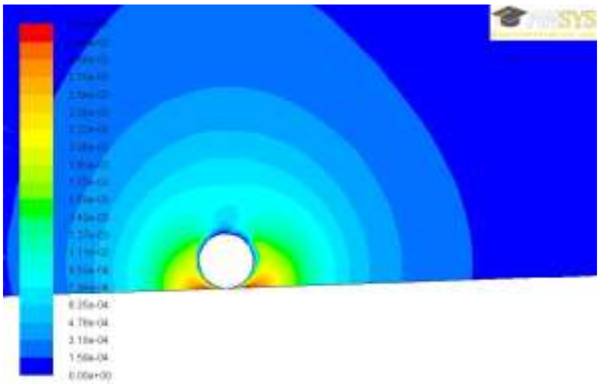

Figure 36 velocity contour for media glycerine θ=2°, t= 0.2 sec & ω=10 rad/sec

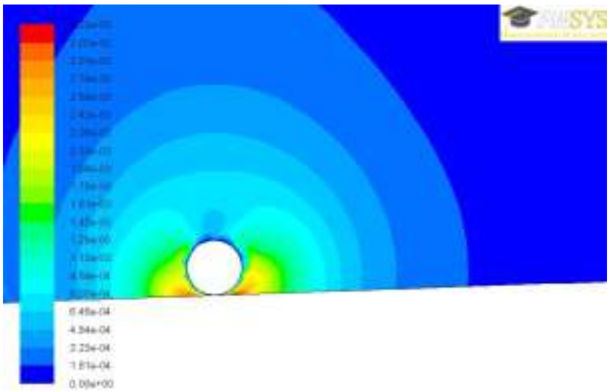

Figure 37 velocity contour for media glycerine θ=2°, t= 0.3 sec & ω=10 rad/sec

Table 12 Values of velocity for media glycerine , θ= 2° and ω= 10 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Glycerine	**2°**	.15sec	10 rad/sec	.01516 m/sec
Glycerine	**2°**	.2 sec	10 rad/sec	.01122 m/sec
Glycerine	**2°**	.3 sec	10 rad/sec	.00704 m/sec

The velocity of a sphere having a constant angular velocity of 10 rad/sec rolling down an inclined plane of inclination 2° in a glycerine media decreases until it reaches a terminal velocity. The velocity in this case is higher than what it was for 5 rad/sec but still lower than water for the same angular velocity and angle.

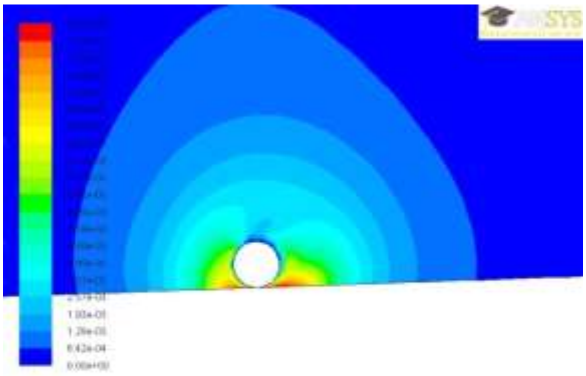

Figure 38 velocity contour for media glycerine θ=2°, t= 0.15 sec & ω=20 rad/sec

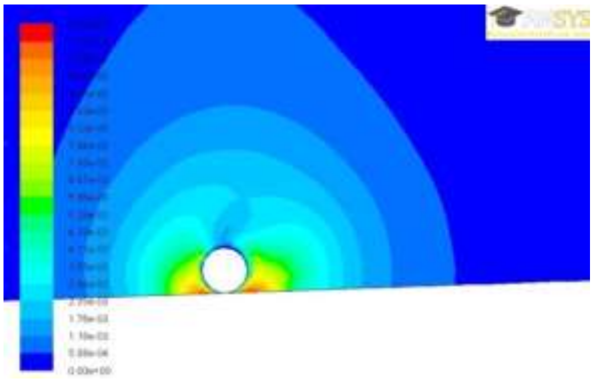

Figure 39 velocity contour for media glycerine θ=2°, t= 0.2 sec & ω=20 rad/sec

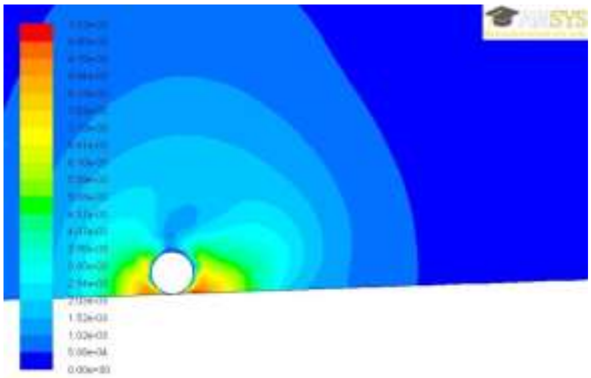

Figure 40 velocity contour for media glycerine θ=2°, t= 0.3 sec & ω=20 rad/sec

Table 13 Values of velocity for media glycerine , θ= 2° and ω= 20 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Glycerine	2°	.15sec	20 rad/sec	.01524 m/sec
Glycerine	2°	.2 sec	20 rad/sec	.01127 m/sec
Glycerine	2°	.3 sec	20 rad/sec	.00715 m/sec

The velocity of a sphere having a constant angular velocity of 20 rad/sec rolling down an inclined plane of inclination 2° in a glycerine media decreases until it reaches a terminal velocity. The velocity is highest in this case for the same media and angle as it has highest angular velocity.

