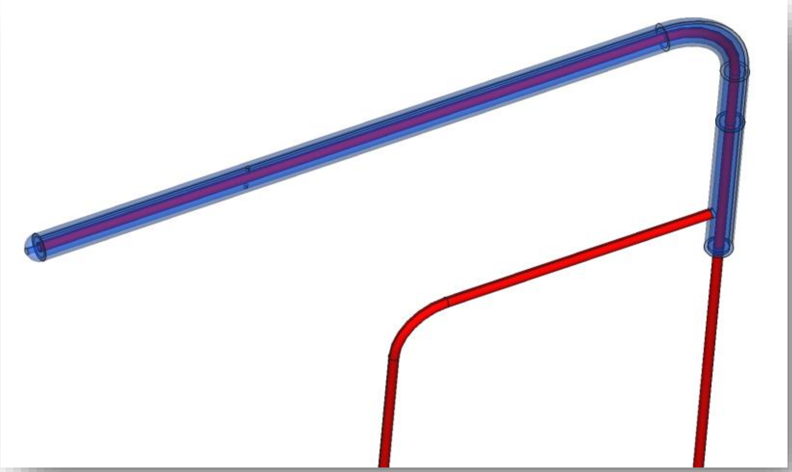
Simulation of Pitot Tube with OpenFoam®

Community Christmas Competition III organised by József Nagy



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Aim:

Simulate Pitot tube for wide range of velocity using OpenFoam®

Road Map:

- Prepare 3D/2D CAD model of Pitot tube considering given velocity range
- Meshing with appropriate tool
- Considering flow physics choose suitable solver for particular velocity
- Calculating velocity of fluid with help of pressure values or liquid height obtained from simulation
- Comparing simulation results with theoretical calculations

Simulation Matrix:

Table 1: Simulation Matrix

Sr. No	Velocity (m/s)	Number of phases	Simulation type	CAD Model	Solver
1	0.1	Single phase	Incompressible steady state -laminar	2D & 3D	simpleFoam
2	0.5	Single phase	Incompressible steady state -laminar	2D & 3D	simpleFoam
3	1	Single phase	Incompressible steady state-laminar	2D & 3D	simpleFoam
4	5	Single phase	Incompressible steady state-laminar	2D & 3D	simpleFoam
5	67	Single &Two Phase	Incompressible steady (3D) & transient (2D) -laminar	2D & 3D	simpleFoam & InterFoam
6	100	Single &Two Phase	Incompressible steady (3D) & transient (2D) -laminar	2D & 3D	simpleFoam & InterFoam
7	240	Single phase	Compressible steady state –turbulent (subsonic)	2D	rhoSimpleFoam
8	570	Single phase	Compressible transient –laminar (supersonic)	2D	rhoCentralFoam

