1. Title – Simulation of Flow through Pipe OpenFoam.

2. Objective –

- **To automate blockmeshdict file using MATLAB which contains pipe dimension and boundaries.**
- **To setup the initial and boundary conditions for simulation and run with a suitable solver.**
- **Create pressure and velocity contours and profiles using paraview and validate them.**

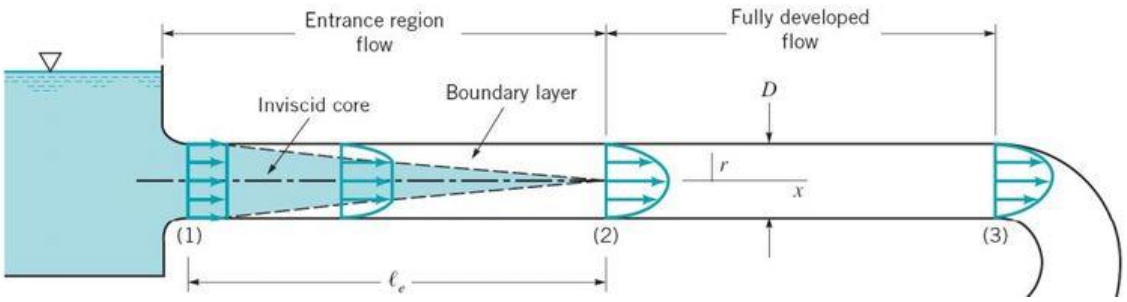
3. Introduction –

A common situation encountered by the CFD engineer is fluid flow through a tube or pipe. This occurs in heat exchangers, water management systems, oil transport in refineries etc. so it becomes important to know about the losses, pressure drop, velocity of fluid and these determines the efficiency of pipe to flow the fluid. In this study we are going simulate laminar-incompressible fluid flow through a pipe. We will generate velocity profile and identify the hydrodynamic length and fully developed flow.

4. Theory –

Flows completely bounded by solid surfaces are called internal flows, which include flows through pipes, nozzles, diffusers, valves, and fittings. The basic principles involved are independent of the cross-sectional shape, although the details of the flow may be dependent on it. The flow regime which is laminar or turbulent, of internal flows is primarily depends a function of Reynolds number. Laminar flow can be solved analytically, on the basis of that we assumed laminar flow for this study and we will draw some results analytically and then we will validate simulation results with analytical results.

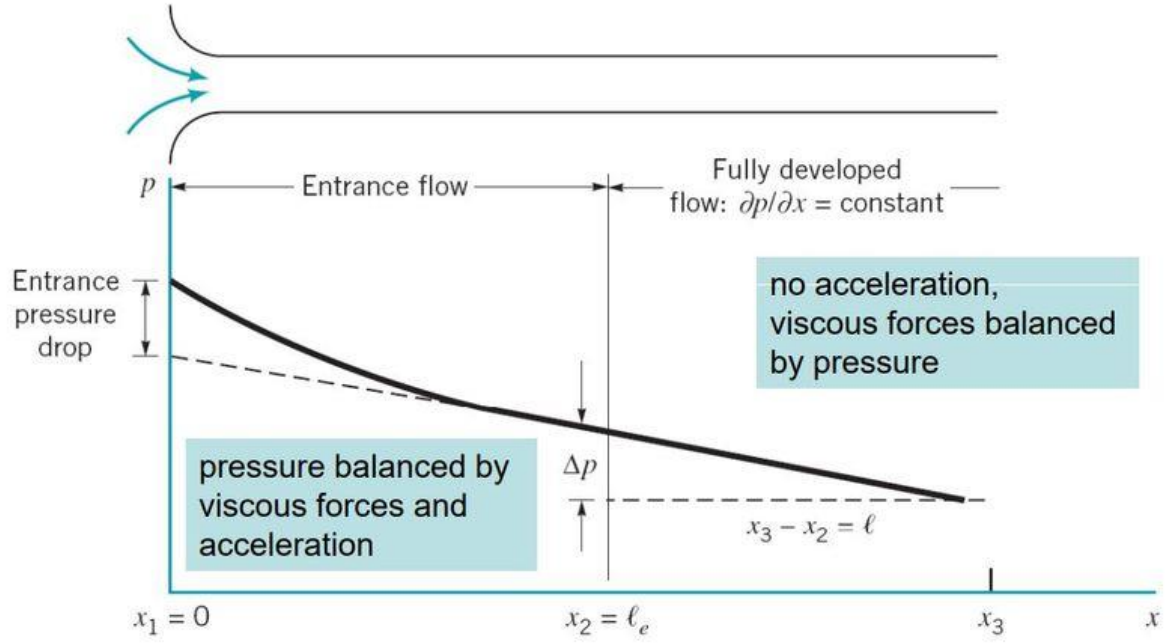
In fluid dynamics, the Hagen–Poiseuille equation, also known as the Hagen–Poiseuille law, is a physical law that gives the pressure drop in a fluid flowing through a long cylindrical pipe. The assumptions of the equation are that the fluid is incompressible and Newtonian; the flow is laminar through a pipe of constant circular cross-section that is substantially longer than its diameter; and there is no acceleration of fluid in the pipe.



Any fluid flowing in a pipe had to enter the pipe at some location. The region of flow near where the fluid enters the pipe is termed the entrance region or developing region. As the fluid moves through the pipe, viscous effects cause it to stick to the pipe wall. Initial velocity profile changes with distance along the pipe x, until the fluid reaches the end of the entrance length, beyond which the velocity profile does not vary with x.

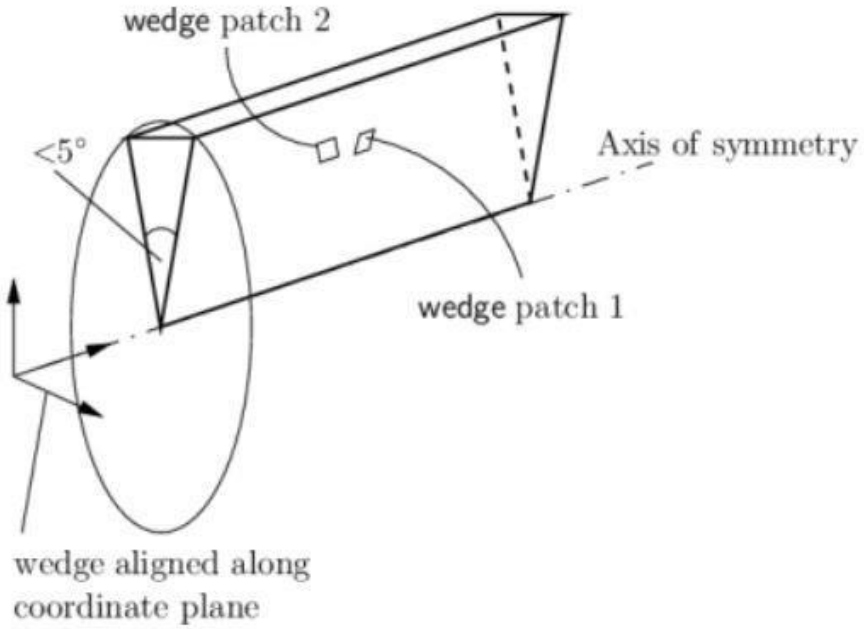
Pressure Distribution along the pipe –

In the entrance region of a pipe, the fluid accelerates or decelerates as it flows. there is a balance between pressure, viscous and inertia force and in fully developed pressure gradient is constant.



Understanding the geometry or blockMeshdict file –

The following image is the sector of pipe-



We can see there are six vertices, in vertices section of blockMeshDict file we need to define them. There are two arcs which will be defined by length of pipe and pipe diameter, in the edges section of the blockmesh File.

Vertices ... (0 0 0), (0 y z) ... here y and z are the distance of particular vertex from origin.

Edges...arc vertices number (0 d 0) and arc vertices number (L d 0)

For meshing define the type of mesh then vertices number then number of cell in all three direction followed by grading factor.

hex (0 3 5 2 0 3 4 1) (80 40 1) simpleGrading (0.01 0.05 0.1)

In boundary condition we need to define the inlet, outlet and wall patches so for inlet and outlet we can write

Inlet (0 1 2 0)

Similarly other boundaries can be defined.

Wedge Boundary conditions - For two dimensional axi-symmetric cases, like a cylinder, the geometry is specified as a wedge of small angle less than 5degree and 1 cell thick running along the plane of symmetry, as shown in Figure, above. The axi-symmetric wedge planes must be specified as separate patches of wedge type.

Symmetry Boundary condition - The symmetry boundary condition defines a mirror face/surface. It should only be used if the physical object or geometry and the expected flow field pattern of the developed solution are mirrored along that surface. By using this boundary condition, the domain can essentially be halved, reducing the time to achieve a solution. It can be applied when fluxes across symmetry are zero, the normal component are set to zero. It is applicable to both planer or non-planer surfaces on the domain boundaries.

Pipe and fluid parameters –

Type of fluid – water

Density of fluid = 997kg/m^3

Reynold number = 2100

Dynamic viscosity(mho) = 8.90e-4 Pa*s

Length of pipe(L) = 4m

Diameter of pipe(d) = 0.025m

Wedge angle = 10/25/45

Formulas and calculations –

1. Entry length = 0.06*R_e*D = 0.06*2100*0.025 =3.15m

2. Average velocity = R_e*mho/(rho*d) = 2100*8.90*10^-4/(997*0.025) = 0.0749m/s

3. Maximum velocity = 2*average velocity = 2*0.0749 = 0.1498 m/s

4. Pressure difference = 32*mho*L*v_avg/(d^2) = 32*8.90*10^-4*4*0.0749/(0.025)^-2 = 13.65Pa

5. Kinematic pressure drop = pressure difference/rho = 13.65/997 = 0.01369 (m/s)^2

5. Procedure –

We are simulating flow through pipe, for that we wrote a programme in MATLAB which replicates the blockMeshdict file. In MATLAB this file saved as text file and text file is directly copied into existing blockMeshDict file. The process has automated because it generates blockMeshdict file automatically after asking the length of pipe, diameter of pipe and wedge angle.

MATLAB code -

```
clear all

close all

clc


% pipe dimensions and fluid parameter

Re = 2100;

mho = 8.90*10^-4;

rho = 997;

nu = 8.917*10^-7;

% user inputs

% diameter of pipe

d = input('Enter pipe diameter - ');

% length of pipe

L =   input('Enter the length of pipe - ');

% wedge angle of pipe

w_a = input('Enter the wedge angle of pipe - ');

% boundary condition type

b = input('Tell the boundary condition, type 1 for wedge 2 for symmetry - ');

if b==1

   b = 'wedge';

else

   b = 'symmetry';

end

% entry length

L_e = 0.06*Re*d;
```

```
% average velocity
v_avg = Re*nu/d;
% pressure drop
P_drop = 32*mho*v_avg*L/(d^2);

% these parameter will be used to calculate vertices along y and z axis
y = (d/2)*cosd(w_a/2);
z = (d/2)*sind(w_a/2);

% opening text file
b_m = fopen('blockMeshDict.txt','w');

% writing first few lines
l = 'FoamFile';
l1 = '{';
l2 = 'version    2.0;';
l3 = 'format     ascii;';
l4 = 'class      dictionary;';
l5 = 'object     blockMeshDict;';
l6 = '}';
l7 = 'convertToMeters 1;';
fprintf(b_m,'%s\n%s\n%s\n%s\n%s\n%s\n%s\n',l,l1,l2,l3,l4,l5,l6,l7);


% printing vertices
fprintf(b_m,'\nvertices\n');
fprintf(b_m,'(\n');
fprintf(b_m,'(0 0 0)\n');
fprintf(b_m,'(0 %s %s)\n',y,z);
fprintf(b_m,'(0 %s -%s)\n',y,z);
fprintf(b_m,'(%f 0 0)\n',L);
```

```
fprintf(b_m,'(%f %s %s)\n',L,y,z);
fprintf(b_m,'(%f %s -%s)\n);\n\n',L,y,z);
% meshing data
fprintf(b_m,'blocks\n');
fprintf(b_m,'(\n hex (0 3 5 2 0 3 4 1) (80 40 1) simpleGrading (0.01 0.05 0.1)\n);\n\n');
% edges
fprintf(b_m,'edges\n(\n arc 1 2 (0 %f 0)\n',d/2);
fprintf(b_m,' arc 4 5 (%f %f 0)\n);\n\n',L,d/2);
% defining boundaries
fprintf(b_m,'boundary\n(\n');
fprintf(b_m,'axis\n{\n');
fprintf(b_m,' type  empty;\n faces\n(',d/2);
fprintf(b_m,'(0 3 3 0));\n}\n',L,d/2);

fprintf(b_m,'wall\n{\n');
fprintf(b_m,' type  wall;\n faces\n(',d/2);
fprintf(b_m,'(1 4 5 2));\n}\n',L,d/2);

fprintf(b_m,'inlet\n{\n');
fprintf(b_m,' type  patch;\n faces\n(',d/2);
fprintf(b_m,'(0 1 2 0));\n}\n',L,d/2);

fprintf(b_m,'outlet\n{\n');
fprintf(b_m,' type  patch;\n faces\n(',d/2);
fprintf(b_m,'(3 5 4 3));\n}\n',L,d/2);

fprintf(b_m,'front\n{\n');
fprintf(b_m,' type  %s',b);
fprintf(b_m,';\n faces\n(',d/2);
fprintf(b_m,'(0 3 4 1));\n}\n',L,d/2);
```

fprintf(b_m,'back\n{\n');

fprintf(b_m,' type %s',b);

fprintf(b_m,';\n faces\n(',d/2);

fprintf(b_m,'(0 2 5 3));\n}\n);\n\n',L,d/2);

fprintf(b_m,'mergePatchPairs\n();');

% closing text file

fclose(b_m);

After text file generated from MATLAB, we copied data to blockMeshdict file and ran blockMeshdict.exe and paraFoam command in terminal to preview the model of pipe.

blockMeshDict file -

FoamFile

{

version 2.0;

format ascii;

class dictionary;

object blockMeshDict;

}

convertToMeters 1;

vertices

(

(0 0 0)

(0 1.154849e-02 4.783543e-03)

(0 1.154849e-02 -4.783543e-03)

(4.000000 0 0)

(4.000000 1.154849e-02 4.783543e-03)

(4.000000 1.154849e-02 -4.783543e-03)

);

blocks

```
(
 hex (0 3 5 2 0 3 4 1) (80 40 1) simpleGrading (0.01 0.05 0.1)
);

edges
(
 arc 1 2 (0 0.012500 0)
 arc 4 5 (4.000000 0.012500 0)
);

boundary
(
axis
{
 type empty;
 faces
((0 3 3 0));
}
wall
{
 type wall;
 faces
((1 4 5 2));
}
inlet
{
 type patch;
 faces
((0 1 2 0));
}
outlet
```

{

type patch;

faces

((3 5 4 3));

}

front

{

type symmetry;

faces

((0 3 4 1));

}

back

{

type symmetry;

faces

((0 2 5 3));

}

);

mergePatchPairs

();