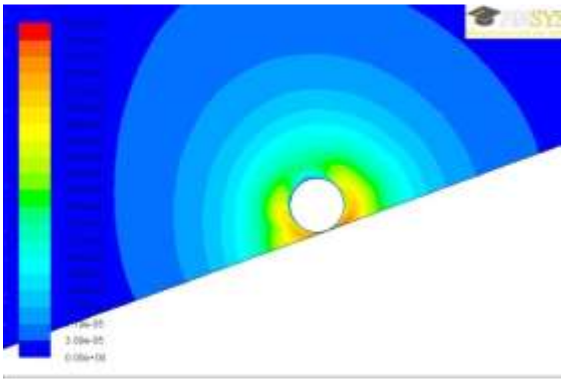

Figure 41 velocity contour for media glycerine θ=20°, t= 0.15 sec & ω=5 rad/sec

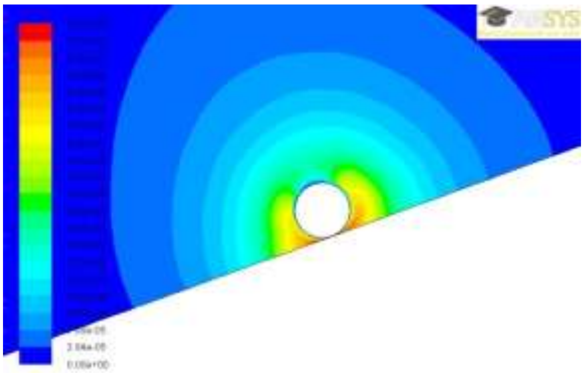

Figure 42 velocity contour for media glycerine θ=20°, t= 0.2 sec & ω=5 rad/sec

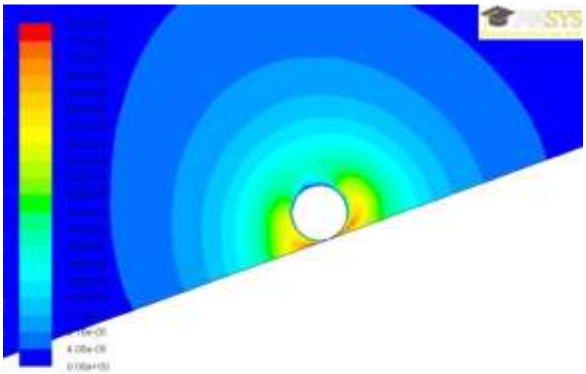

Figure 43 velocity contour for media glycerine θ=20°, t= 0.3 sec & ω=5 rad/sec

Table 14 Values of velocity for media glycerine , θ= 20° and ω= 5 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Glycerine	20°	.15sec	5 rad/sec	.01651 m/sec
Glycerine	20°	.2 sec	5 rad/sec	.01235 m/sec
Glycerine	20°	.3 sec	5 rad/sec	.00821 m/sec

The velocity of a sphere having a constant angular velocity of 5 rad/sec rolling down an inclined plane of inclination 20° in a glycerine media decreases until it reaches a terminal velocity. The velocity in this case is same as with water media so it shows that for higher angle the effect of media is minimal.

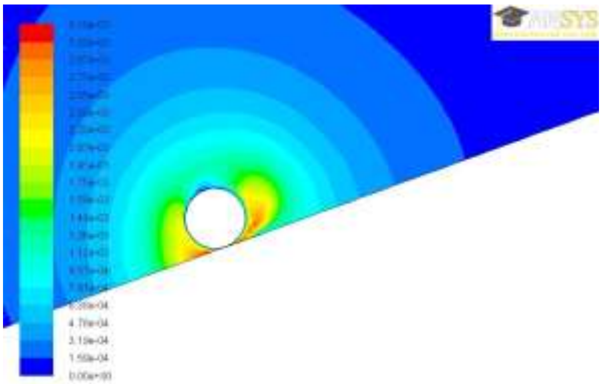

Figure 44 velocity contour for media glycerine θ=20°, t= 0.15 sec & ω=10 rad/sec

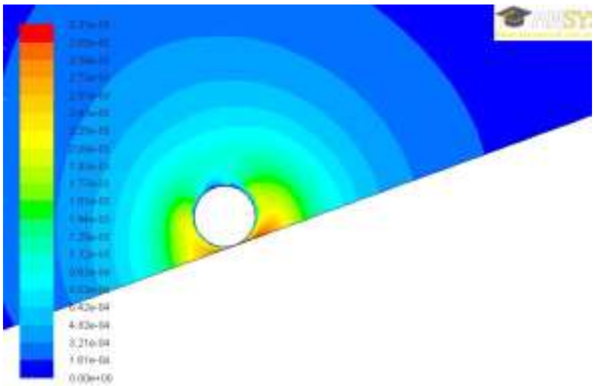

Figure 45 velocity contour for media glycerine θ=20°, t= 0.2 sec & ω=10 rad/sec

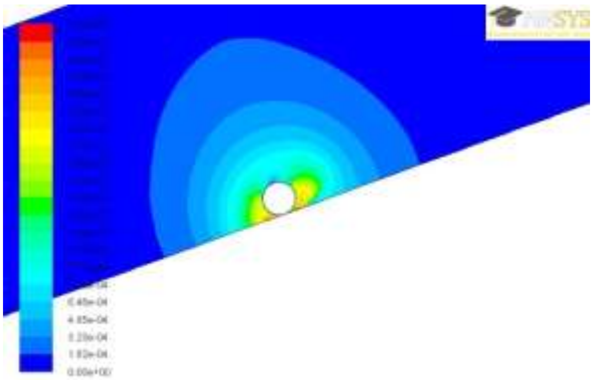

Figure 46 velocity contour for media glycerine θ=20°, t= 0.3 sec & ω=10 rad/sec

Table 15 Values of velocity for media glycerine , θ= 20° and ω= 10 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Glycerine	20°	.15sec	10 rad/sec	.01659 m/sec
Glycerine	20°	.2 sec	10 rad/sec	.01241 m/sec
Glycerine	20°	.3 sec	10 rad/sec	.00829 m/sec

The velocity of a sphere having a constant angular velocity of 10 rad/sec rolling down an inclined plane of inclination 20° in a glycerine media decreases until it reaches a terminal velocity. The velocity increases with increase in angular velocity but the velocity change due to media is still negligible for the same angle.