CAD Model

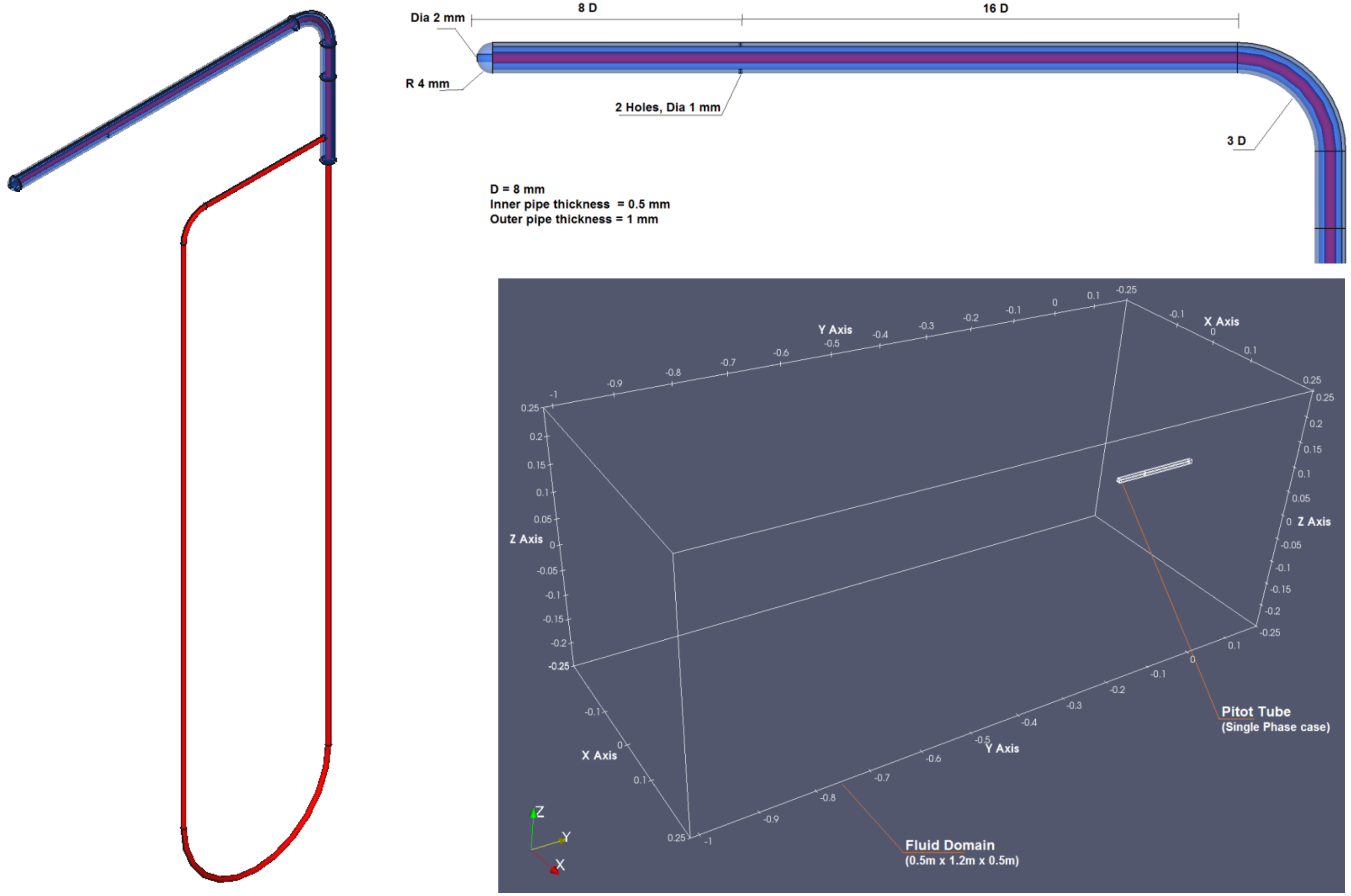


Fig 1: Pitot Tube CAD model

- 3D CAD model of pitot tube is built in Salome 8.3.0. In case of multiphase flow simulation, 3D CAD model is projected on a mid plane to get 2D model.
- Model essentially consisting of inner pipe and outer pipe to measure stagnation pressure and static pressure. Inner pipe has cavity whose opening is perpendicular to flow direction. Outer pipe has two holes as shown in above figure whose openings are parallel to flow direction. Fluid domain is selected as rectangular box.

Meshing

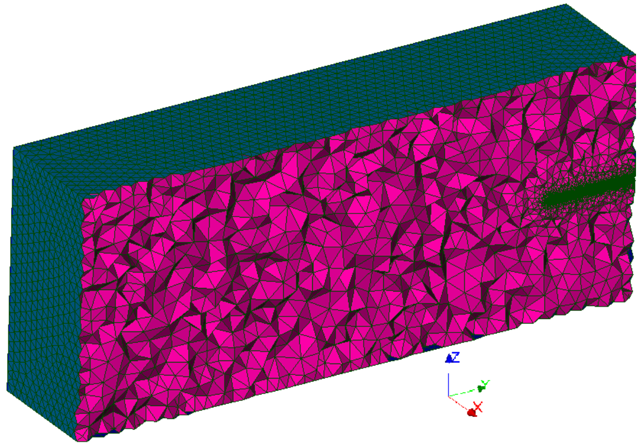
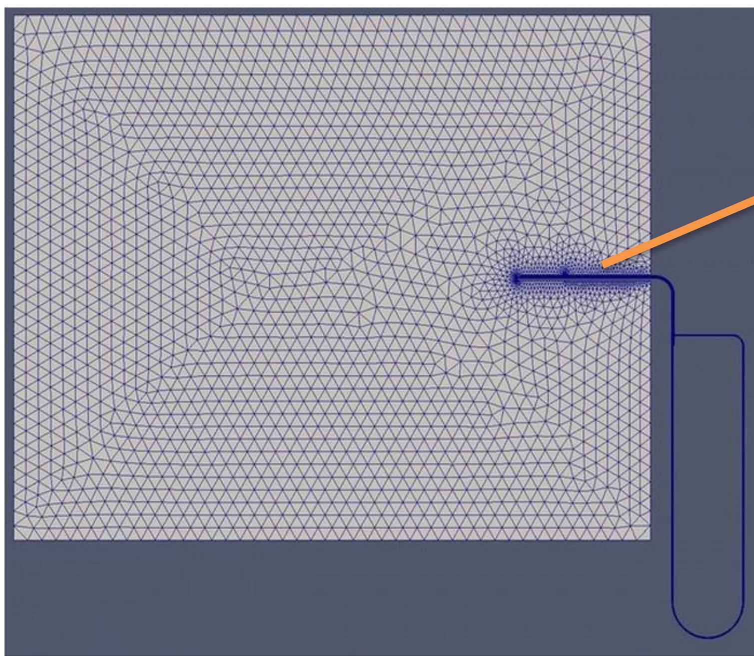