Initial and Boundary conditions -

Pressure -

/*--------------------------------*- C++ -*----------------------------------*\

| ========= | |

| \\ / F ield | OpenFOAM: The Open Source CFD Toolbox |

| \\ / O peration | Version: v2012 |

| \\ / A nd | Website: www.openfoam.com |

| \\/ M anipulation | |

---/

FoamFile

```
{
    version    2.0;
    format     ascii;
    class      volScalarField;
    object     p;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

dimensions     [0 2 -2 0 0 0 0];

internalField   uniform 0;

boundaryField
{
    axis
    {
        type         empty;
    }

    wall
    {
        type         zeroGradient;
    }

   inlet
    {
        type         zeroGradient;
    }

    outlet
    {
```

```
    type        fixedValue;
    value       uniform 0.017116;
  }
  front
  {
    type        symmetry;
  }
  back
  {
    type        symmetry;
  }
}********************************************************************* //
Velocity -
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  v2012                                 |
|   \\  /    A nd           | Website:  www.openfoam.com                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
  version    2.0;
  format     ascii;
  class      volVectorField;
  object     U;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

dimensions     [0 1 -1 0 0 0 0];
```

```
internalField   uniform (0.0749 0 0);


boundaryField
{
    axis
    {
        type        empty;
    }

    wall
    {
        type        noSlip;
    }

    inlet
    {
        type        fixedValue;
        value       uniform (0.0749 0 0);
    }

    outlet
    {
        type        zeroGradient;
    }
    front
    {
        type        symmetry;
    }
    back
    {
        type        symmetry;
```

```
    }
}

// ************************************************************************* //
Physical Properties -
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  v2012                                 |
|   \\  /    A nd           | Website:  www.openfoam.com                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "constant";
    object      transportProperties;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

nu          [0 2 -1 0 0 0 0] 8.917e-7;


// ************************************************************************* //
control -
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  v2012                                 |
```

```
|  \\ /   A nd        | Website:  www.openfoam.com                |
|   \\/    M anipulation |                                       |
\*---------------------------------------------------------------------------*/
FoamFile
{
  version    2.0;
  format     ascii;
  class      dictionary;
  location   "system";
  object     controlDict;
}
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

application    pimpleFoam;

startFrom      startTime;

startTime      0;

stopAt         endTime;

endTime        20;

deltaT         0.01;

writeControl   timeStep;

writeInterval  20;

purgeWrite     0;
```

writeFormat ascii;

writePrecision 6;

writeCompression off;

timeFormat general;

timePrecision 6;

runTimeModifiable true;

// *** //

Solution and scheme -

fvSolution -

```
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  v2012                                 |
|   \\  /    A nd           | Website:  www.openfoam.com                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version     2.0;
    format      ascii;
    class       dictionary;
    location    "system";
    object      fvSolution;
}
```

```
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * //

solvers
{
    p
    {
        solver          PCG;
        preconditioner  DIC;
        tolerance       1e-06;
        relTol          0.05;
    }

    pFinal
    {
        $p;
        relTol          0;
    }

    U
    {
        solver          smoothSolver;
        smoother        symGaussSeidel;
        tolerance       1e-05;
        relTol          0;
    }
}

PISO
{
    nCorrectors     2;
    nNonOrthogonalCorrectors 0;
```

```
    pRefCell      0;
    pRefValue     0;
}


// ************************************************************************* //
fvScheme -
/*--------------------------------*- C++ -*----------------------------------*\
| =========                 |                                                 |
| \\      /  F ield         | OpenFOAM: The Open Source CFD Toolbox           |
|  \\    /   O peration     | Version:  v2012                                 |
|   \\  /    A nd           | Website:  www.openfoam.com                      |
|    \\/     M anipulation  |                                                 |
\*---------------------------------------------------------------------------*/
FoamFile
{
    version    2.0;
    format     ascii;
    class      dictionary;
    location   "system";
    object     fvSchemes;
}
// ************************************************************************* //

ddtSchemes
{
    default       Euler;
}

gradSchemes
{
```

```
    default       Gauss linear;
    grad(p)       Gauss linear;
}

divSchemes
{
    default       none;
    div(phi,U)    Gauss linear;
}

laplacianSchemes
{
    default       Gauss linear orthogonal;
}

interpolationSchemes
{
    default       linear;
}

snGradSchemes
{
    default       orthogonal;
}


// ************************************************************************* //
```

After writing for control parameters, boundary conditions we ran the command icoFoam.exe to solve the case and after paraFoam command executed again to generate desire result.

MATLAB code to generate velocity profile -

```
clear all
```

```
close all
clc

% radius of the pipe
R = 0.0125;
% points along the radius
r = linspace(0,R,50);
% maximum velocity
v_max = 0.1444;

% velocity calculation along the radius
for i = 1:length(r)
v(i) = v_max*(1-(r(i)/R).^2);
end

% plotting
plot(r,v)
hold on
plot(-r,v)
xlabel('vertical distance(y axis)')
ylabel('Velocity')
```

MATLAB code to generate shear stress profile -

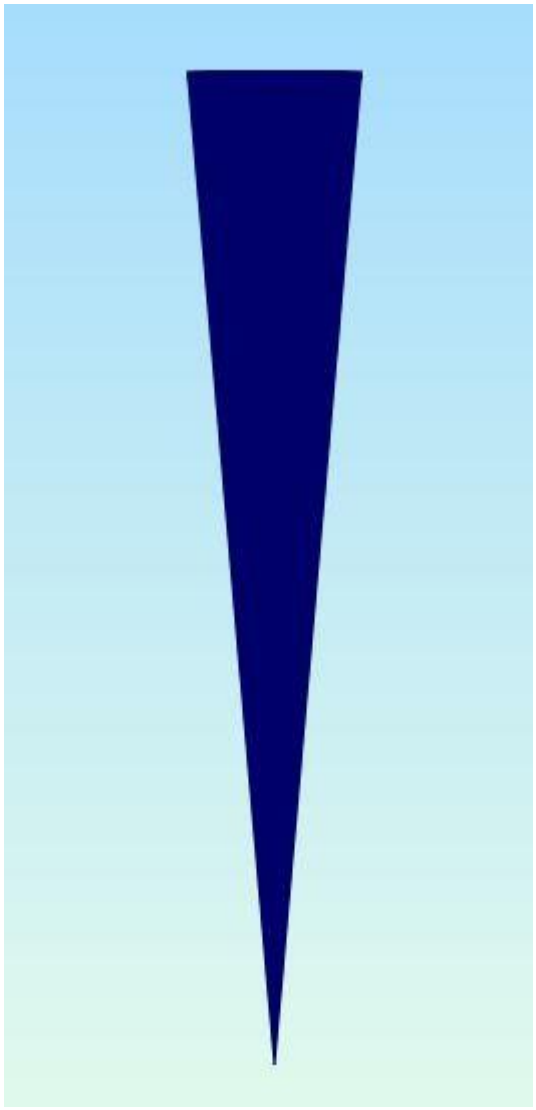
```
clear all
close all
clc

% dynamic viscosity
mho = 8.9*10^-4;
% maximum  velocity
v_max = 0.1498;
% pipe radius
```

```
R = 0.0125;
% points along the radius
r = linspace(0,R,100);
% pressure drop
dp = 0.01369;
% length of pipe
l = 4;

% shear stress calculation along the radius of pipe
for i = 1:length(r)
tau(i) = (dp/2*l)*(r(i)/R);
end

% plotting
plot(r,tau)
xlabel('y axis')
ylabel('Shear stress')
```

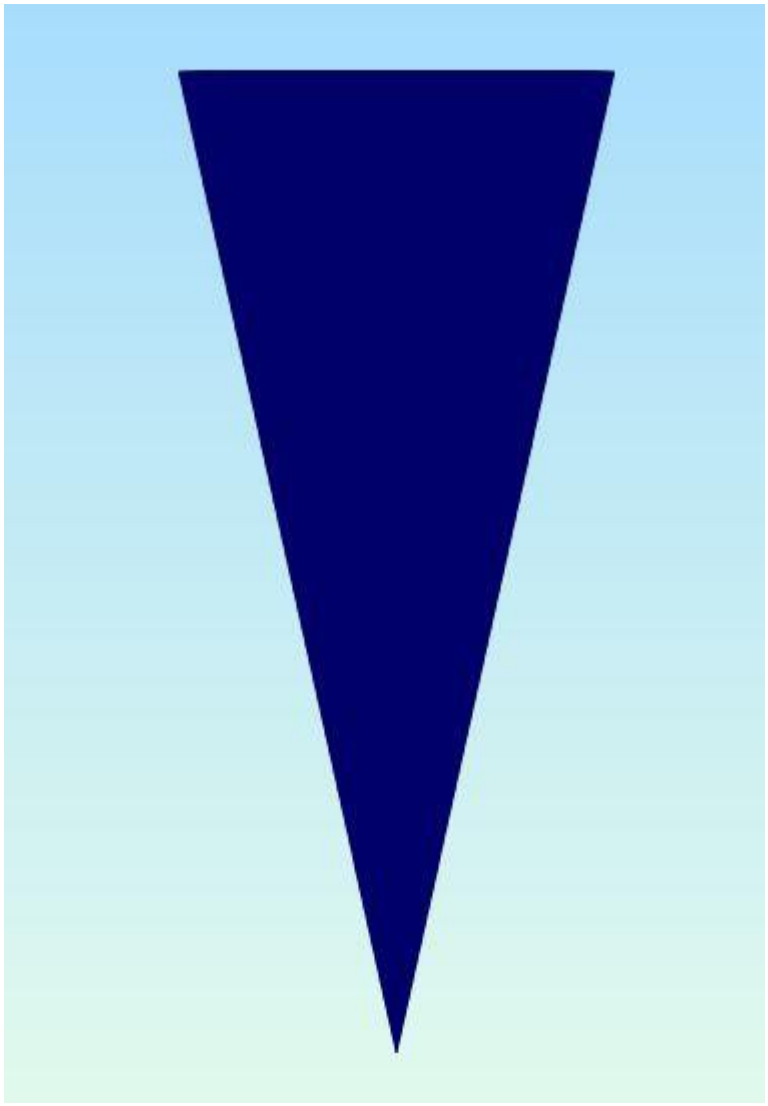
6. Results –

Geometry -

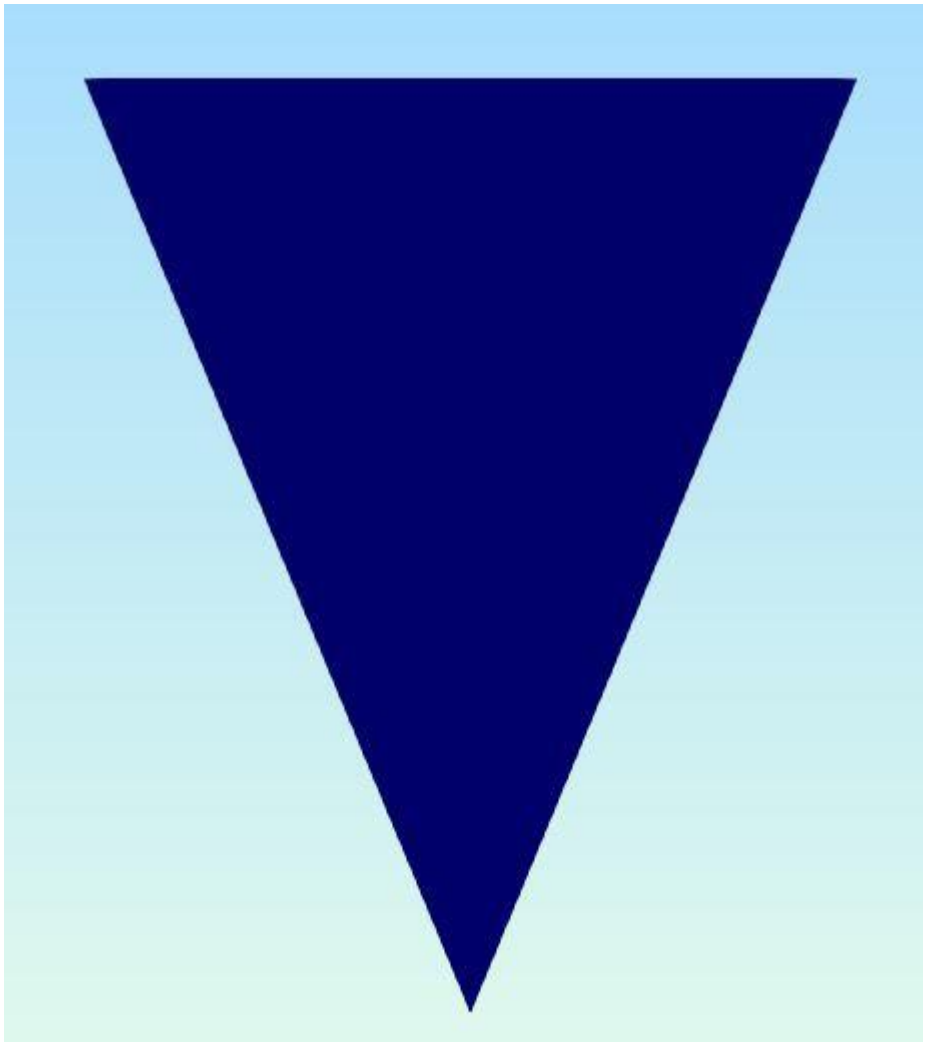
wedge angle - 10



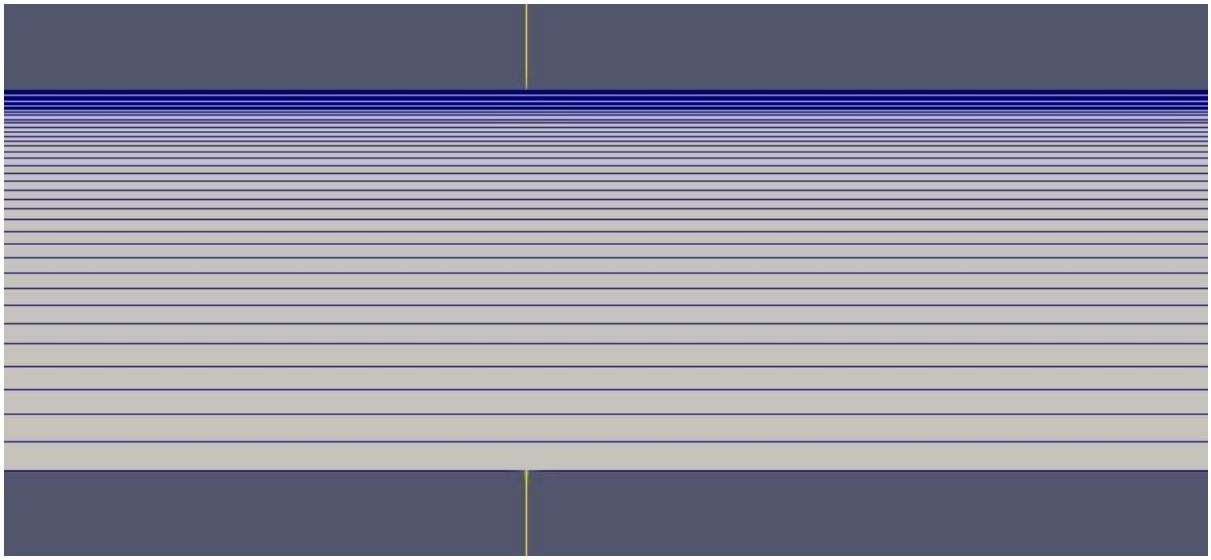
wedge angle - 25



wedge angle - 45



with mesh -



1. Hydrodynamic length – from analytical result we go hydrodynamic length 3.15m, means here, velocity profile will be fully developed. In simulation velocity graphs has created to identify the location of hydrodynamic length for both boundary condition types.