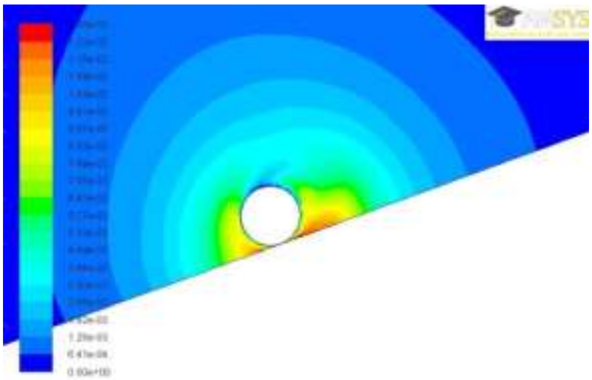

Figure 47 velocity contour for media glycerine θ=20°, t= 0.15 sec & ω=20 rad/sec

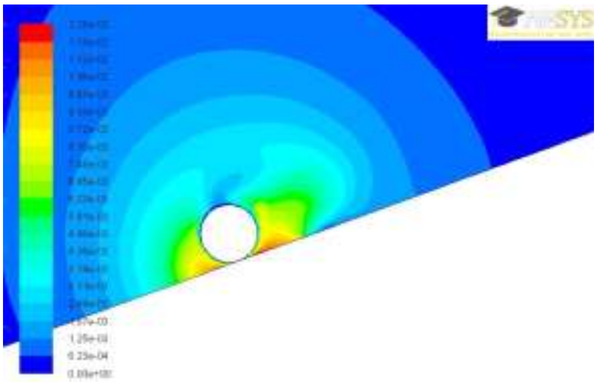

Figure 48 velocity contour for media glycerine θ=20°, t= 0.2 sec & ω=20 rad/sec

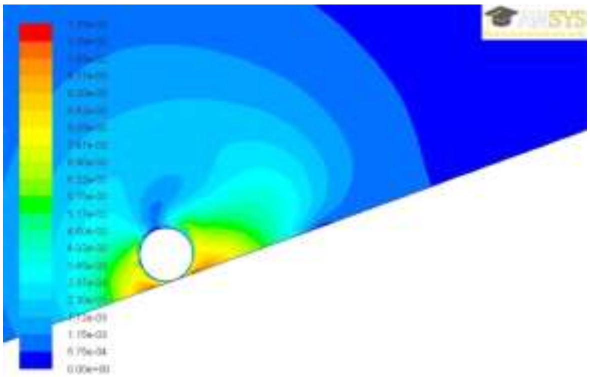

Figure 49 velocity contour for media glycerine θ=20°, t= 0.3 sec & ω=20 rad/sec

Table 16 Values of velocity for media glycerine , θ= 20° and ω= 20 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Glycerine	20°	.15sec	20 rad/sec	.01668 m/sec
Glycerine	20°	.2 sec	20 rad/sec	.01261 m/sec
Glycerine	20°	.3 sec	20 rad/sec	.00831 m/sec

The velocity of a sphere having a constant angular velocity of 20 rad/sec rolling down an inclined plane of inclination 20° in a glycerine media decreases until it reaches a terminal velocity. The velocity increases with increase in angular velocity and the velocity is higher with respect to same media for 2° angle.

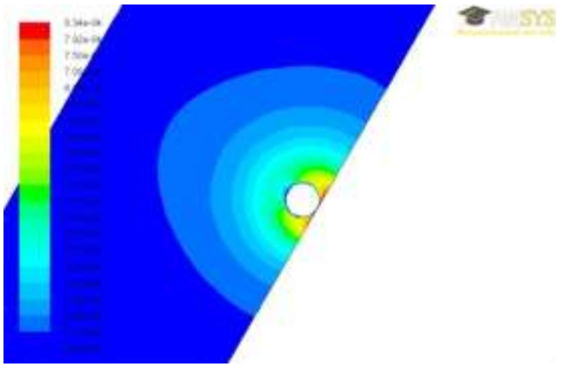

Figure 50 velocity contour for media glycerine θ=60°, t= 0.15 sec & ω=5 rad/sec

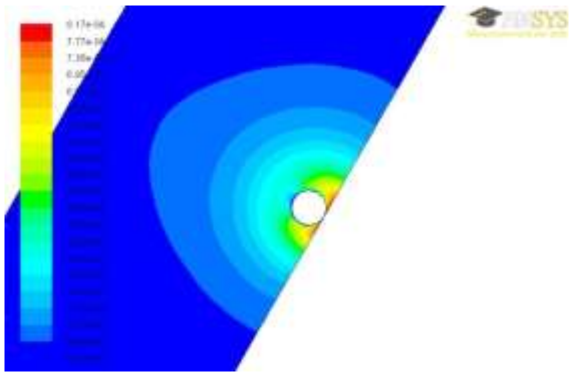

Figure 51 velocity contour for media glycerine θ=60°, t= 0.2 sec & ω=5 rad/sec

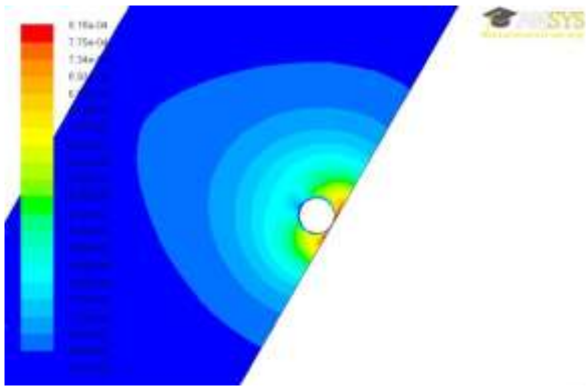

Figure 52 velocity contour for media glycerine θ=60°, t= 0.3 sec & ω=5 rad/sec

Table 17 Values of velocity for media glycerine , θ= 60° and ω= 5 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Glycerine	60°	.15sec	5 rad/sec	.17524 m/sec
Glycerine	60°	.2 sec	5 rad/sec	.13188 m/sec
Glycerine	60°	.3 sec	5 rad/sec	.00880 m/sec

The velocity of a sphere having a constant angular velocity of 5 rad/sec rolling down an inclined plane of inclination 60° in a glycerine media decreases until it reaches a terminal velocity. The velocity as increases by 11.4 times with respect to 2° angle because of high angle of inclination.