Fig 2: Pitot Tube mesh : 3D model

- Meshing Tool: Salome 8.3.0
- 2D Mesh Statistics:
  - Tet: 23K
  - Prism:1K



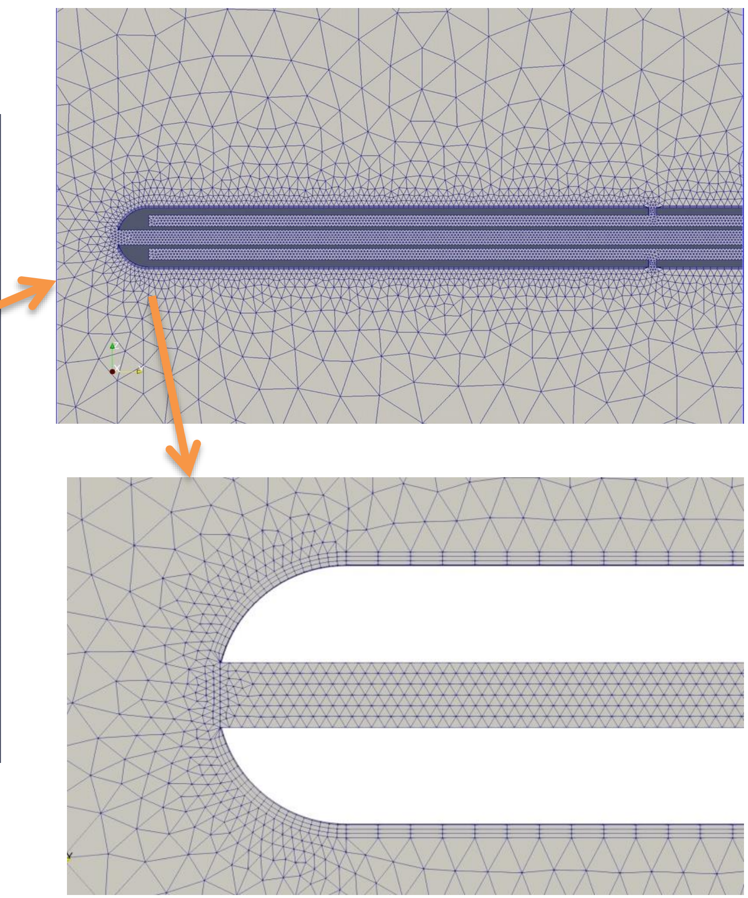


Fig 3: Pitot Tube mesh : 2D model

Boundary Conditions

Table 2: Boundary Conditions

Sr. No	Velocity (m/s)	Variable	Inlet	Outlet	Wall
1	0.1	p	type zeroGradient; Value uniform 0;	type fixedValue; Value uniform 0;	type zeroGradient
	(similar for 0.5m/s, 1m/s, 5 m/s, 100m/s-Single phase)	phi	type calculated; Value uniform 0;	type calculated; Value uniform 0;	type calculated; Value uniform 0;
		U	type fixedValue; value uniform (0 0.1 0);	type zeroGradient;	type movingWallVelocity; value uniform (0 0 0);
2	67	alpha.air	type fixedValue; value uniform 0;	type zeroGradient;	type zeroGradient;
	(Similar for 100m/s-Two phase)	alpha.mercury	type fixedValue; value uniform 0;	type zeroGradient;	type zeroGradient;
		p & p_rgh	type fixedFluxPressure; gradient uniform 0; value uniform 100000;	type fixedValue; value uniform 100000;	type fixedFluxPressure; gradient uniform 0; value uniform 100000;
		T, T.air, T.mercury	type fixedValue; value uniform 300;	type zeroGradient;	type zeroGradient;
		U	type fixedValue; value uniform (0 67 0);	type zeroGradient;	type movingWallVelocity; value uniform (0 0 0);
3	240	alphat	type calculated; Value uniform 0;	type calculated; Value uniform 0;	type compressible::alphatWallFunction; Prt 0.71; value uniform 0;