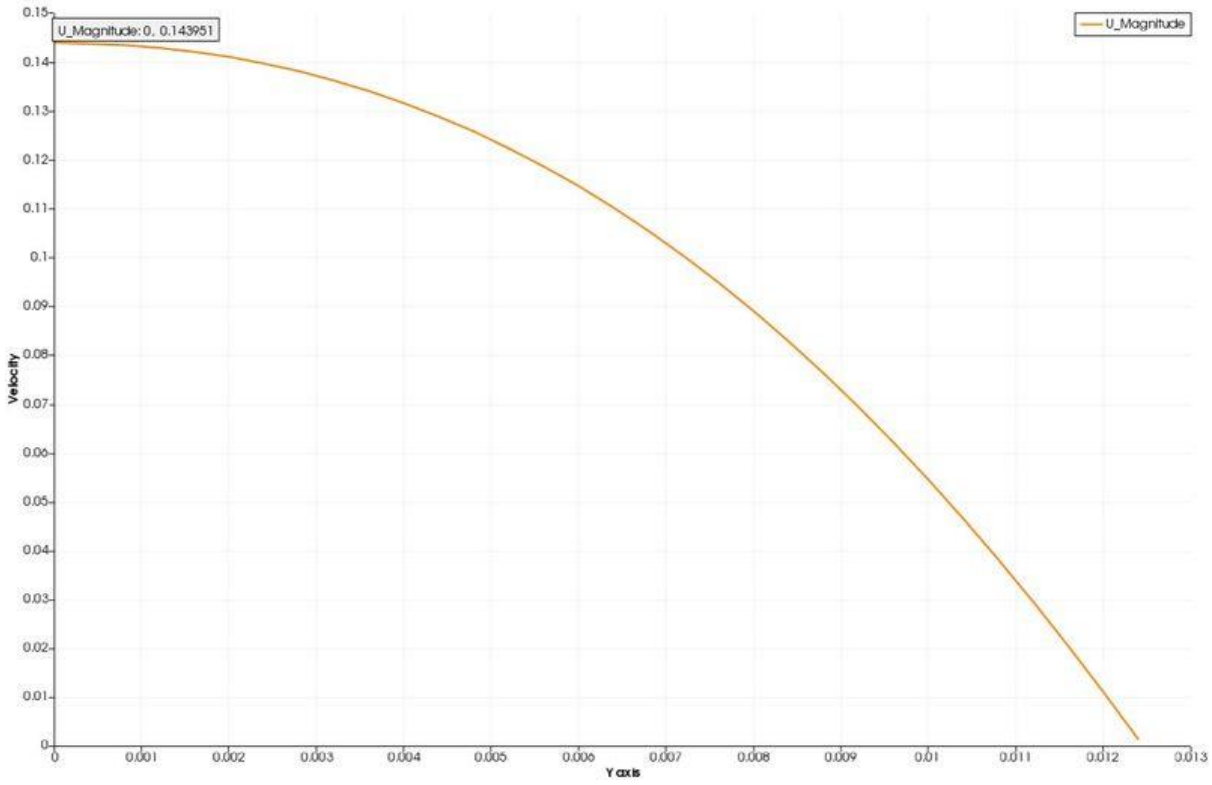
From the graphs it is clear that velocity is not varing after 3.15m, along the diameter of pipe or y axis, so it validates analytical result and We can say hydrodynamic length is independent of wedge and boundary condition type.