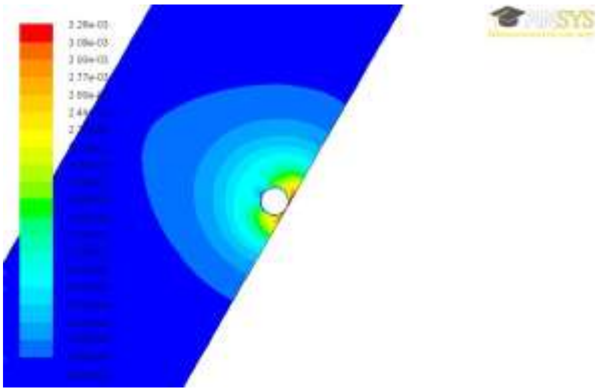

Figure 53 velocity contour for media glycerine θ=60°, t= 0.15 sec & ω=10 rad/sec

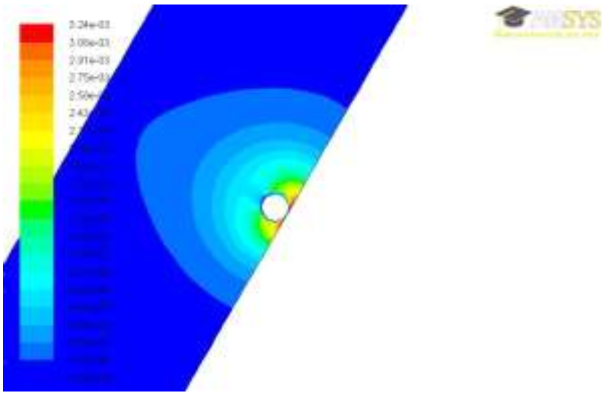

Figure 54 velocity contour for media glycerine θ=60°, t= 0.2 sec & ω=10 rad/sec

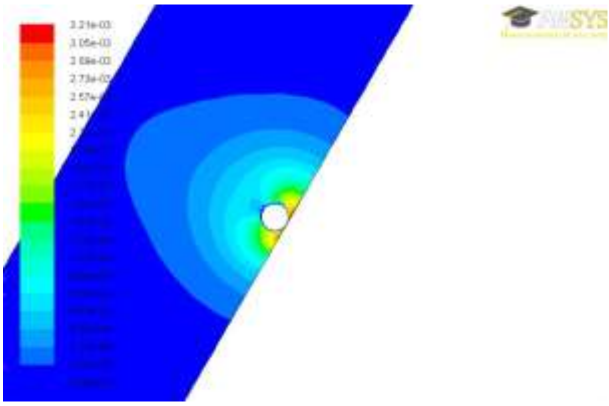

Figure 55 velocity contour for media glycerine θ=60°, t= 0.3 sec & ω=10 rad/sec

Table 18 Values of velocity for media glycerine , θ= 60° and ω= 10 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Glycerine	60°	.15sec	10 rad/sec	.17947 m/sec
Glycerine	60°	.2 sec	10 rad/sec	.13279 m/sec
Glycerine	60°	.3 sec	10 rad/sec	.089 m/sec

The velocity of a sphere having a constant angular velocity of 10 rad/sec rolling down an inclined plane of inclination 60° in a glycerine media decreases until it reaches a terminal velocity. The effect of increase in angular velocity can be seen clearly when compared with the previous case.

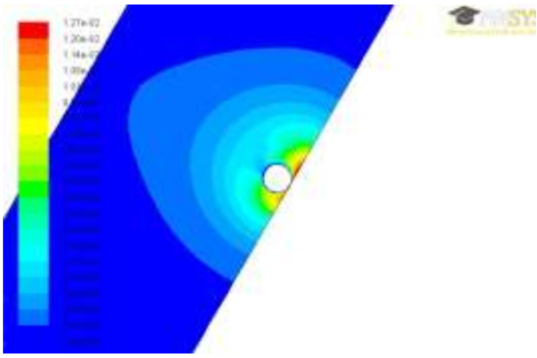

Figure 56 velocity contour for media glycerine θ=60°, t= 0.15 sec & ω=20 rad/sec

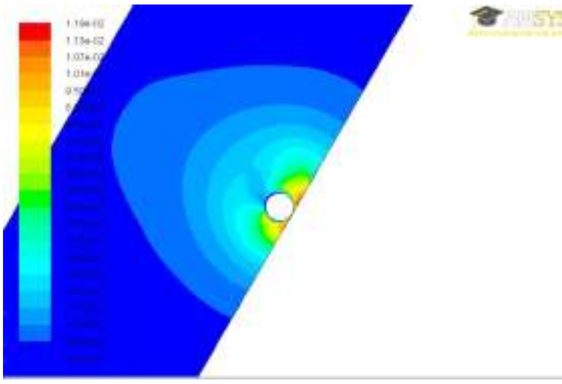

Figure 57 velocity contour for media glycerine θ=60°, t= 0.2 sec & ω=20 rad/sec

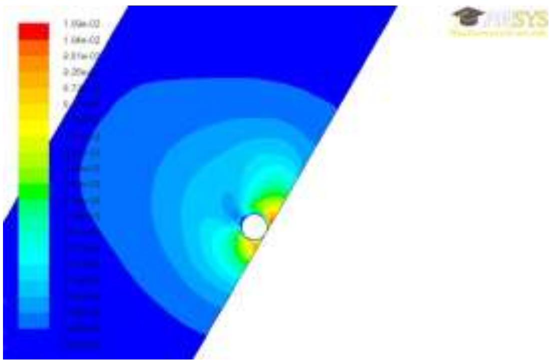

Figure 58 velocity contour for media glycerine θ=60°, t= 0.3 sec & ω=20 rad/sec

Table 19 Values of velocity for media glycerine , θ= 60° and ω= 20 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Glycerine	60°	.15sec	20 rad/sec	.1796 m/sec
Glycerine	60°	.2 sec	20 rad/sec	.1388 m/sec
Glycerine	60°	.3 sec	20 rad/sec	.0968 m/sec

The velocity of a sphere having a constant angular velocity of 20 rad/sec rolling down an inclined plane of inclination 60° in a glycerine media decreases until it reaches a terminal velocity. The velocity in this case is the highest among all the cases simulated for this media.

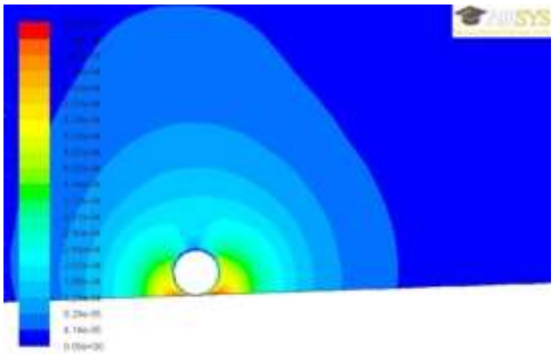

Figure 59 velocity contour for media olive oil θ=2°, t= 0.15 sec & ω=5 rad/sec

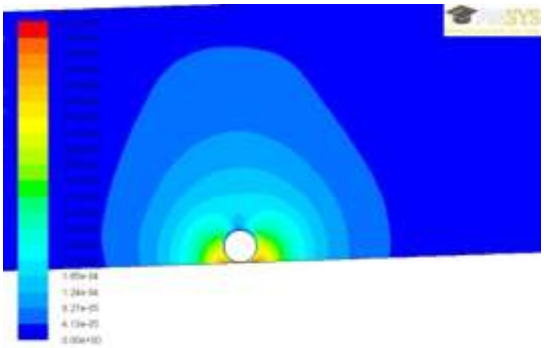

Figure 60 velocity contour for media olive oil θ=2°, t= 0.2 sec & ω=5 rad/sec

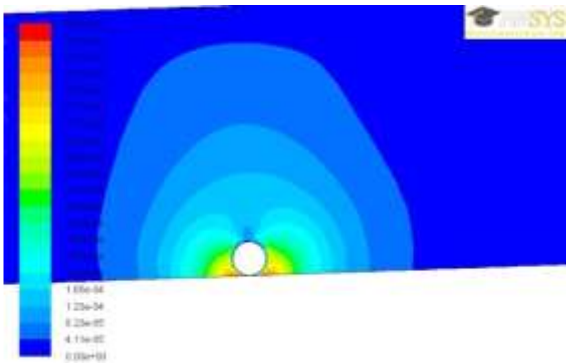

Figure 61 velocity contour for media olive oil θ=2°, t= 0.3 sec & ω=5 rad/sec

Table 20 Values of velocity for media olive oil, θ= 2° and ω= 5 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Olive oil	2°	.15sec	5 rad/sec	.01502 m/sec
Olive oil	2°	.2sec	5 rad/sec	.01109 m/sec
Olive oil	2°	.3sec	5 rad/sec	.00692 m/sec

The velocity of a sphere having a constant angular velocity of 5 rad/sec rolling down an inclined plane of inclination 2° in a olive oil media decreases until it reaches a terminal velocity. The value of velocity is lowest in this case for all simulated cases because it has the lowest angle nad angular velocity as well as the highest viscosity of .0840 kg/m.sec.