		k	type inletOutlet; inletValue uniform $kInlet; //(kInlet 0.01) Value uniform $kInlet;	type inletOutlet; inletValue uniform $kInlet; //(kInlet 0.01) Value uniform $kInlet;	type kqRWallFunction; Value uniform $kInlet;
		nut	type calculated; Value uniform 0;	type calculated; Value uniform 0;	type nutkWallFunction; Value uniform 0;
		Omega	type inletOutlet; inletValue uniform $omegaInlet; Value uniform $omegaInlet; //omegaInlet 10;	type inletOutlet; inletValue uniform $omegaInlet; Value uniform $omegaInlet; //omegaInlet 10;	type omegaWallFunction; Value uniform $omegaInlet;
		p	type fixedValue; Value uniform 1e5;	type fixedValue; Value $internalField;	type zeroGradient;
		T	type fixedValue; Value uniform 293;	type zeroGradient;	type zeroGradient;
		U	type fixedValue; Value uniform (0 240 0)	type zeroGradient;	type noSlip;
4	570	p	type fixedValue; Value uniform 1e5;	type zeroGradient;	type zeroGradient;
		T	type fixedValue; Value uniform 300;	type fixedValue; Value uniform 300;	type fixedValue; Value uniform 300;
		U	type fixedValue; value uniform (0 570 0);	type zeroGradient;	type slip

Results

Convergence : All simulations were converged with residuals below 1e-3

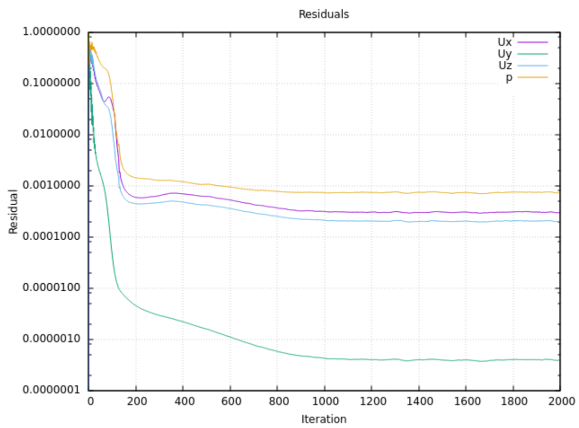


Fig 4a: Convergence plot for 5m/s

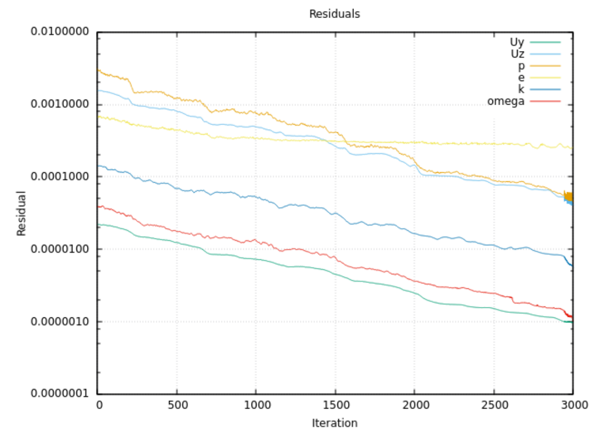


Fig 4b:Convergence plot for 240m/s

Formulae used:

1. For Multiphase :

$$U = \sqrt{2g(\rho_m - \rho_f)\Delta h/\rho_f}$$

$\rho_m = Density\ of\ mercury$

$\rho_f = Density\ of\ fluid\ (air)$

$\Delta h = Liquid\ column\ difference$

2. For Single phase incompressible:

$$U = \sqrt{\frac{2\left(p_0 - p\right)}{\rho}}$$

$p0 = stagnation\ pressure$

$p = static\ pressure$

$\rho = density\ of\ fluid\ (air)$

3. For Single phase compressible Subsonic:

$$U = \sqrt{\frac{2\gamma}{\gamma - 1}\frac{p_0}{\rho_0}\left(1 - \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

$\gamma = 1.4$

4. For Single phase compressible Supersonic:

$$\frac{p_{0_2}}{p_1} = \left(\frac{\left(\gamma+1\right)^2 M_1{}^2}{4\gamma M_1{}^2 - 2\left(\gamma-1\right)}\right)^{\frac{\gamma}{\gamma-1}}\left(\frac{\left(1-\gamma\right)+2\gamma M_1{}^2}{\gamma+1}\right)$$

Calculated U from CFD values:

Table 3: Velocity Calculations

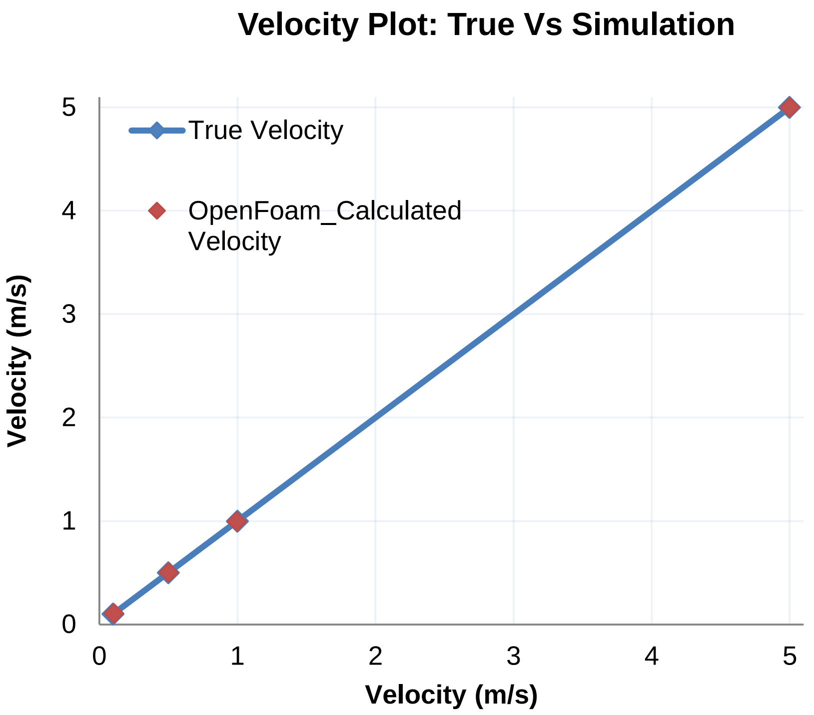
2D Single Phase Simulation						
Sr No	Velocity (m/s)	P_stagnation (Pa): CFD data	P_static (Pa): CFD data	rho_air (kg/m3)	Calculated Velocity (m/s)	% Error
1	0.1	5.736E-03	-1.737E-04	1	0.109	**-8.72**
2	0.5	1.308E-01	-1.678E-04	1	0.512	**-2.37**
3	1	5.158E-01	-1.169E-02	1	1.027	**-2.71**
4	5	1.268E+01	1.026E-01	1	5.014	**-0.29**
5	67	2.233E+03	-3.060E+01	1	67.290	**-0.43**
6	100	4.852E+03	-4.398E+01	1	98.950	**1.05**