from Numerical method -

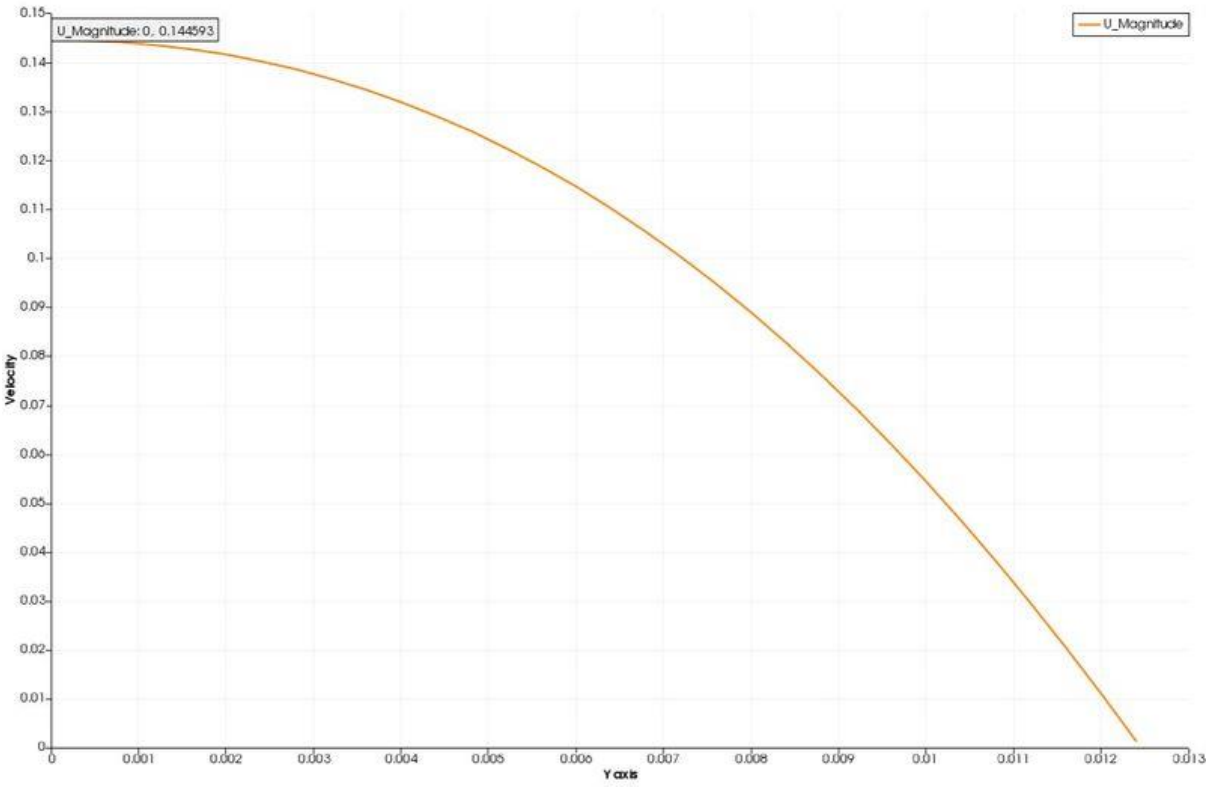
Boundary Condition type - wedge

wedge angle - 10

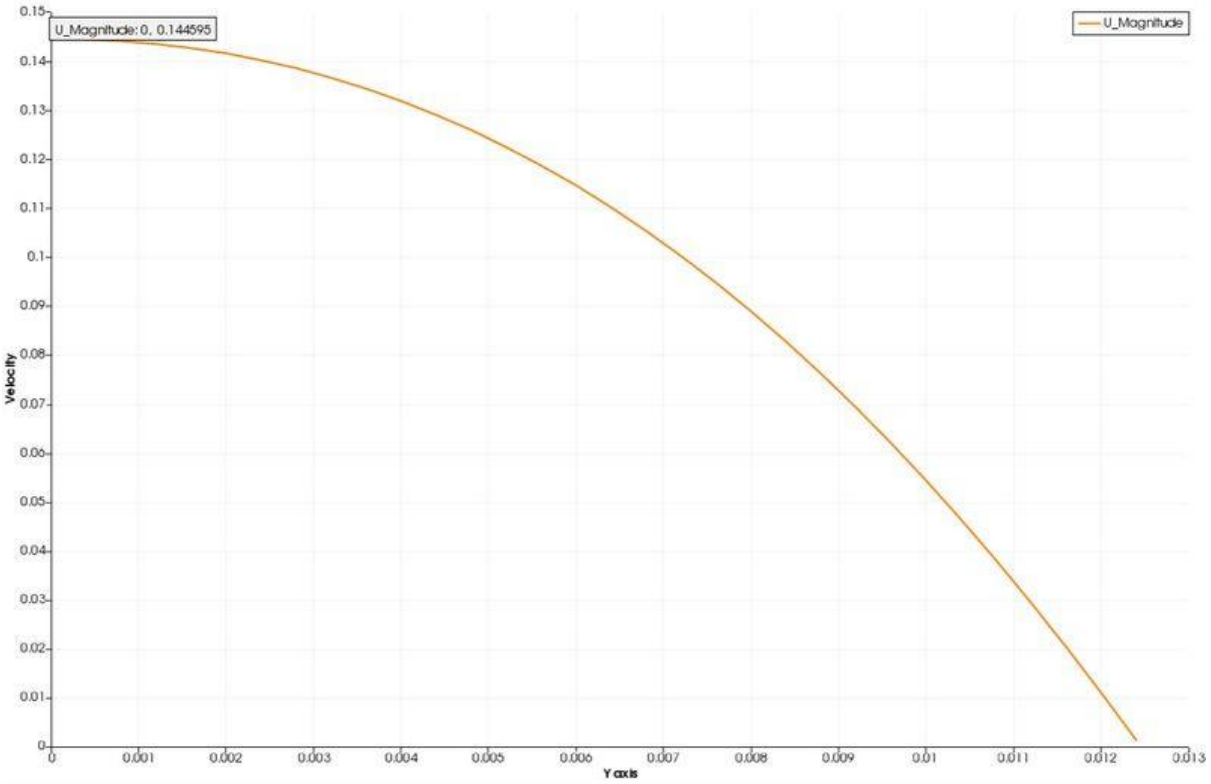
at 2m from inlet -



at 3.15m from inlet -

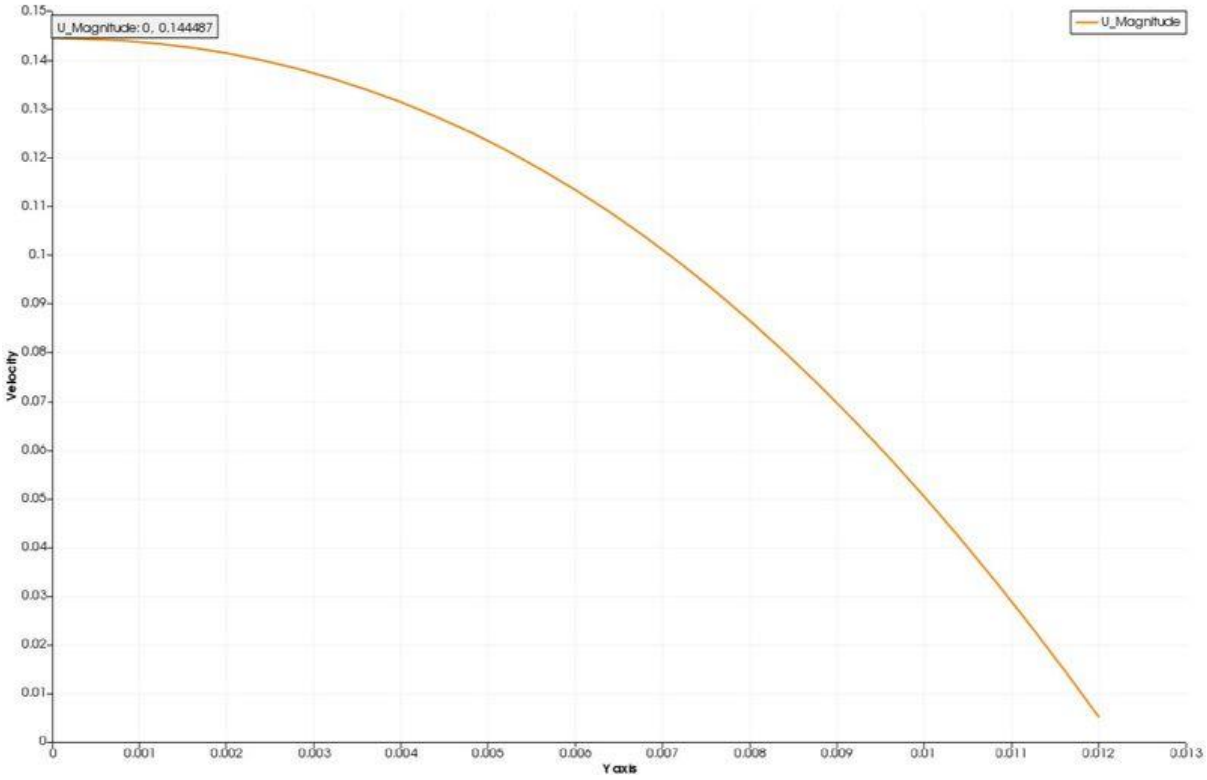


at 3.50m from inlet -

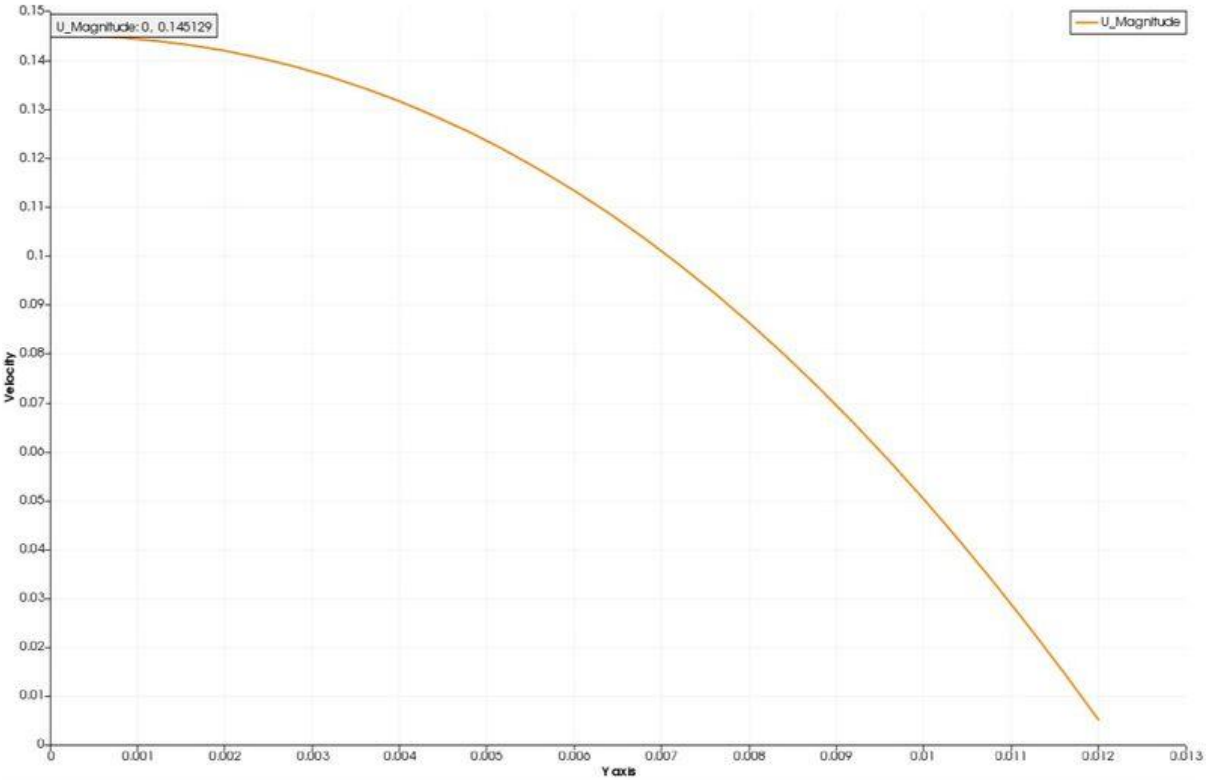


wedge angle - 25

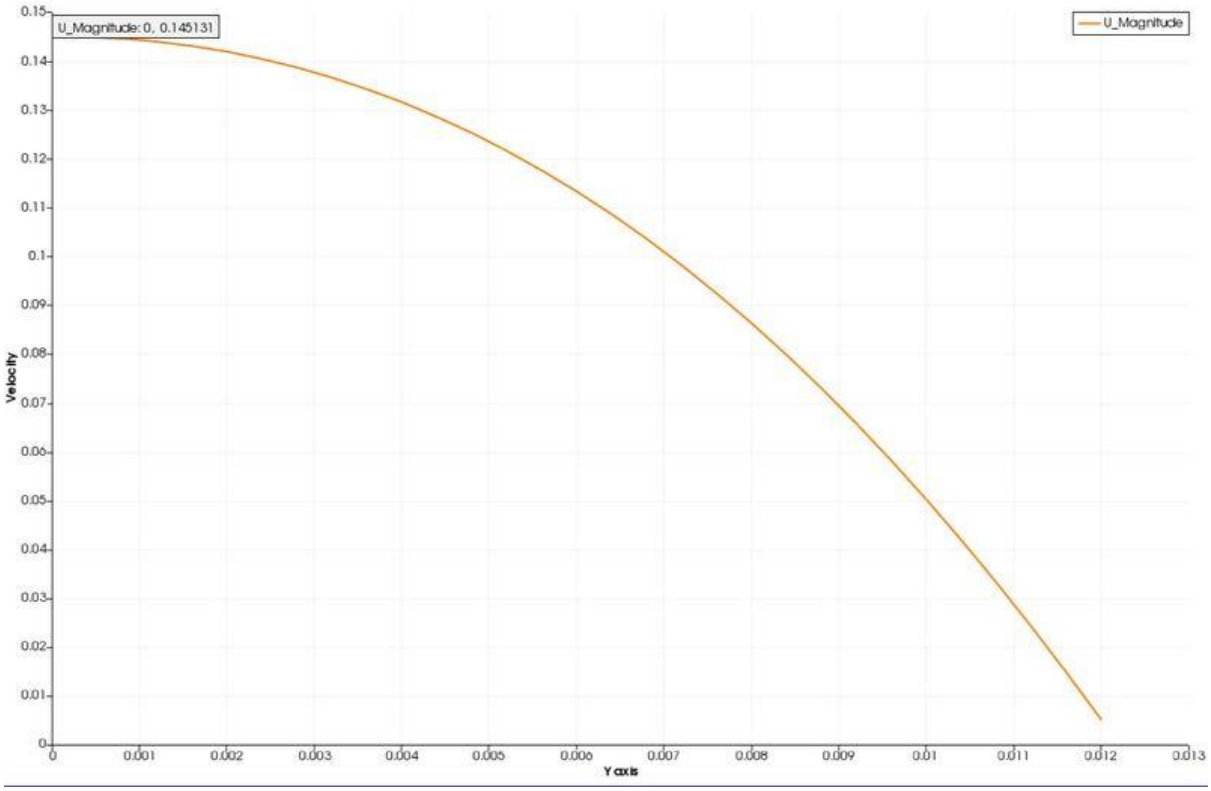
at 2m from inlet -



at 3.15m from inlet -

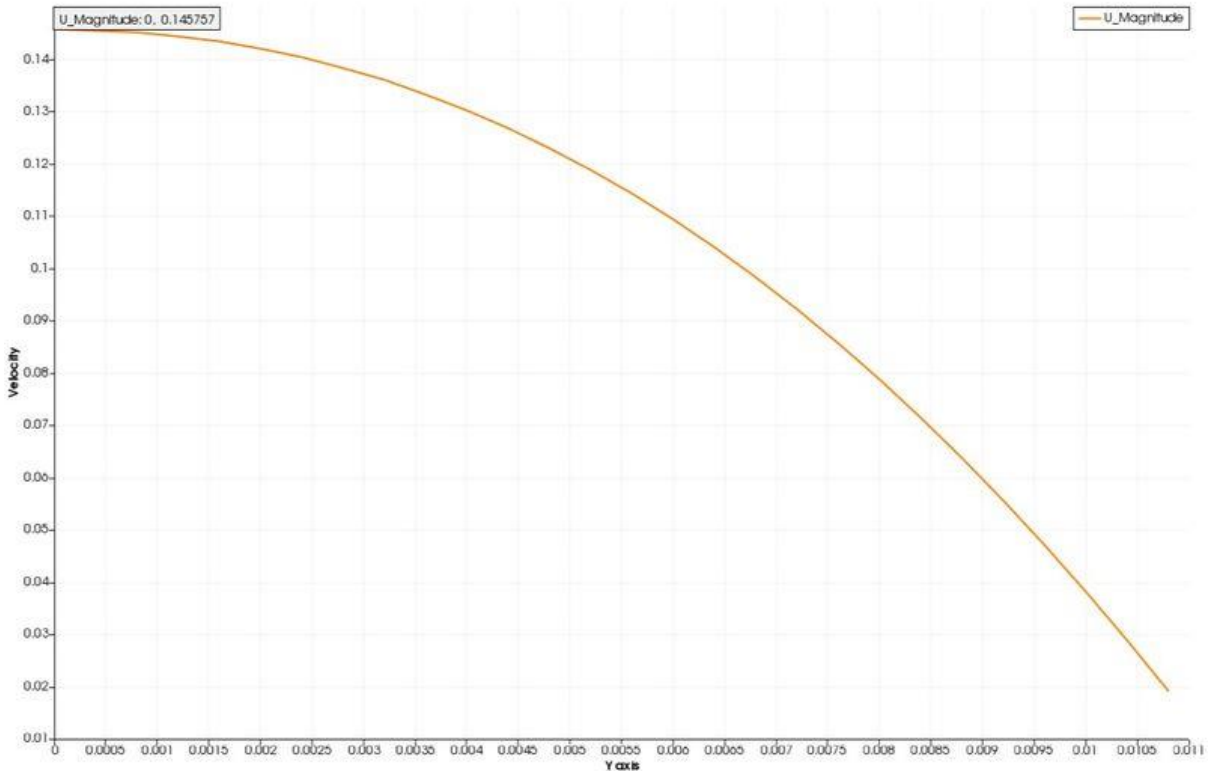


at 3.50m from inlet -

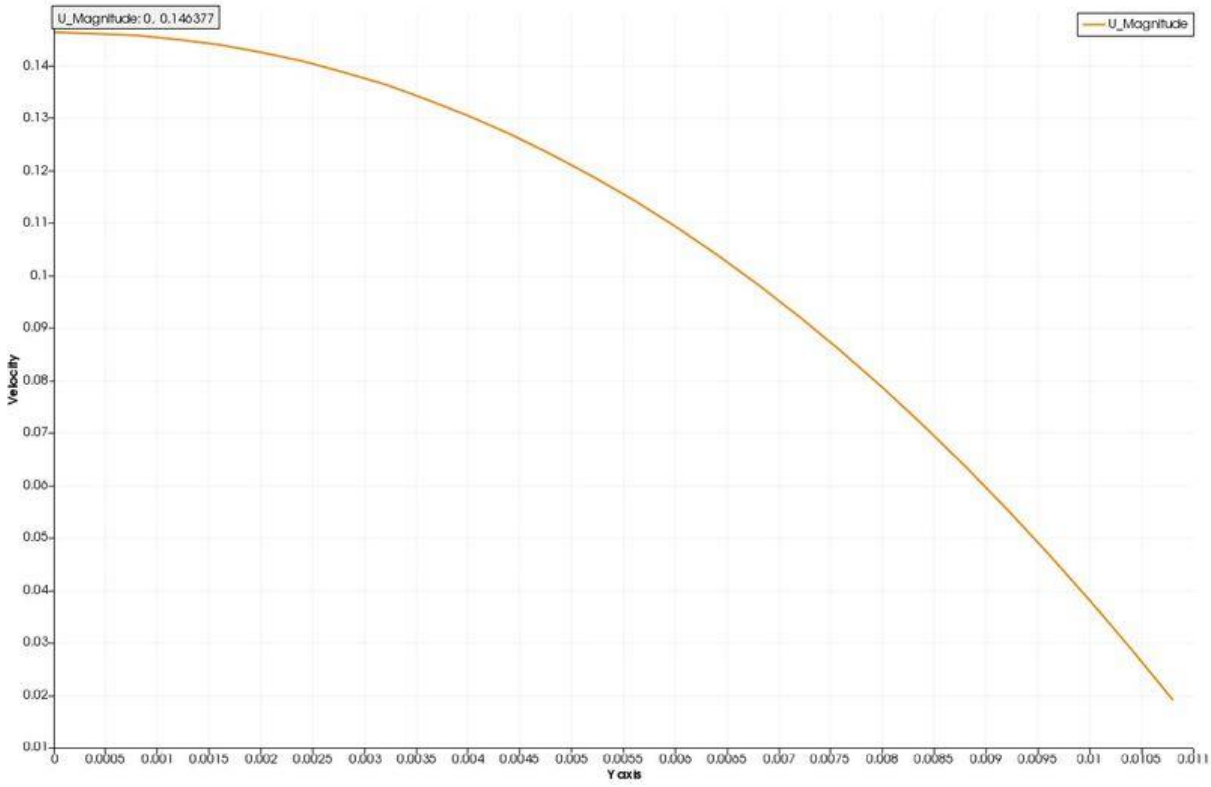


wedge angle - 45

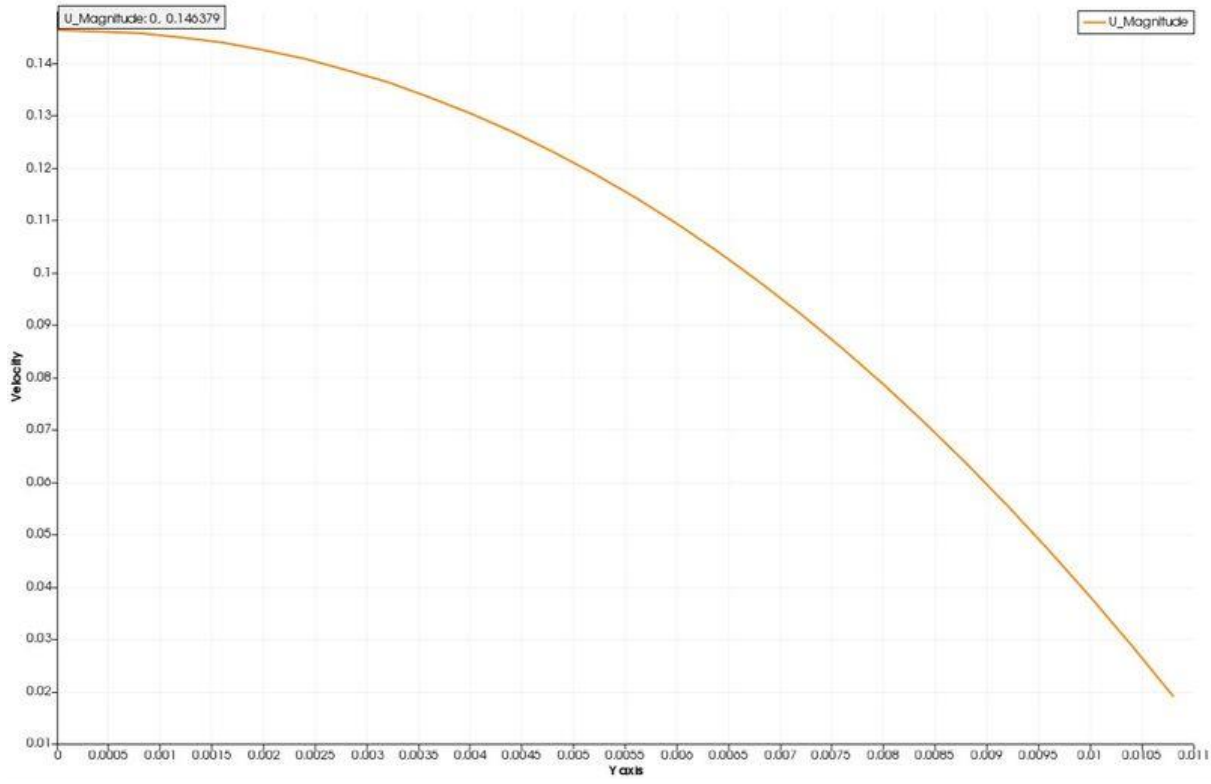
at 2m from inlet -



at 3.15m from inlet -



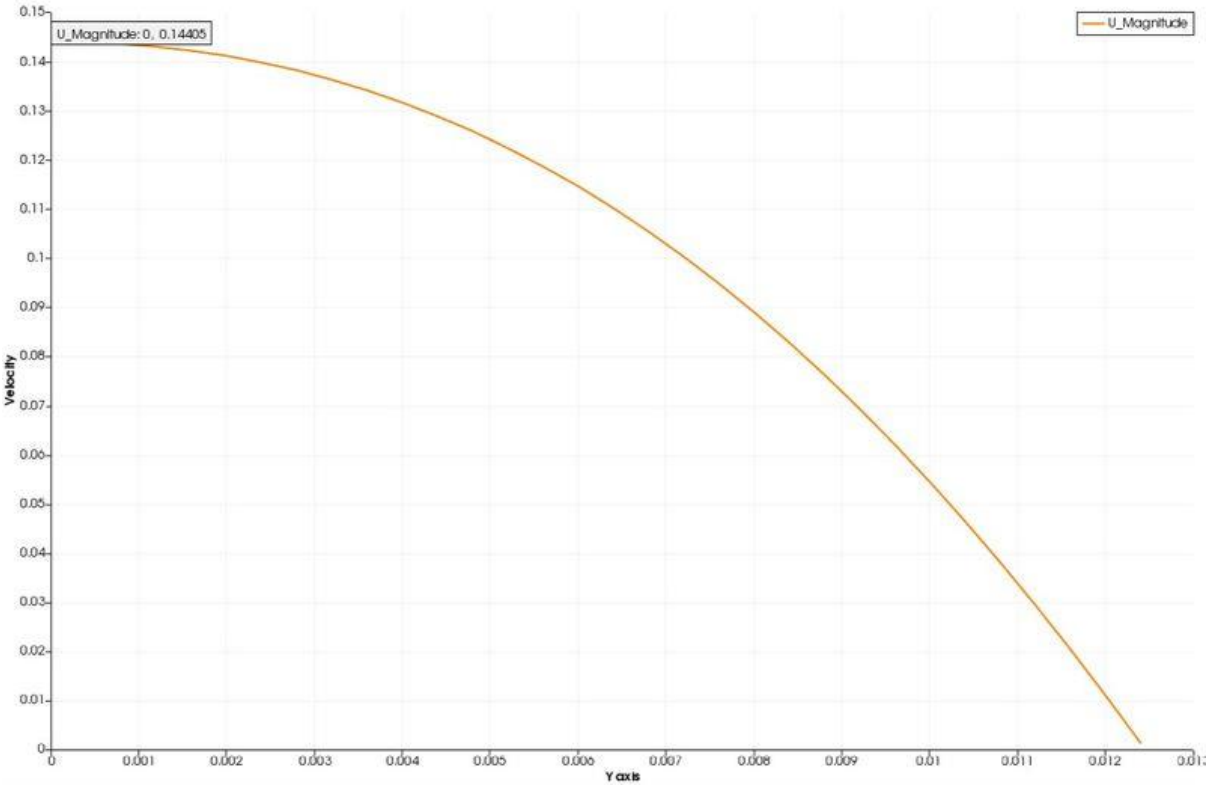