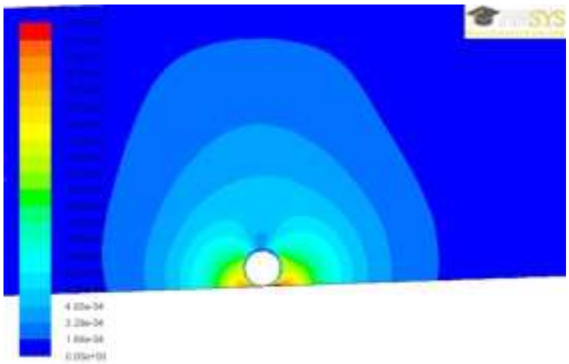

Figure 62 velocity contour for media olive oil   θ=2°, t= 0.15 sec & ω=10 rad/sec

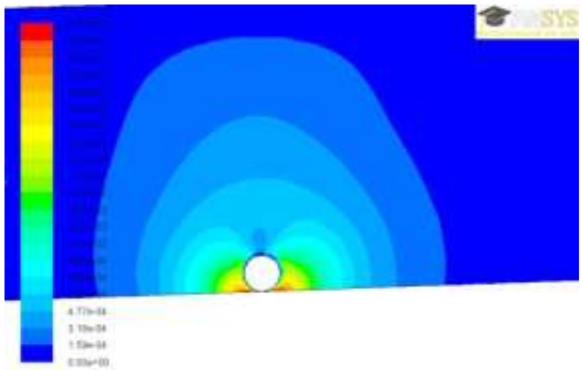

Figure 63 velocity contour for media olive oil   θ=2°, t= 0.2 sec & ω=10 rad/sec

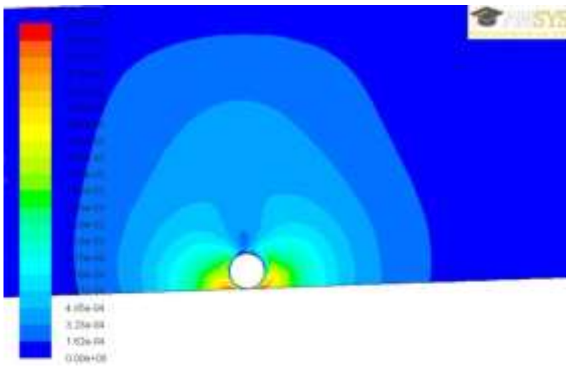

Figure 64 velocity contour for media olive oil   θ=2°, t= 0.3 sec & ω=10 rad/sec

Table 21 Values of velocity for media olive oil, θ= 2° and ω= 10 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Olive OIl	2°	.15sec	10 rad/sec	.01516 m/sec
Olive OIl	2°	.2 sec	10 rad/sec	.01119 m/sec
Olive OIl	2°	.3 sec	10 rad/sec	.00698 m/sec

The velocity of a sphere having a constant angular velocity of 10 rad/sec rolling down an inclined plane of inclination 2° in an olive oil media decreases until it reaches a terminal velocity. There is a slight increase in velocity for increase in angular velocity but this is minimal in nature.

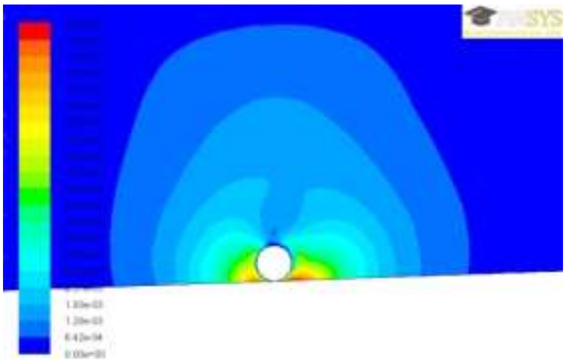

Figure 65 velocity contour for media olive oil θ=2°, t= 0.15 sec & ω=20 rad/sec

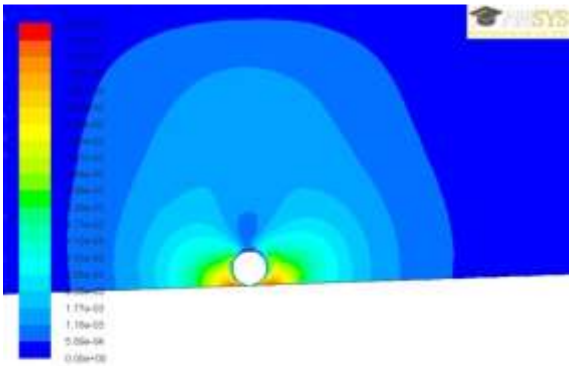

Figure 66 velocity contour for media olive oil θ=2°, t= 0.2 sec & ω=20 rad/sec

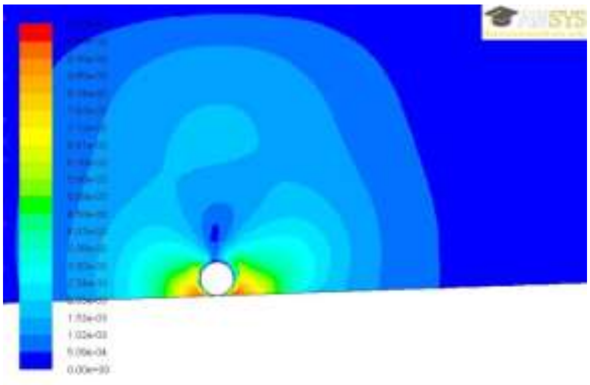

Figure 67 velocity contour for media olive oil θ=2°, t= 0.3 sec & ω=20 rad/sec

Table 22 Values of velocity for media olive oil, θ= 2° and ω= 20 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Olive OIl	2°	.15sec	20 rad/sec	.01522 m/sec
Olive OIl	2°	.2 sec	20 rad/sec	.01125 m/sec
Olive OIl	2°	.3 sec	20 rad/sec	.00719 m/sec

The velocity of a sphere having a constant angular velocity of 20 rad/sec rolling down an inclined plane of inclination 2° in an olive oil media decreases until it reaches a terminal velocity. The velocity in this case is highest among all other cases for the same media and angle because of the lowest highest angular velocity.