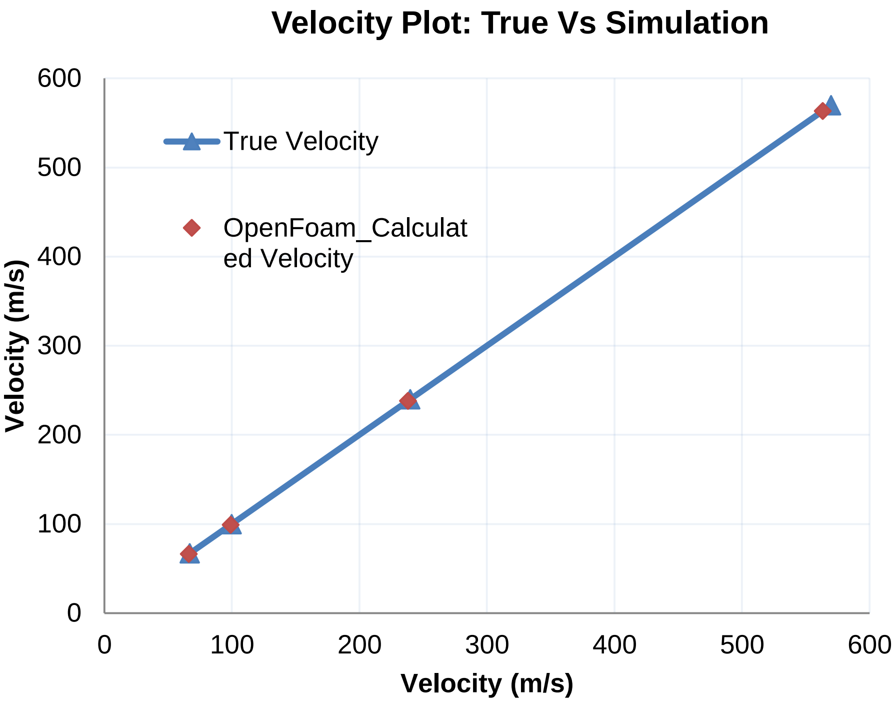
3D Single Phase Simulations						
Sr No	Velocity (m/s)	P_stagnation (Pa): CFD data	P_static (Pa): CFD data	rho_air (kg/m3)	Calculated Velocity (m/s)	% Error
1	0.1	5.733E-03	-2.500E-05	1	0.107	**-7.31**
2	0.5	1.258E-01	-9.141E-05	1	0.502	**-0.36**
3	1	4.956E-01	-6.622E-04	1	0.996	**0.37**
4	5	1.240E+01	-1.124E-01	1	5.002	**-0.04**
5	67	2.183E+03	-1.919E+01	1	66.361	**0.95**
6	100	4.867E+03	-4.387E+01	1	99.104	**0.90**

2D Multiphase Simulation					
Sr No	Velocity (m/s)	Δh (mm): CFD data	rho_mercury (kg/m3)	Calculated Velocity (m/s)	% Error
1	67	16.381	13545	65.98	**1.52**
2	100	36.96	13545	99.11	**0.89**

2D Single Phase- Subsonic and Supersonic simulation						
Sr No	Velocity (m/s)	P_stagnation (Pa)	P_static (Pa)	rho_air (kg/m3)	Calculated Velocity (m/s)	% Error
1	240	130015	99852.6	0.9645	238.26	**0.73**
2	570	389493	100000	No required	563.33	**1.17**

Graph: True velocity Vs Simulation velocity





- 3D incompressible simulation results are selected further since those have less % error compared to 2D simulation results.
- Most of simulation results almost coincide with expected values.