at 3.50m from inlet -



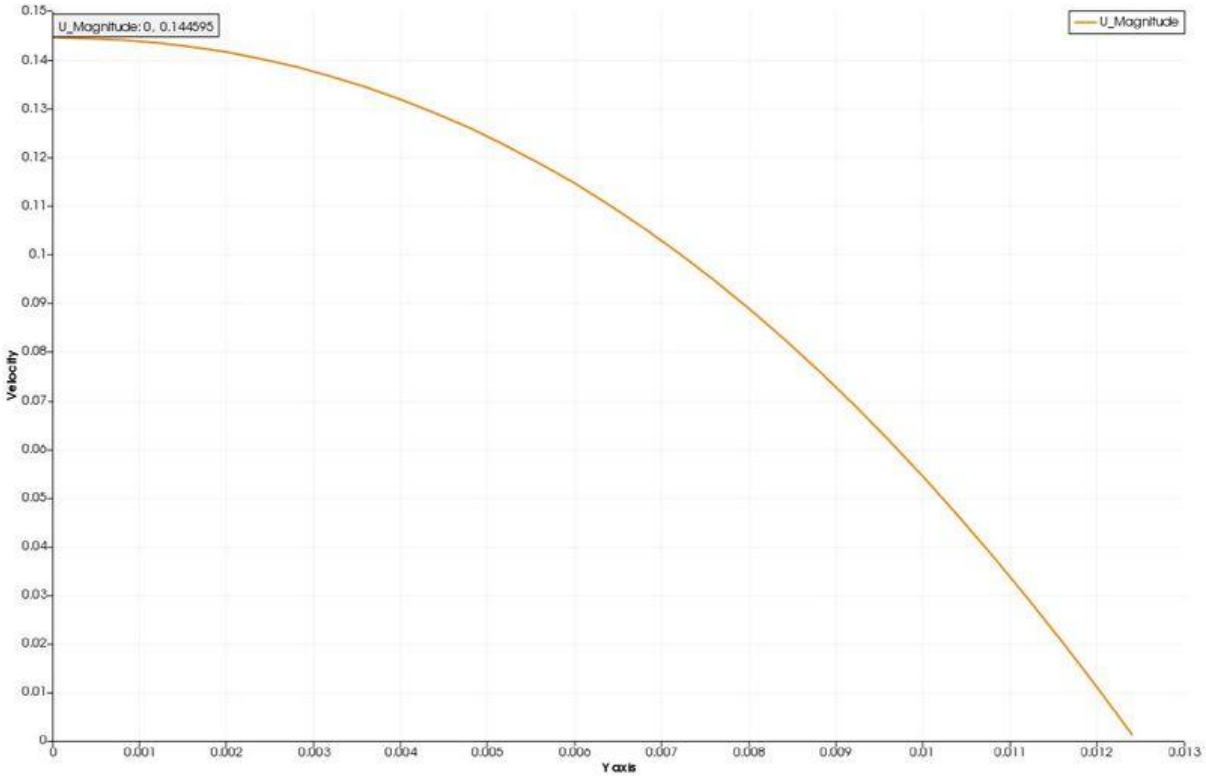
Boundary Condition type - symmetry

wedge angle - 10

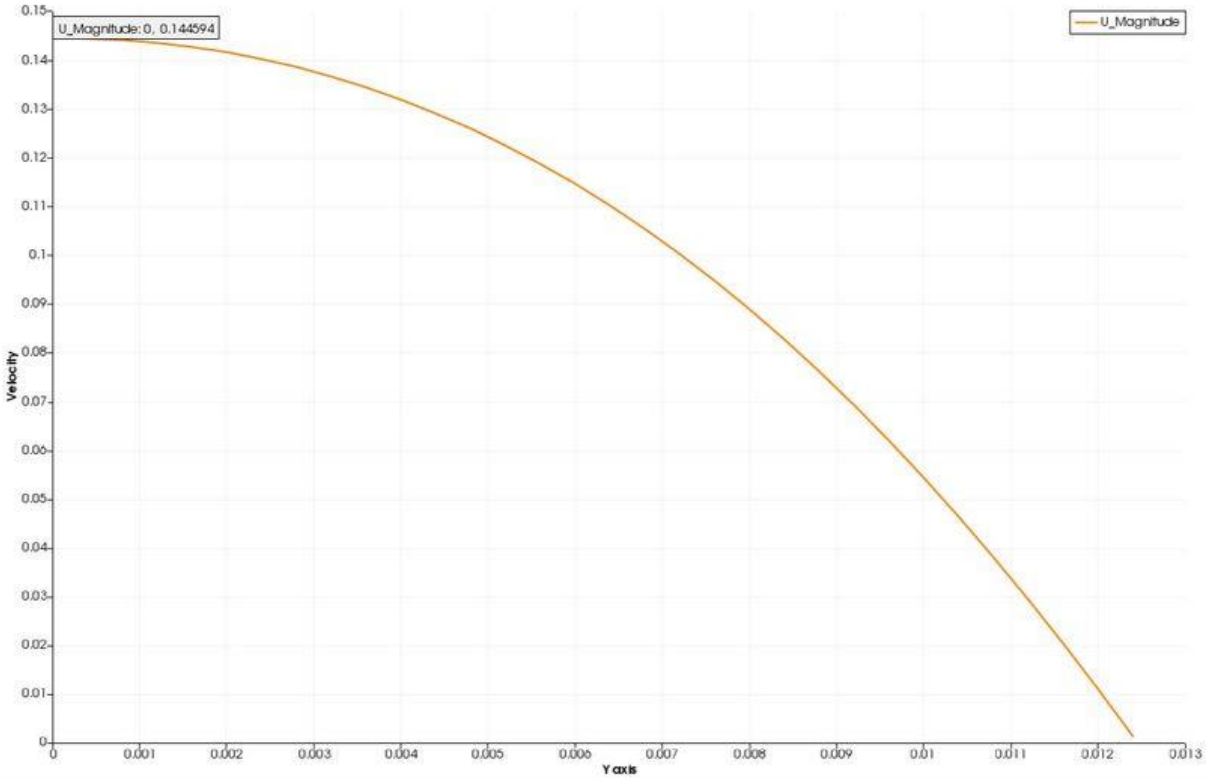
at 2m from inlet -



at 3.15m from inlet -

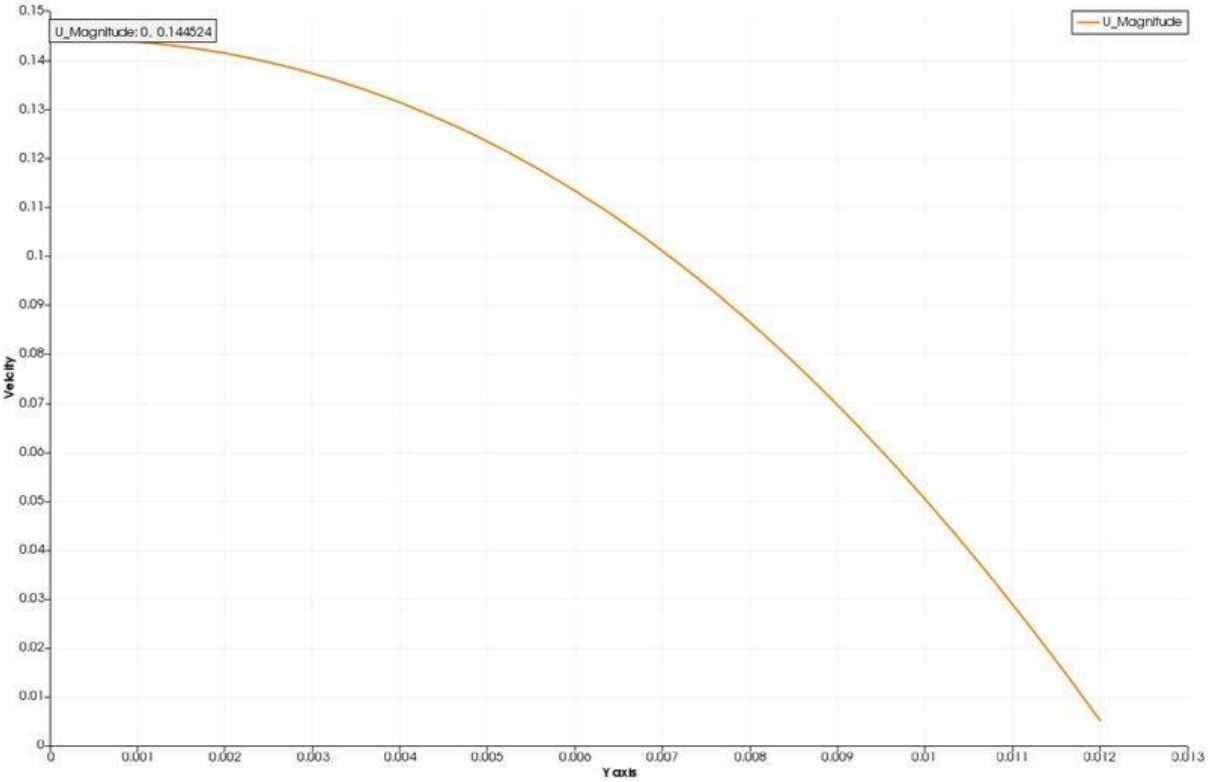


at 3.50m from inlet -

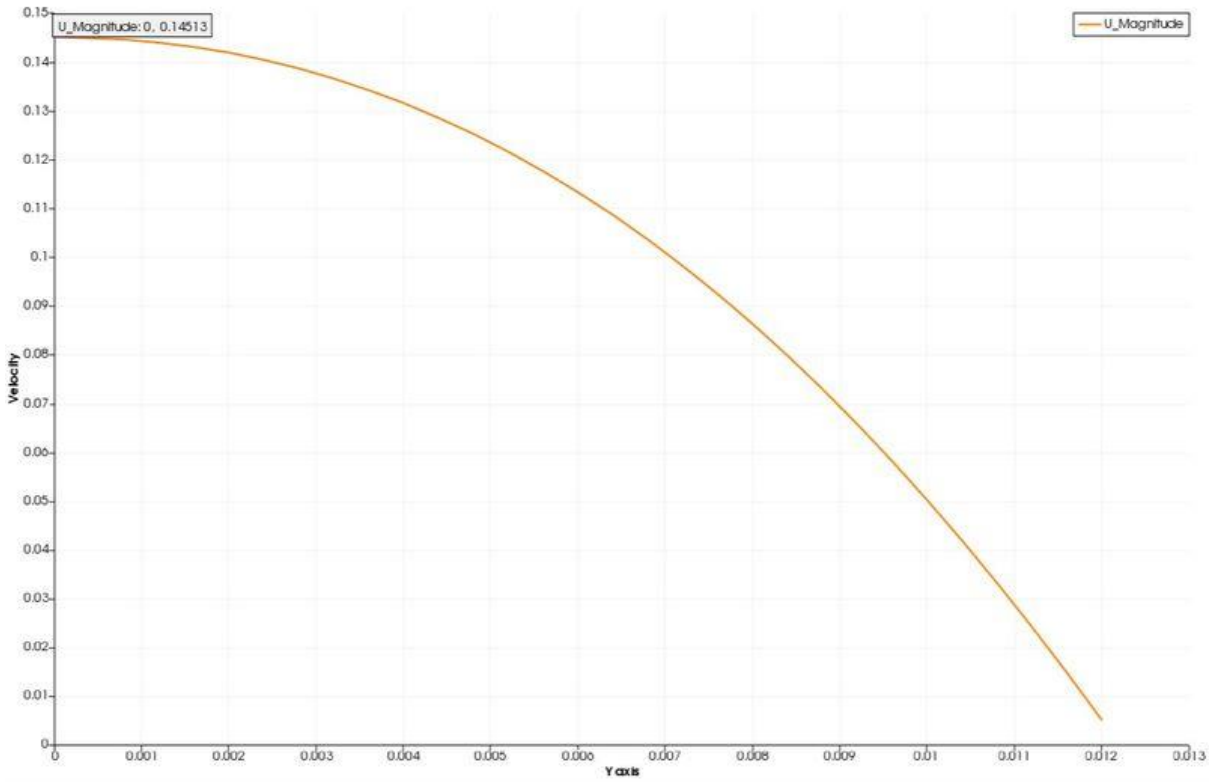


wedge angle - 25

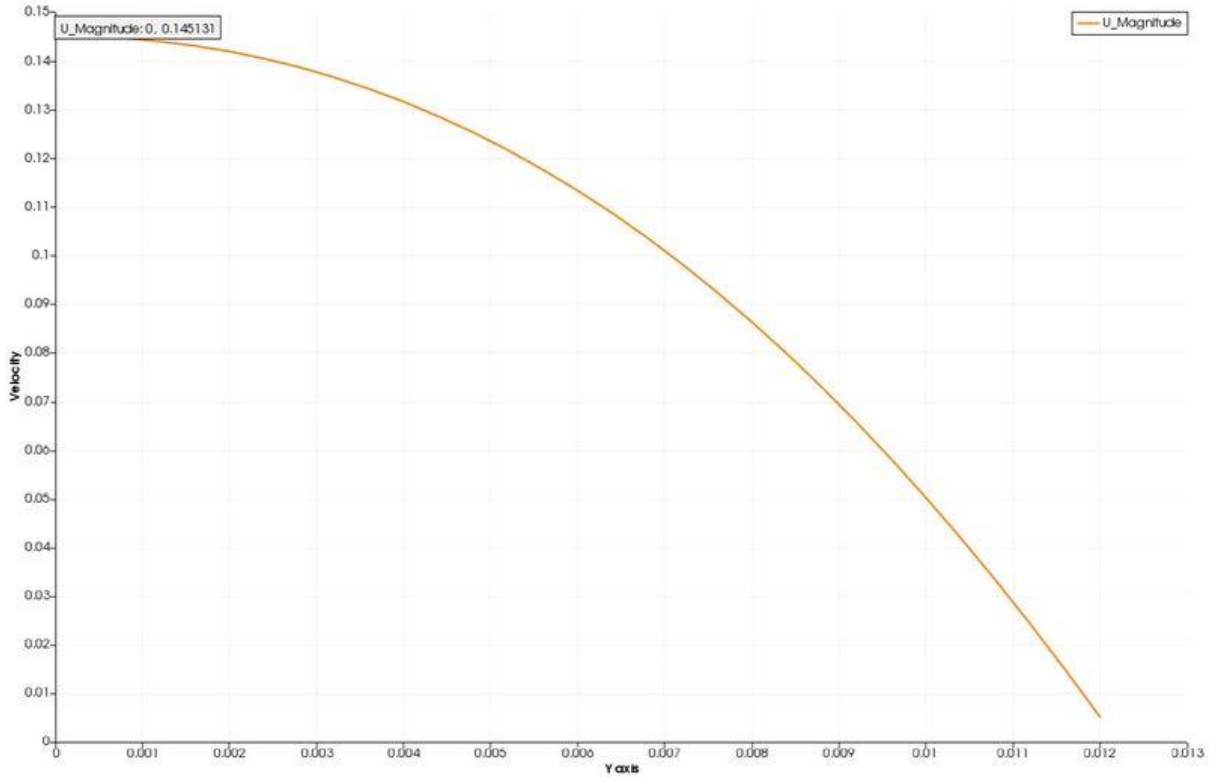
at 2m from inlet -



at 3.15m from inlet -

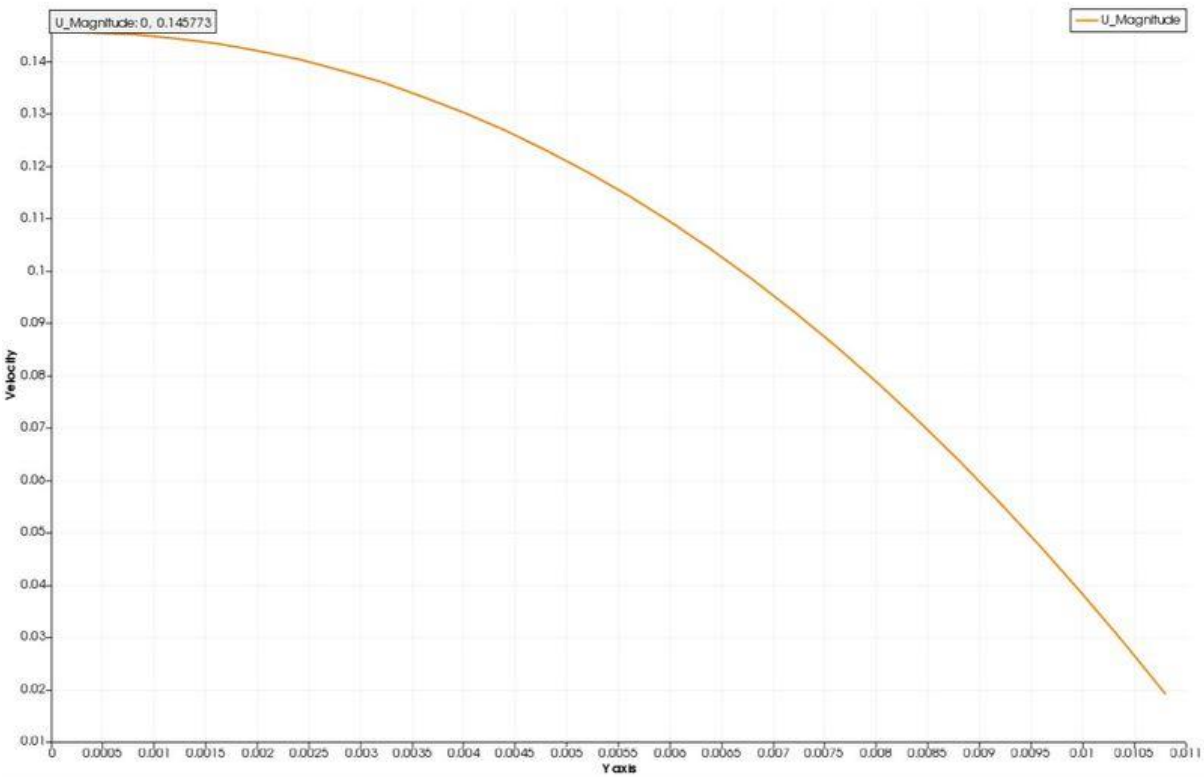


at 3.50m from inlet -

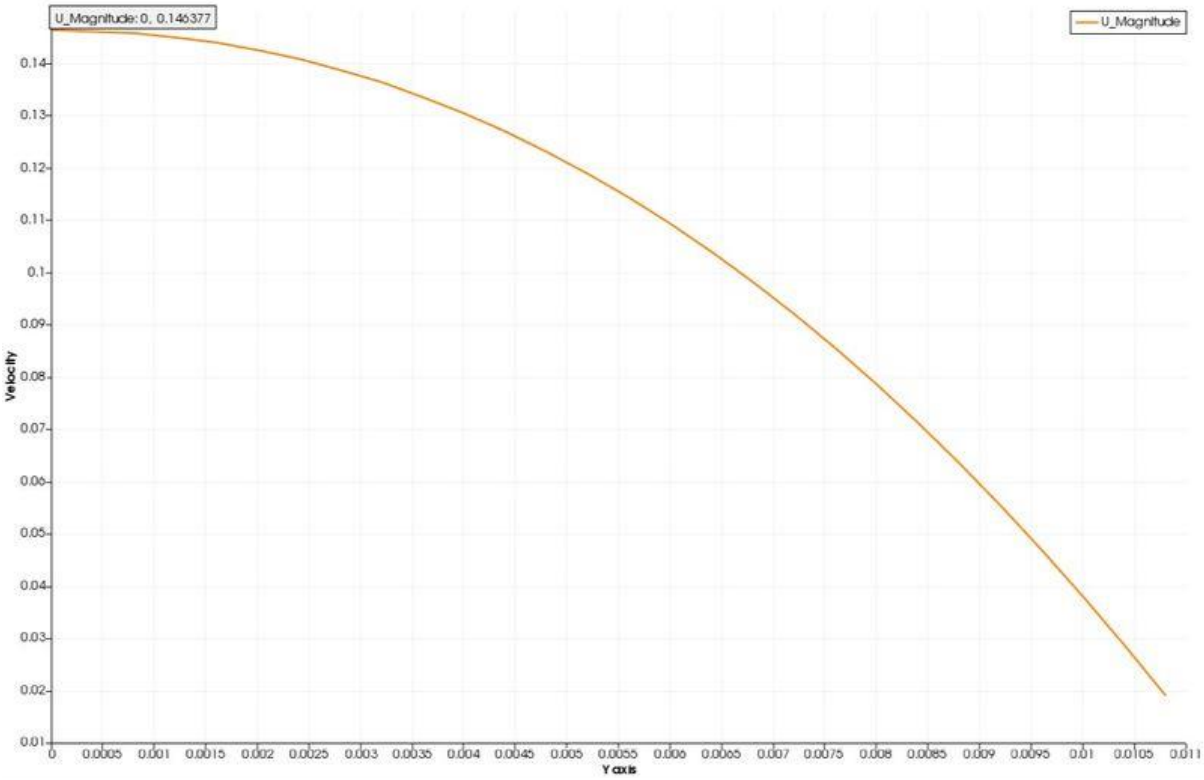


wedge angle - 45

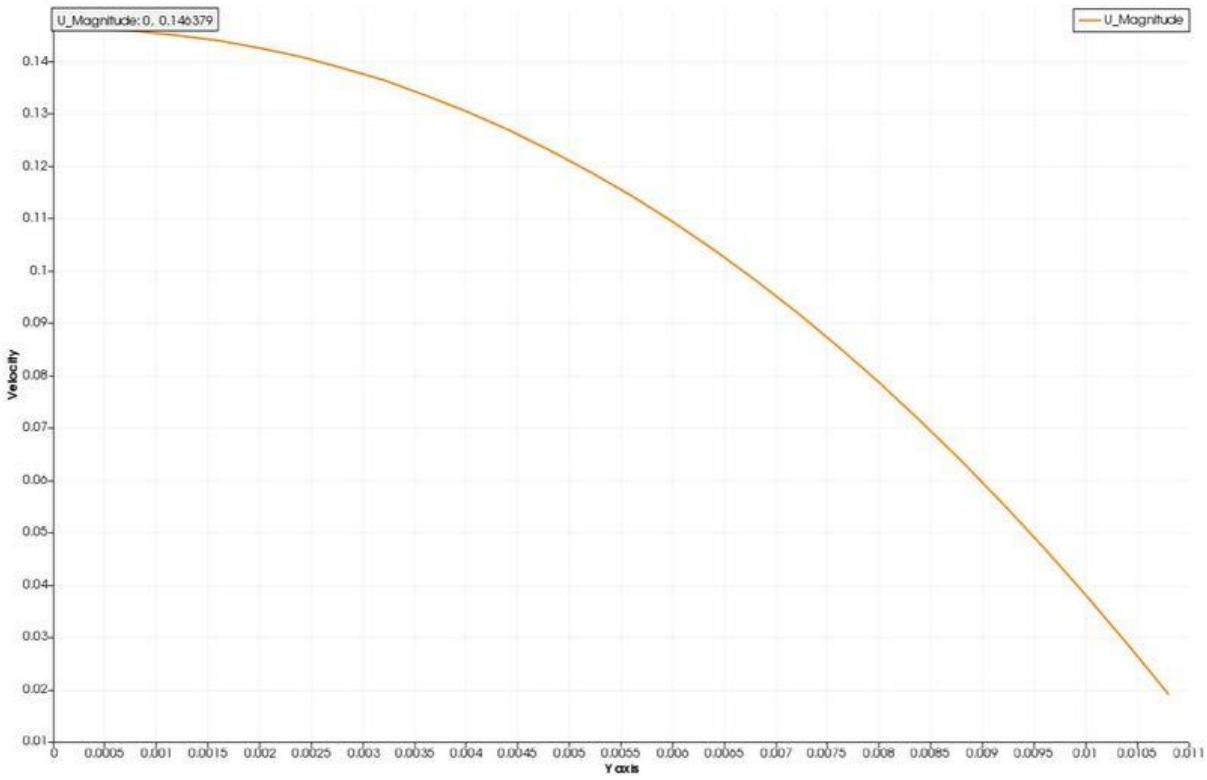
at 2m from inlet -



at 3.15m from inlet -