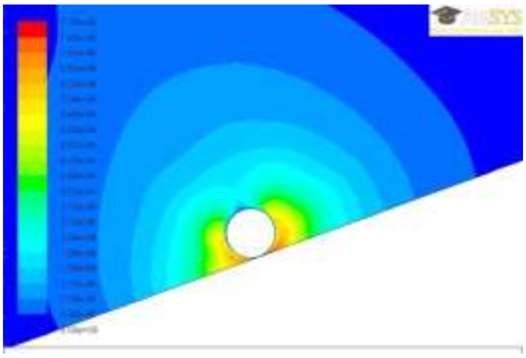

Figure 68 velocity contour for media olive oil θ=20°, t= 0.15 sec & ω=5 rad/sec

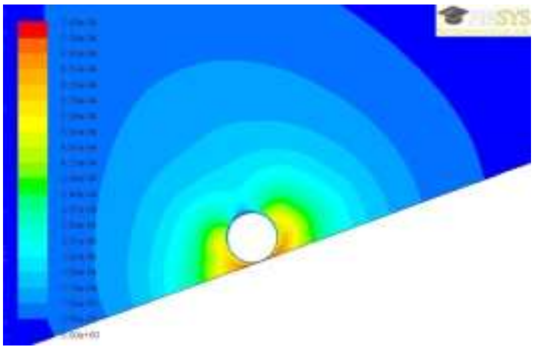

Figure 69 velocity contour for media olive oil θ=20°, t= 0.2 sec & ω=5 rad/sec

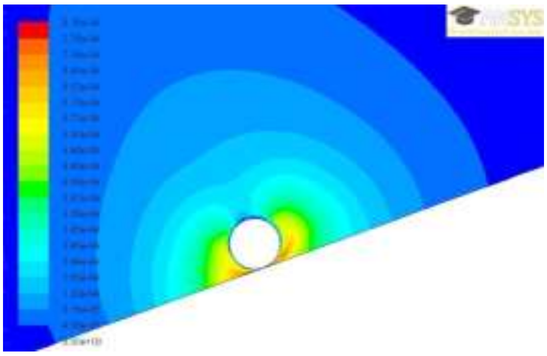

Figure 70 velocity contour for media olive oil θ=20°, t= 0.3 sec & ω=5 rad/sec

Table 23 Values of velocity for media olive oil, θ= 20° and ω= 5 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Olive OIl	20°	.15sec	5 rad/sec	.01651 m/sec
Olive OIl	20°	.2 sec	5 rad/sec	.01238 m/sec
Olive OIl	20°	.3 sec	5 rad/sec	.00822 m/sec

The velocity of a sphere having a constant angular velocity of 5 rad/sec rolling down an inclined plane of inclination 20° in an olive oil media decreases until it reaches a terminal velocity. The velocity in this case is same as the velocity for different media with the same angle and angular velocity thus telling the minimal effect of media.

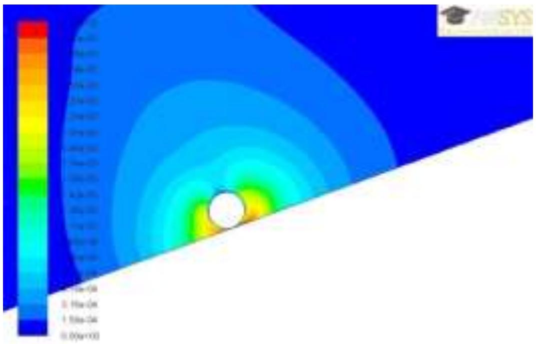

Figure 71 velocity contour for media olive oil θ=20°, t= 0.15 sec & ω=10 rad/sec

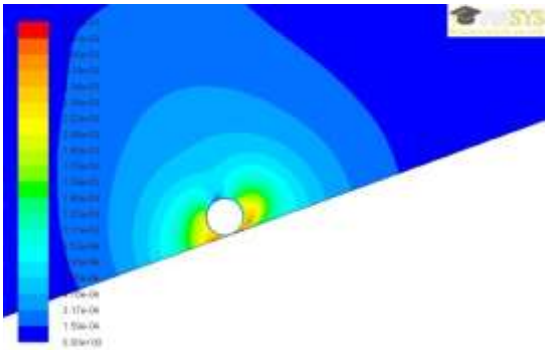

Figure 72 velocity contour for media olive oil θ=20°, t= 0.2 sec & ω=10 rad/sec

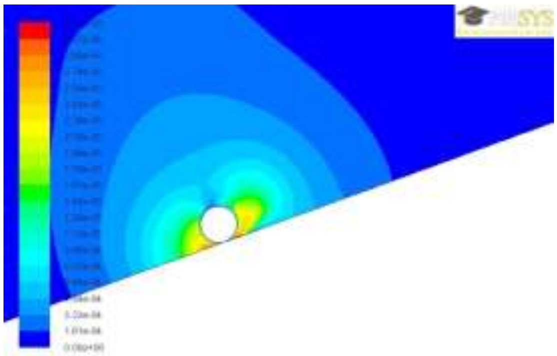

Figure 73 velocity contour for media olive oil θ=20°, t= 0.3 sec & ω=10 rad/sec

Table 24 Values of velocity for media olive oil, θ= 20° and ω= 10 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Olive OIl	20°	.15sec	10 rad/sec	.01656 m/sec
Olive OIl	20°	.2 sec	10 rad/sec	.01241 m/sec
Olive OIl	20°	.3 sec	10 rad/sec	.00829 m/sec

The velocity of a sphere having a constant angular velocity of 10 rad/sec rolling down an inclined plane of inclination 20° in an olive oil media decreases until it reaches a terminal velocity. The velocity is higher than the previous case because of higher angular velocity.