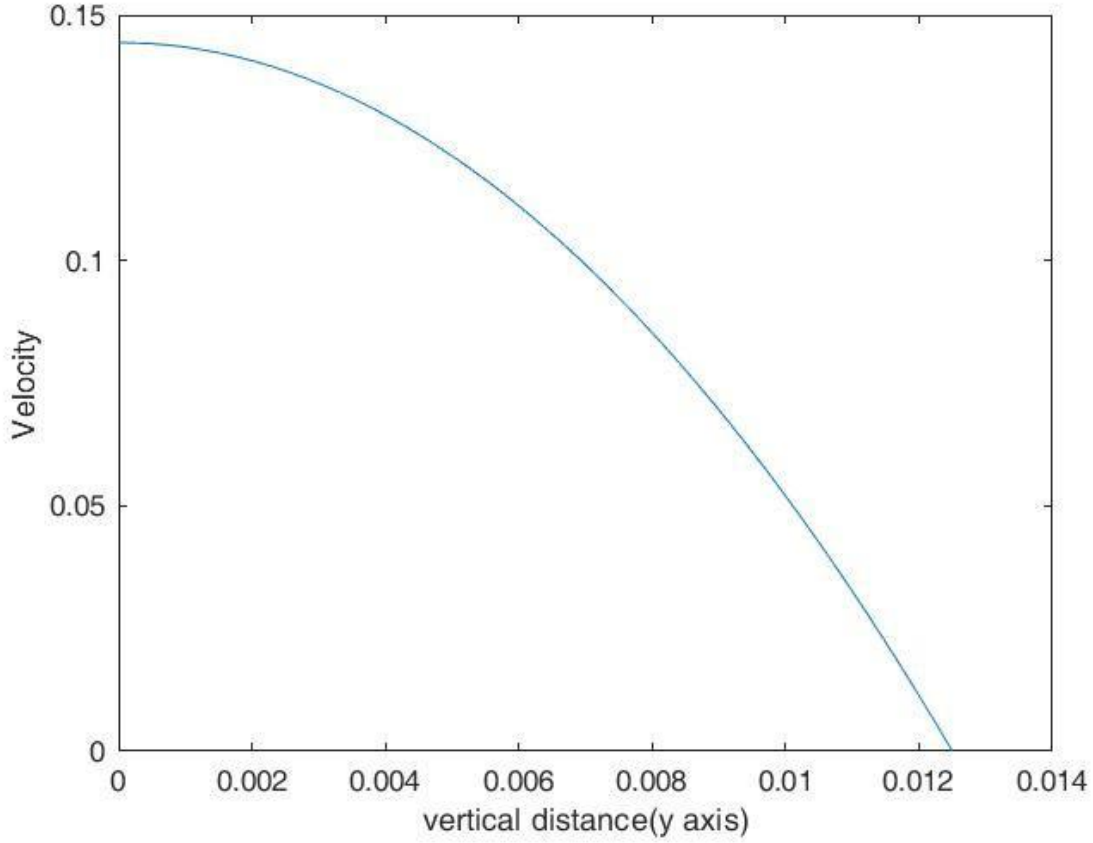
at 3.50m from inlet -

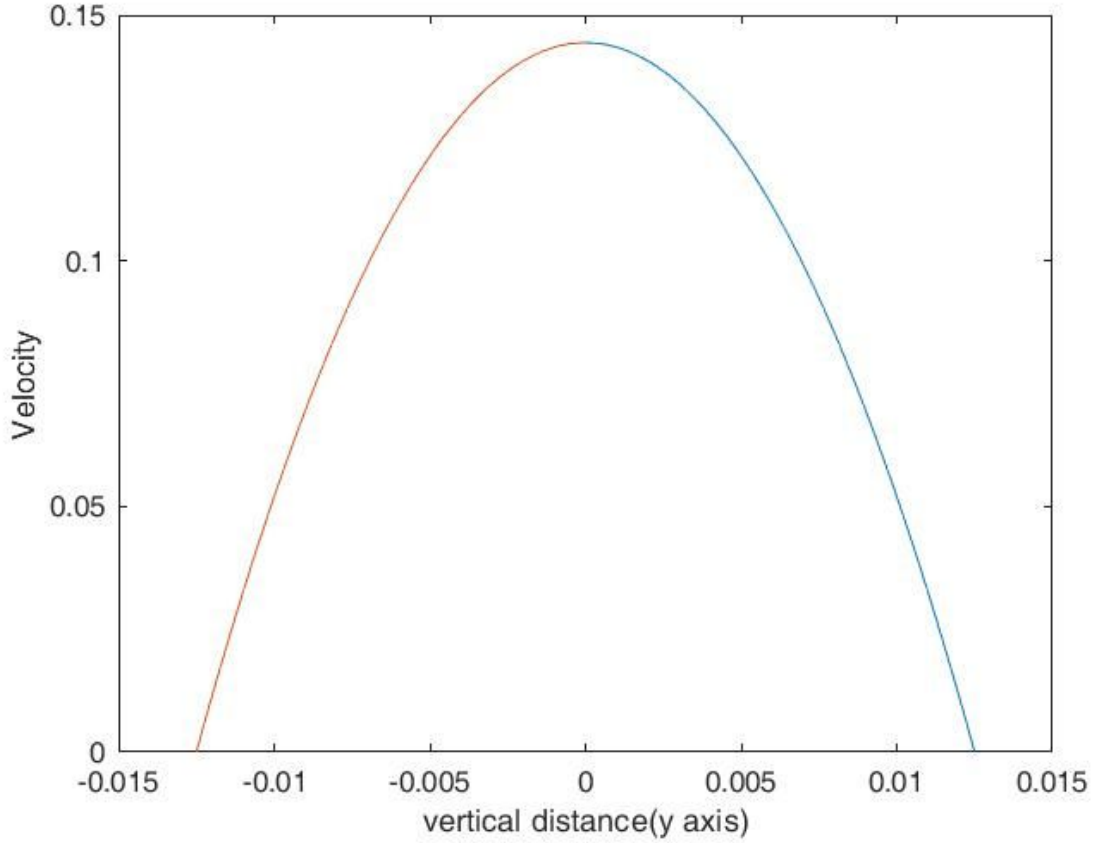


2. Fully flow developed profile analytic solution vs numerical solution

Form the graph(in point 1 at inlet 3.15m) it is easily seen that velocity profile is parabolic and it is matches with analytic solution. To plot velocity from the formula a separate MATLAB programme was written which is in the procedure. Velocity is varing with the wedge angle and when we are applying higher wedge angle we are getting close to analytical result, but for wedge and symmetric boundary condition it is indifferent. The velocity values can be seen in table.