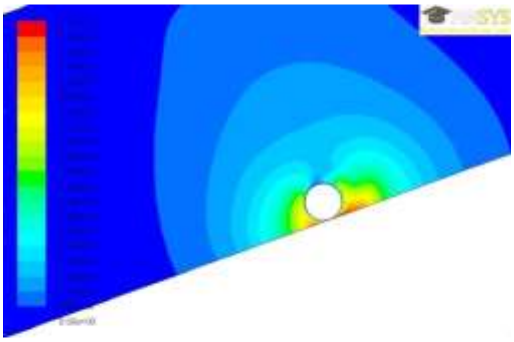

Figure 74 velocity contour for media olive oil θ=20°, t= 0.15 sec & ω=20 rad/sec

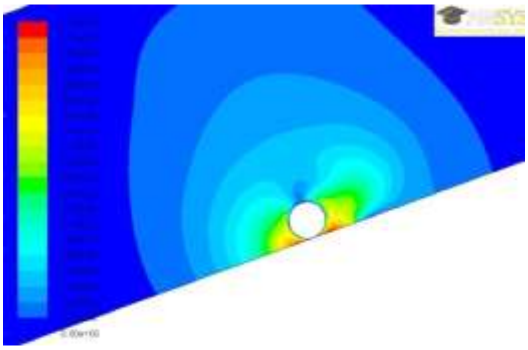

Figure 75 velocity contour for media olive oil θ=20°, t= 0.2 sec & ω=20 rad/sec

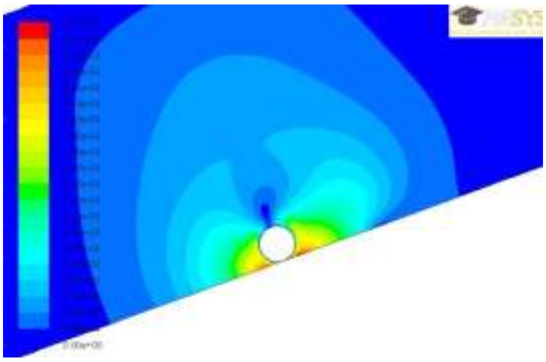

Figure 76 velocity contour for media olive oil θ=20°, t= 0.3 sec & ω=20 rad/sec

Table 25 Values of velocity for media olive oil, θ= 20° and ω= 20 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Olive OIl	20°	.15sec	20 rad/sec	.01658 m/sec
Olive OIl	20°	.2 sec	20 rad/sec	.01261 m/sec
Olive OIl	20°	.3 sec	20 rad/sec	.00831 m/sec

The velocity of a sphere having a constant angular velocity of 20 rad/sec rolling down an inclined plane of inclination 20° in an olive oil media decreases until it reaches a terminal velocity. The velocity increases for the same angle owing to the higher angular velocity.

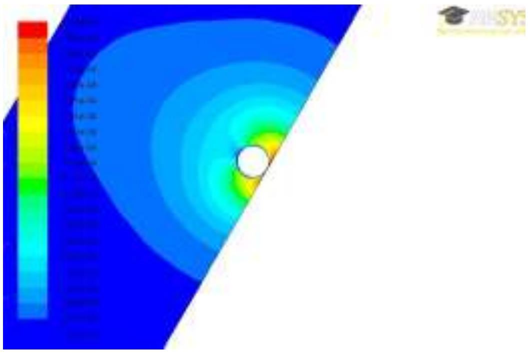

Figure 77 velocity contour for media olive oil θ=60°, t= 0.15 sec & ω=5 rad/sec

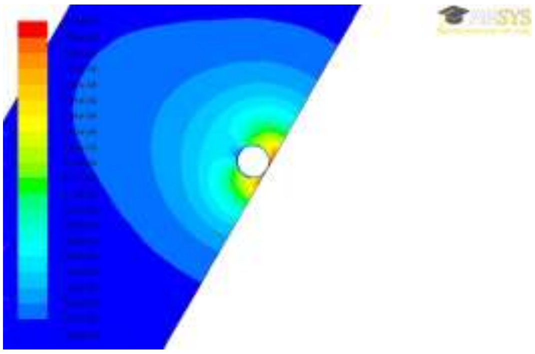

Figure 78 velocity contour for media olive oil θ=60°, t= 0.2 sec & ω=5 rad/sec

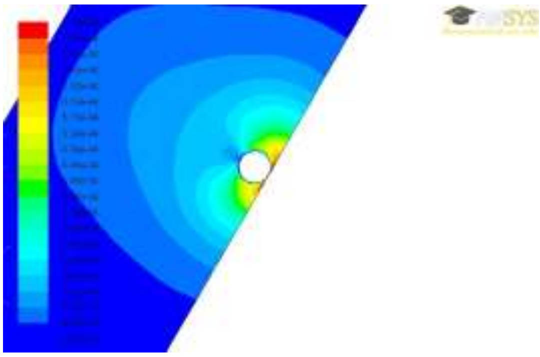

Figure 79 velocity contour for media olive oil θ=60°, t= 0.3 sec & ω=5 rad/sec

Table 26 Values of velocity for media olive oil, θ= 60° and ω= 5 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Olive OIl	60°	.15sec	5 rad/sec	.17524 m/sec
Olive OIl	60°	.2 sec	5 rad/sec	.13188 m/sec
Olive OIl	60°	.3 sec	5 rad/sec	.00880 m/sec

The velocity of a sphere having a constant angular velocity of 5 rad/sec rolling down an inclined plane of inclination 60° in an olive oil media decreases until it reaches a terminal velocity. This has the highest velocity for the media olive oil for angular velocity of 5 rad/sec as it has the highest angle of inclination.

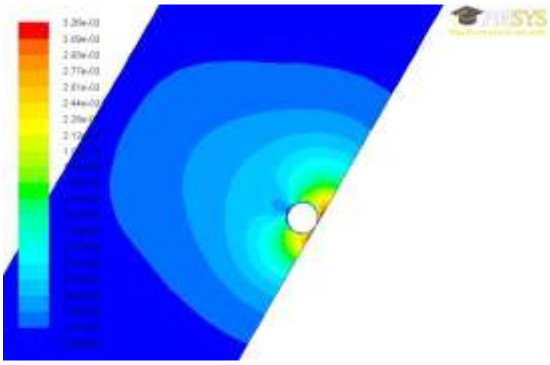

Figure 80 velocity contour for media olive oil θ=60°, t= 0.15 sec & ω=10 rad/sec

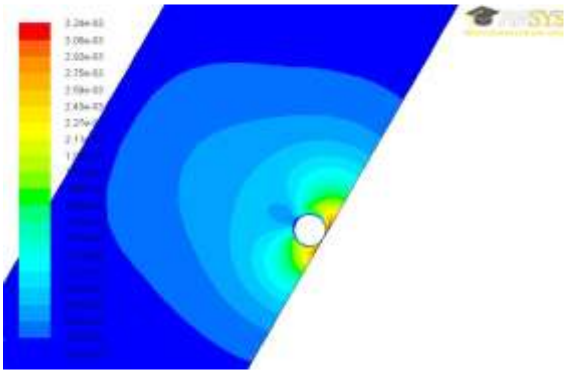

Figure 81 velocity contour for media olive oil θ=60°, t= 0.2 sec & ω=10 rad/sec

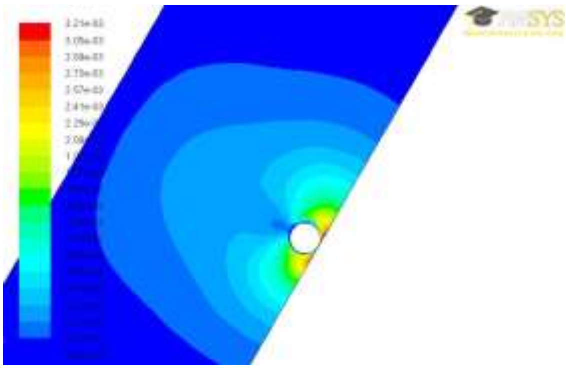

Figure 82 velocity contour for media olive oil θ=60°, t= 0.3 sec & ω=10 rad/sec

Table 27 Values of velocity for media olive oil, θ= 60° and ω= 10 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Olive OIl	60°	.15sec	10 rad/sec	.17947 m/sec
Olive OIl	60°	.2 sec	10 rad/sec	.13279 m/sec
Olive OIl	60°	.3 sec	10 rad/sec	.089 m/sec

The velocity of a sphere having a constant angular velocity of 10 rad/sec rolling down an inclined plane of inclination 60° in an olive oil media decreases until it reaches a terminal velocity.

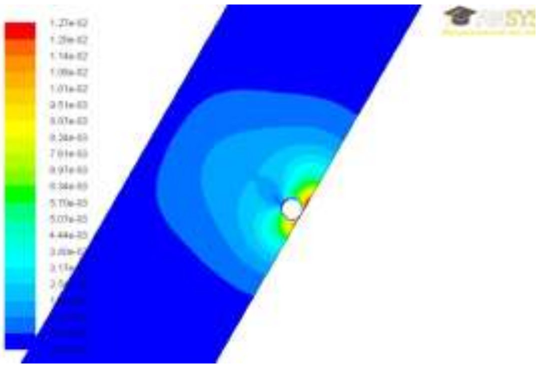

Figure 83 velocity contour for media olive oil θ=60°, t= 0.15 sec & ω=20 rad/sec

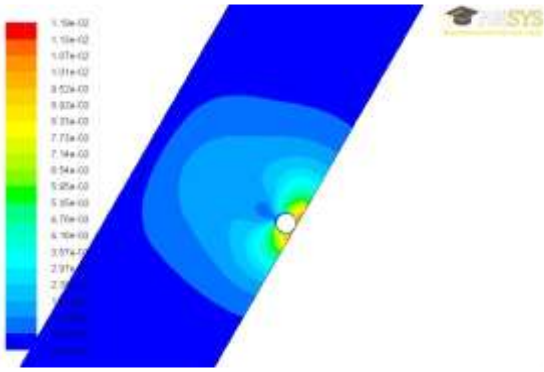

Figure 84 velocity contour for media olive oil θ=60°, t= 0.2 sec & ω=20 rad/sec

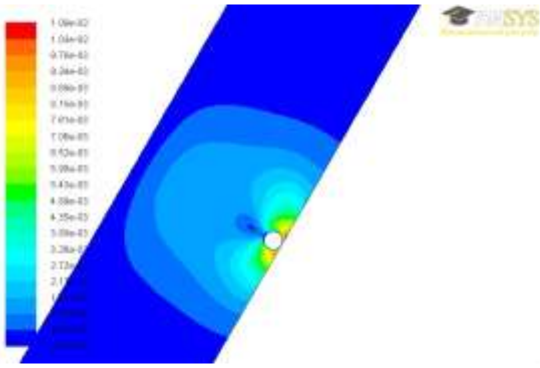

Figure 85 velocity contour for media olive oil θ=60°, t= 0.3 sec & ω=20 rad/sec

Table 28 Values of velocity for media olive oil, θ= 60° and ω= 20 rad/sec

Media	Angle	Time	Angular Velocity	Velocity
Olive OIl	60°	.15sec	20 rad/sec	.1790 m/sec
Olive OIl	60°	.2 sec	20 rad/sec	.1388 m/sec
Olive OIl	60°	.3 sec	20 rad/sec	.0968 m/sec

The velocity of a sphere having a constant angular velocity of 20 rad/sec rolling down an inclined plane of inclination 60° in an olive oil media decreases until it reaches a terminal velocity. The velocity is the highest for olive oil for all angles and angular velocities.

CONCLUSION:-

In the present study hydrodynamics of a moving object immersed in an incompressible Newtonian media is simulated using CFD models.

1. Nearer to the solid body surface fluid receives more momentum from the moving solid body and hence the magnitude of velocity was found more nearer to solid surface.
2. As the angle of inclination of the surface increases the velocity change is more pronounced with velocity changes as high as 11.5 times more than that of velocity at lower angles.
3. The change in velocity with varying angular velocity is minimal in comparison to change in velocity with varying angles.
4. The effect of change in the media in which the sphere is immersed can only be seen for angle of 2°.
5. The sphere at first has the maximum velocity owing to initial angular velocity but it gradually decreases with increase in time as it gradually reaches its terminal velocity.
6. The sphere has higher velocity for higher angular velocity for each media and angle in comparison to lower angular velocities for the same media and angle. This is because of higher initial angular velocity.

APPENDIX

User Defined Function used in this simulation.

```
#include "udf.h"

#include <math.h>

#define m 3.81e-5

#define rho 998.2

#define D 3e-3

#define rhos 2702

#define mu 0.001003

#define theta 2

static real v_prev = 0.0;

DEFINE_CG_MOTION(ball,dt,vel,omega,time,dtime)

{

Thread *t;

face_t f;

real  dv;

real a = m*(1.4+2*(rho/rhos));

real b = 321.906*3.14*D*mu/8;

real c = 0.861*3.14*D*D*rho/8;
```

```
real d = m*9.81*(1-(rho/rhos))*sin(theta);

/* reset velocities */

NV_S(vel, =, 0.0);

NV_S(omega, =, 0.0);

if (!Data_Valid_P())

return;

/* get the thread pointer for which this motion is defined */

t = DT_THREAD(dt);

/*compute change in velocity, i.e., dv = F * dt / mass

velocity update using explicit Euler formula */

dv = (d - v_prev*(b - c*v_prev))*dtime / a;

v_prev += dv;

omega[1] =5;

}
```

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