Analytical -


0.15
0.1
0.05
0
Velocity
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
vertical distance(y axis)

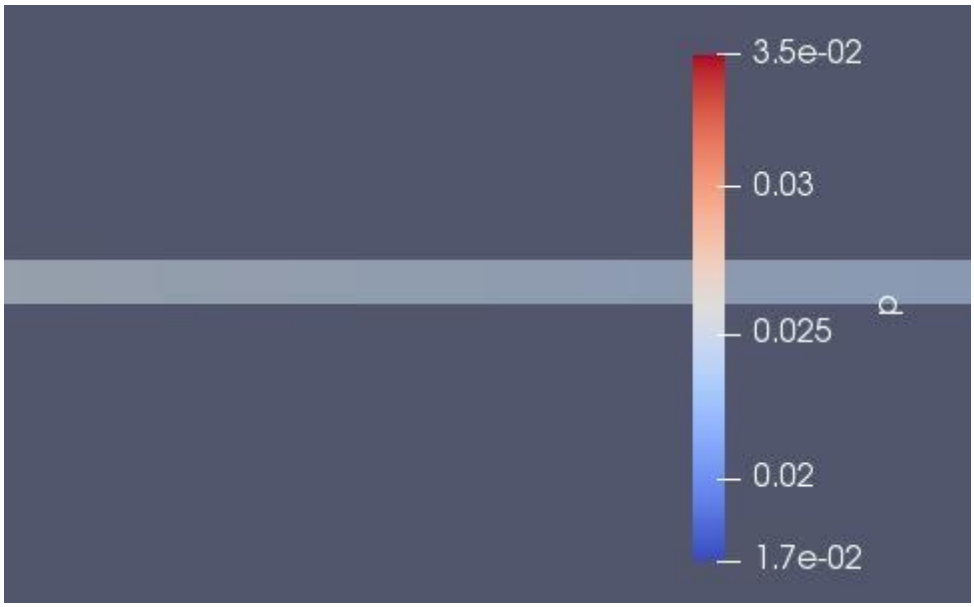

0.15
0.1
0.05
0
Velocity
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
vertical distance(y axis)

3. Pressure drop and maximum velocity analytic solution vs numerical solution

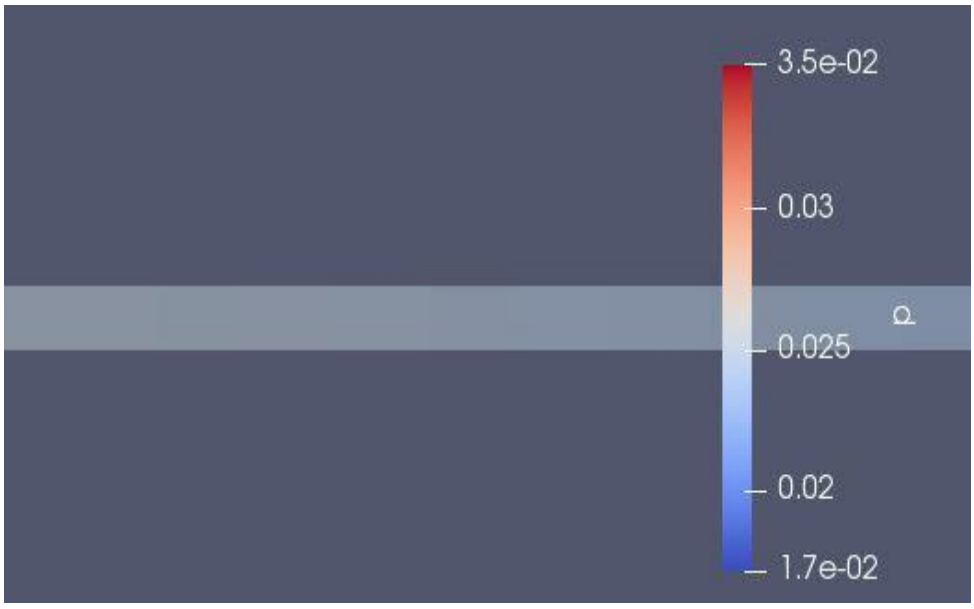
The value of pressure drop is increasing when we go at high value of wedge angle but we are going away from analytical value of pressure drop and it is reverse for velocity. Again, the results are indifferent to type of boundary condition, if minute changes can be neglected.contours for both the cases are more or less same.

Pressure Contour -

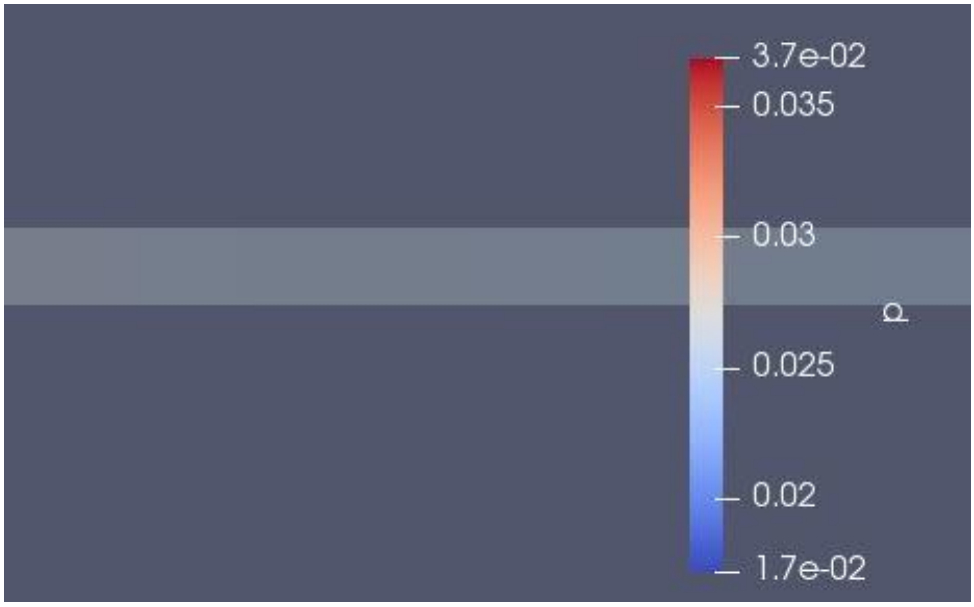
wedge angle -10



wedge angle -25

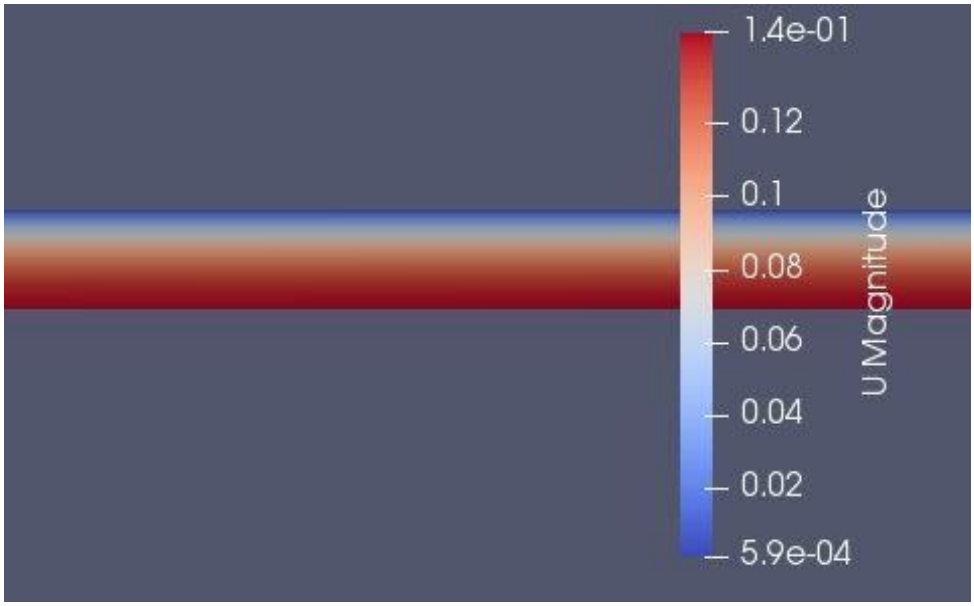


wedge angle -45

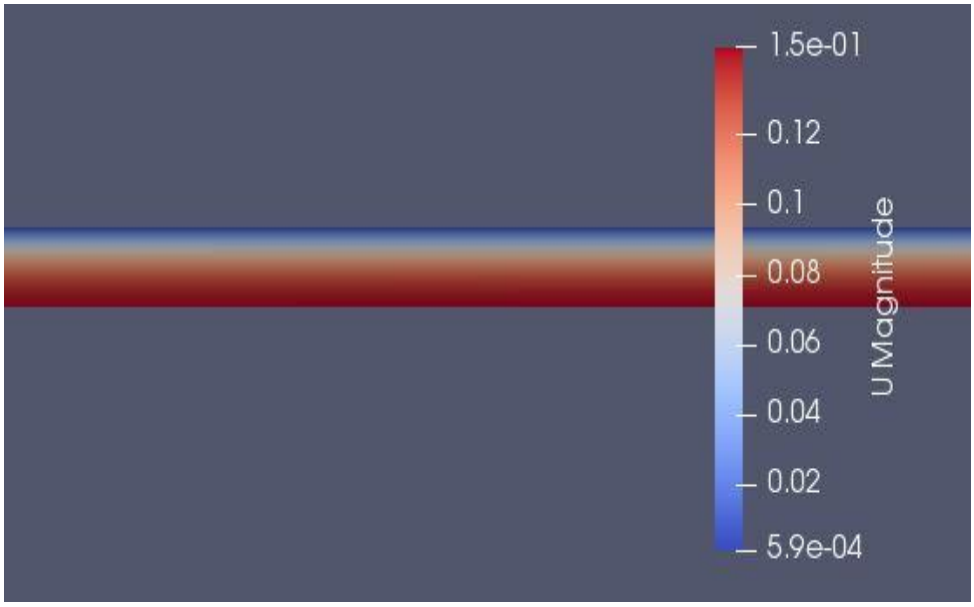


Velocity Contour -

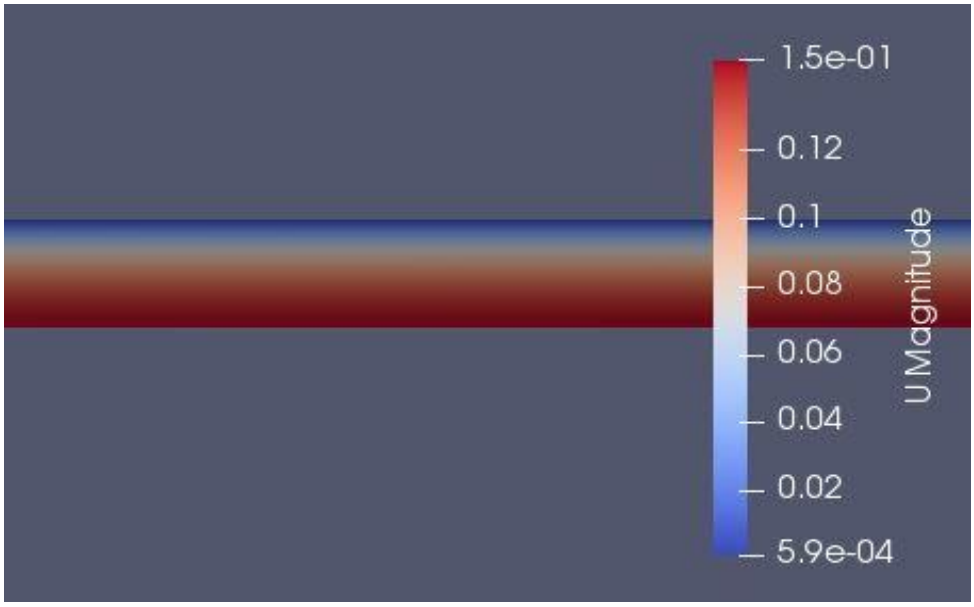
wedge angle -10



wedge angle -25



wedge angle -45

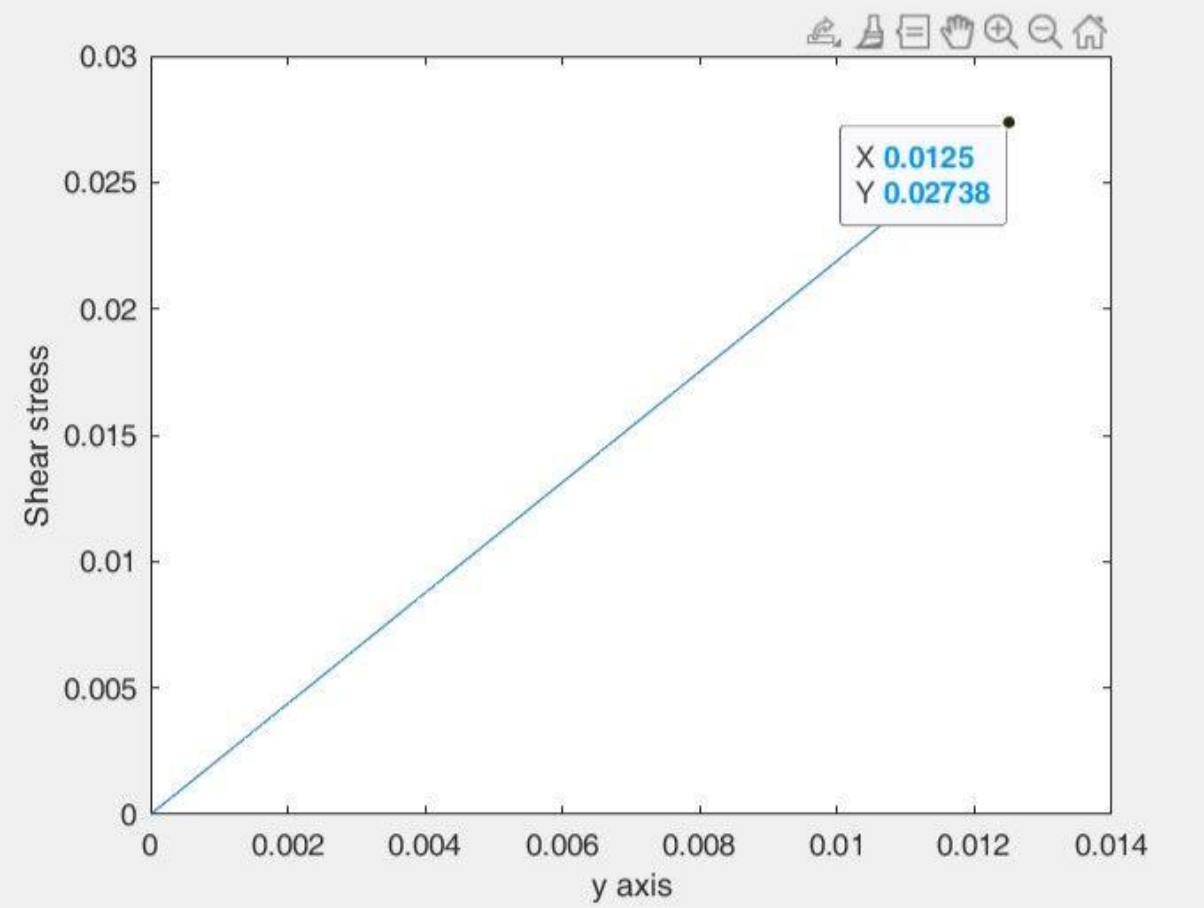


4. Shear stress profile and wall shear stress analytic solution vs numerical solution –

To calculate shear profile separate programme was written and plot has created for each case. All the cases follow same profile as analytical results has, values of wall shear stress can been seen in table.

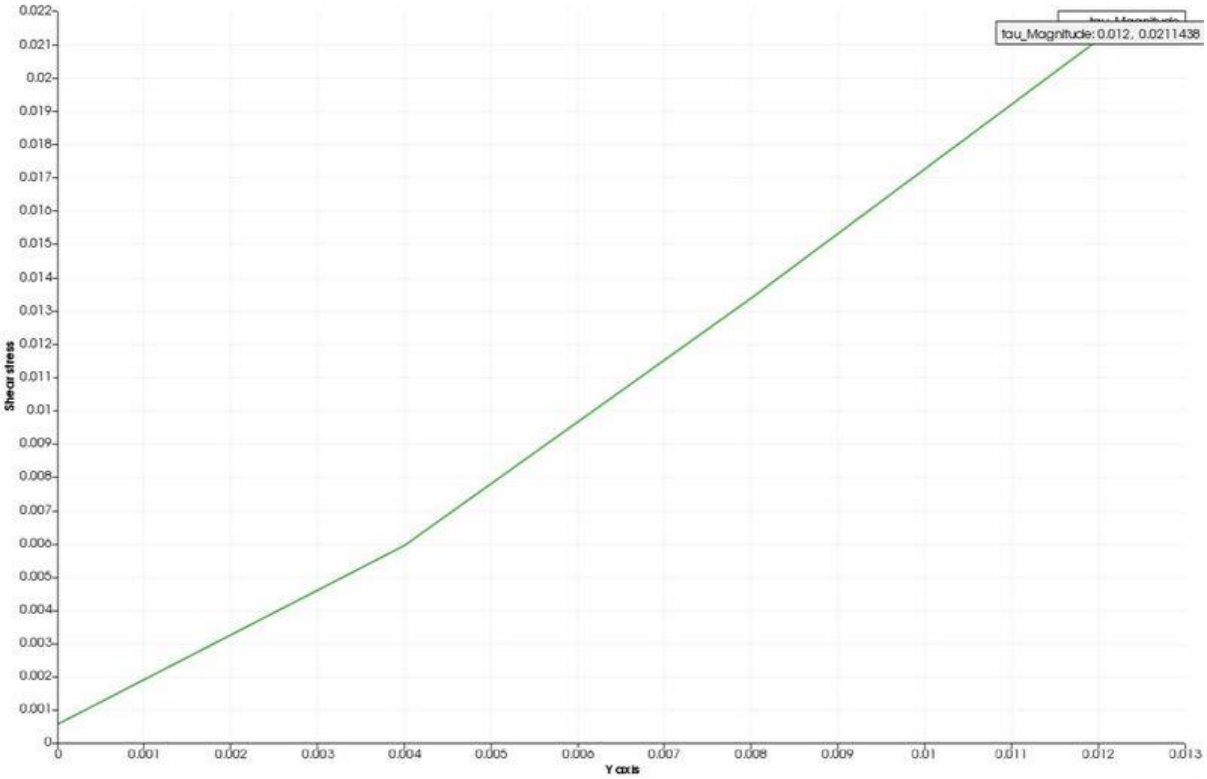
From Analytical method -

Shear stress profile -

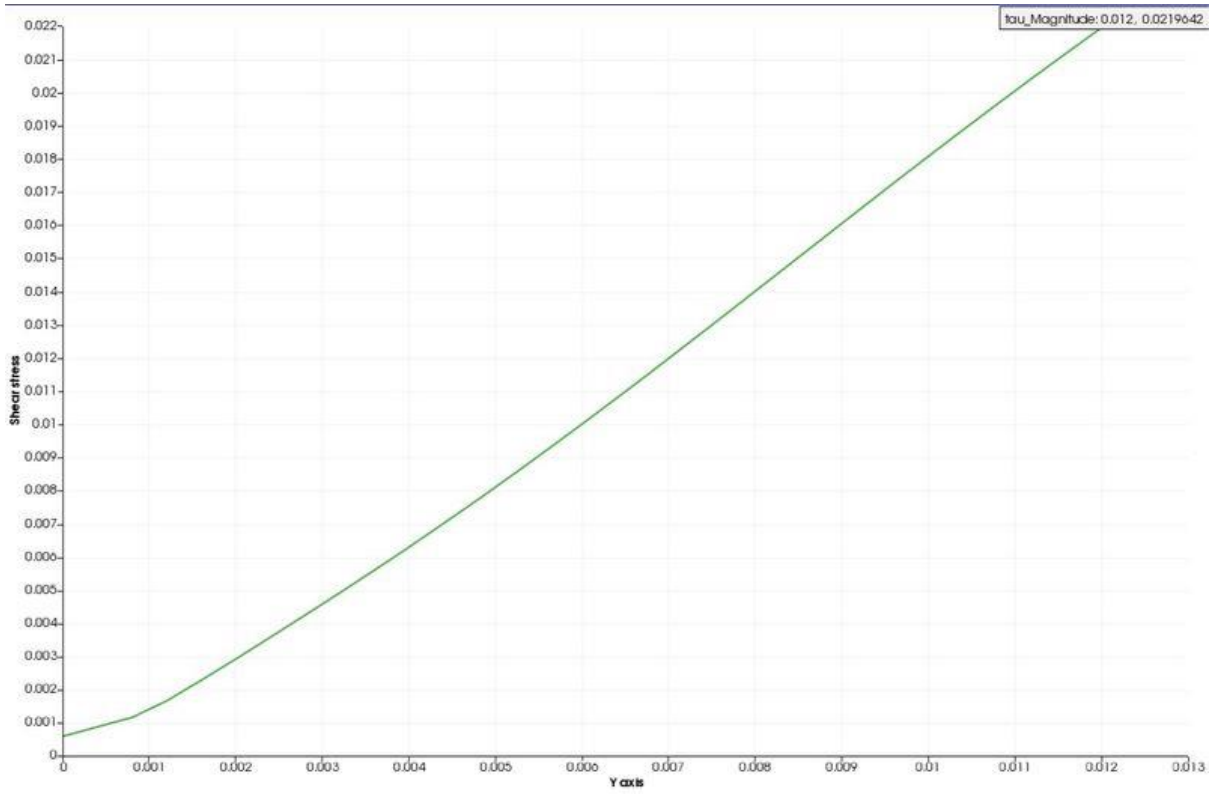


Boundary condition type - wedge

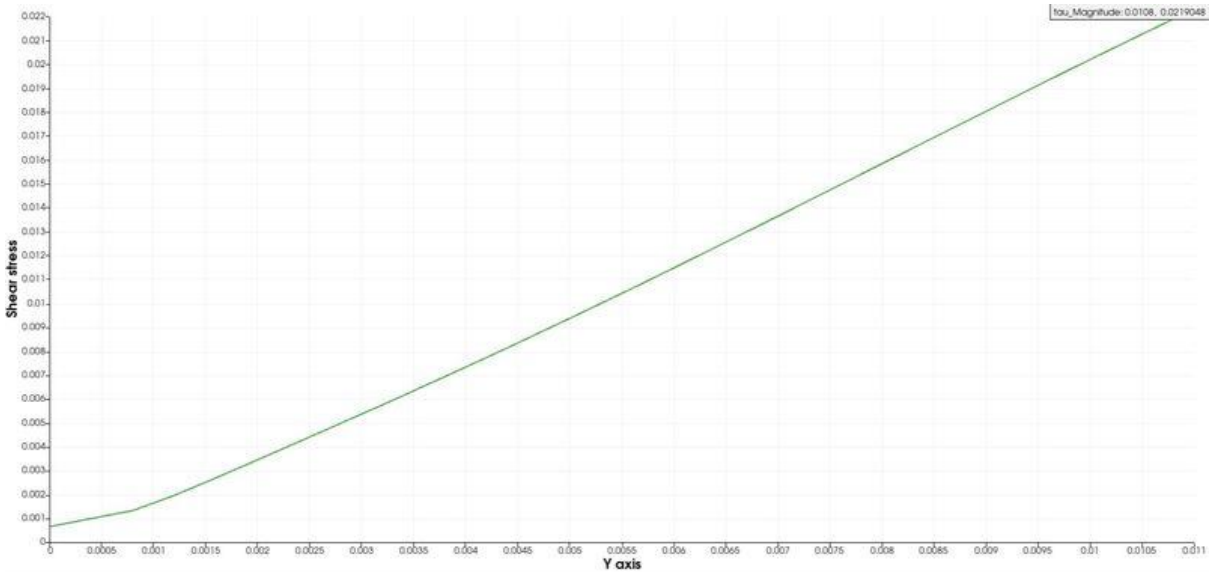
wedge angle -10



wedge angle -25

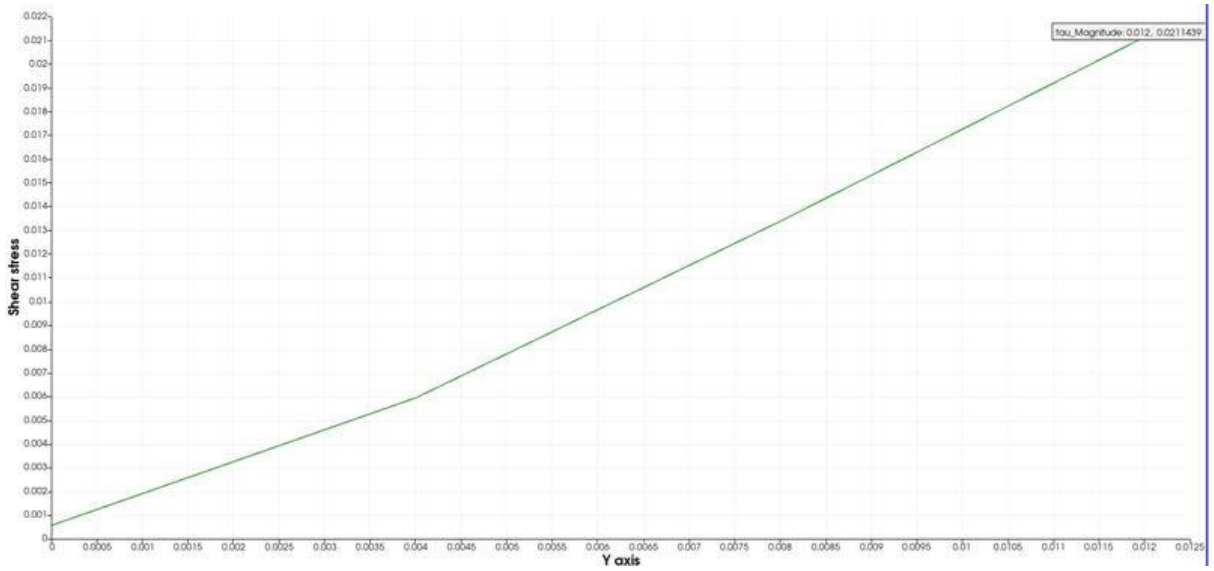


wedge angle -45

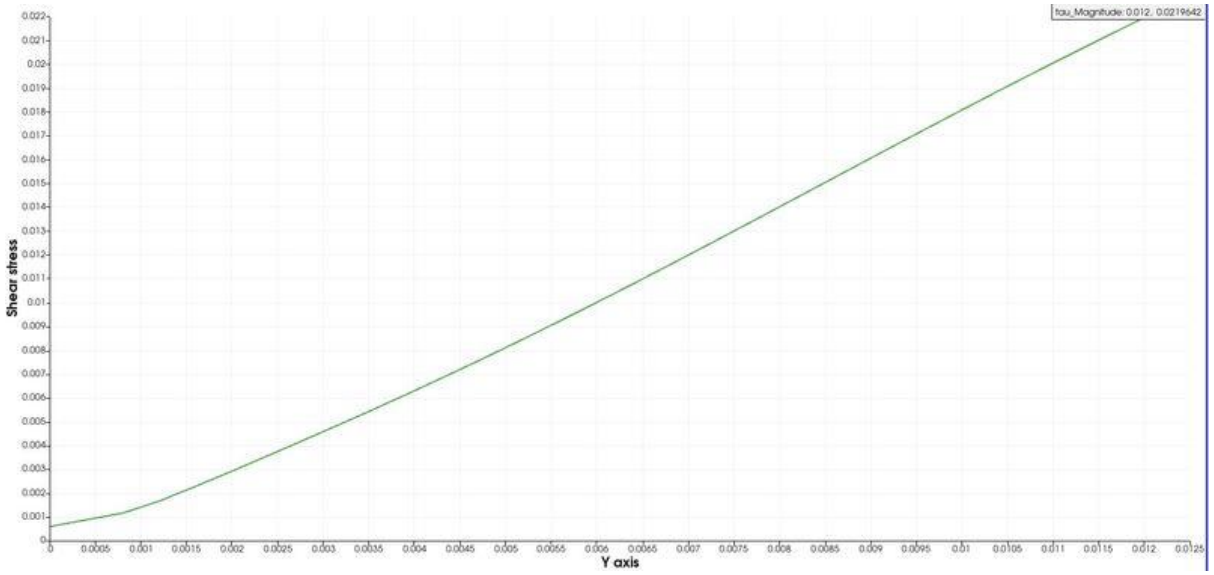


Boundary condition type - symmetry

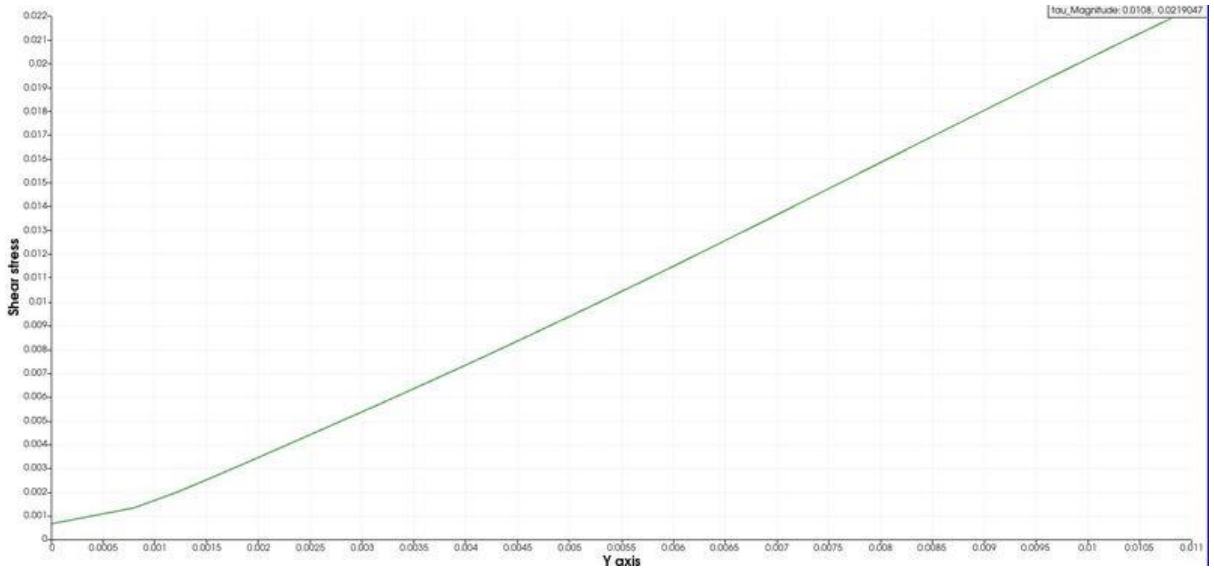
wedge angle -10



wedge angle -25



wedge angle -45



We compared the results and we can conclude that symmetric boundary condition is producing better results than wedged one.

Results at a glance -

Variables and Boundary type and solution method	wedged	wedged	wedged	Symmetric	Symmetric	Symmetric	Results Analytical solution
Wedge angle (Degree)	10	25	45	10	25	45	-
Maximum velocity (m/s)	0.1445	0.1451	0.1474	0.1445	0.1451	0.1485	0.1498
Kinematic Pressure drop (m/s)^2	0.0180	0.0180	0.020	0.0180	0.0180	0.020	0.01369
Wall shear stress (N/m^2)	0.0211	0.0220	0.023	0.0211	0.0220	0.025	0.02738
Hydrodynamic length (m)	3.15	3.15	3.15	3.15	3.15	3.15	3.15