Animation Video : Multiphase simulation

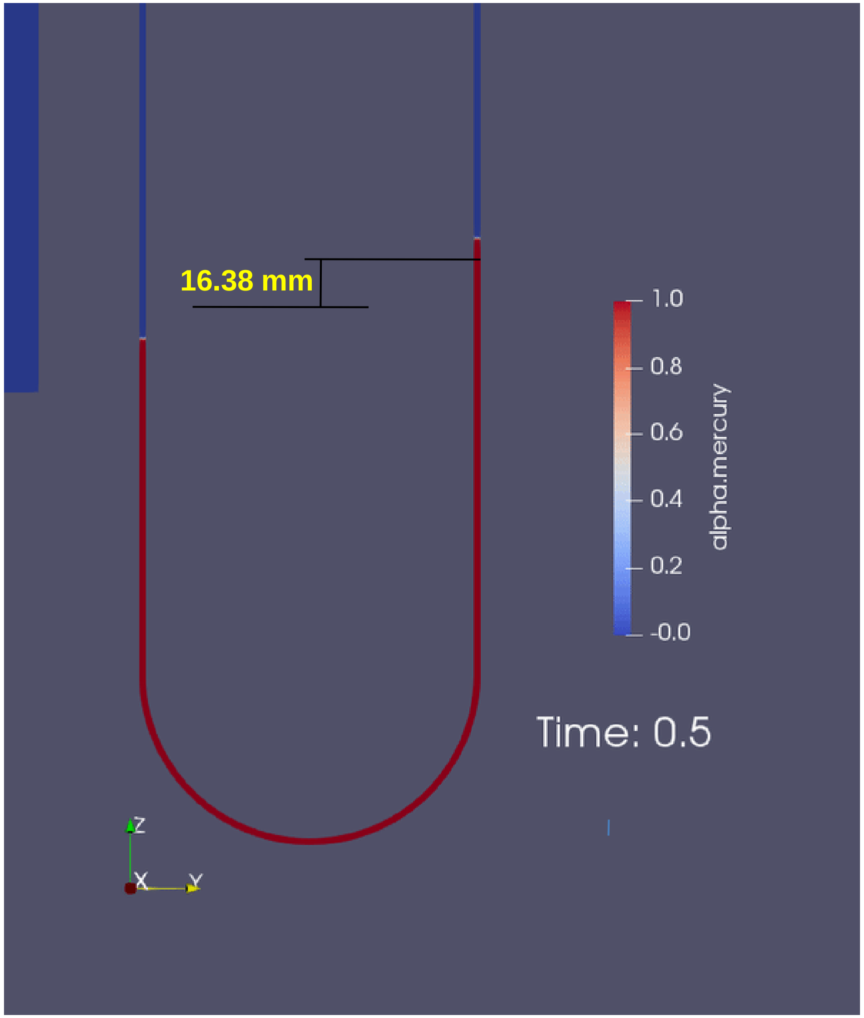


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Fig 5: 67 m/s alpha.mercury

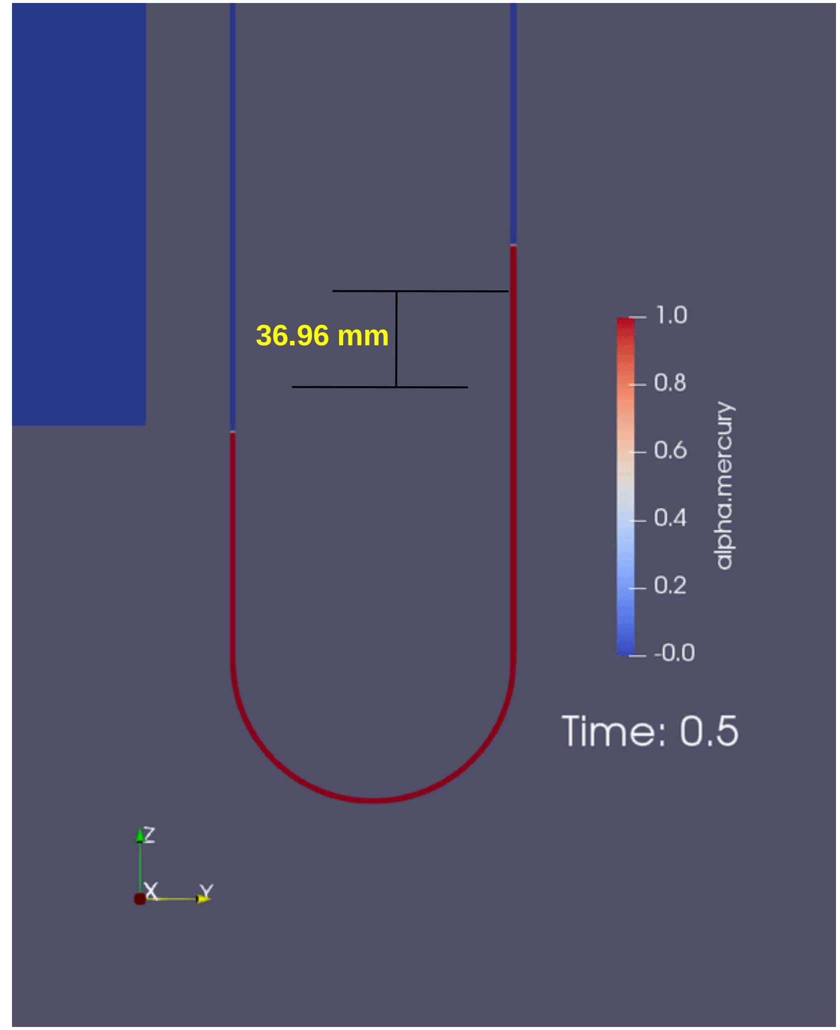

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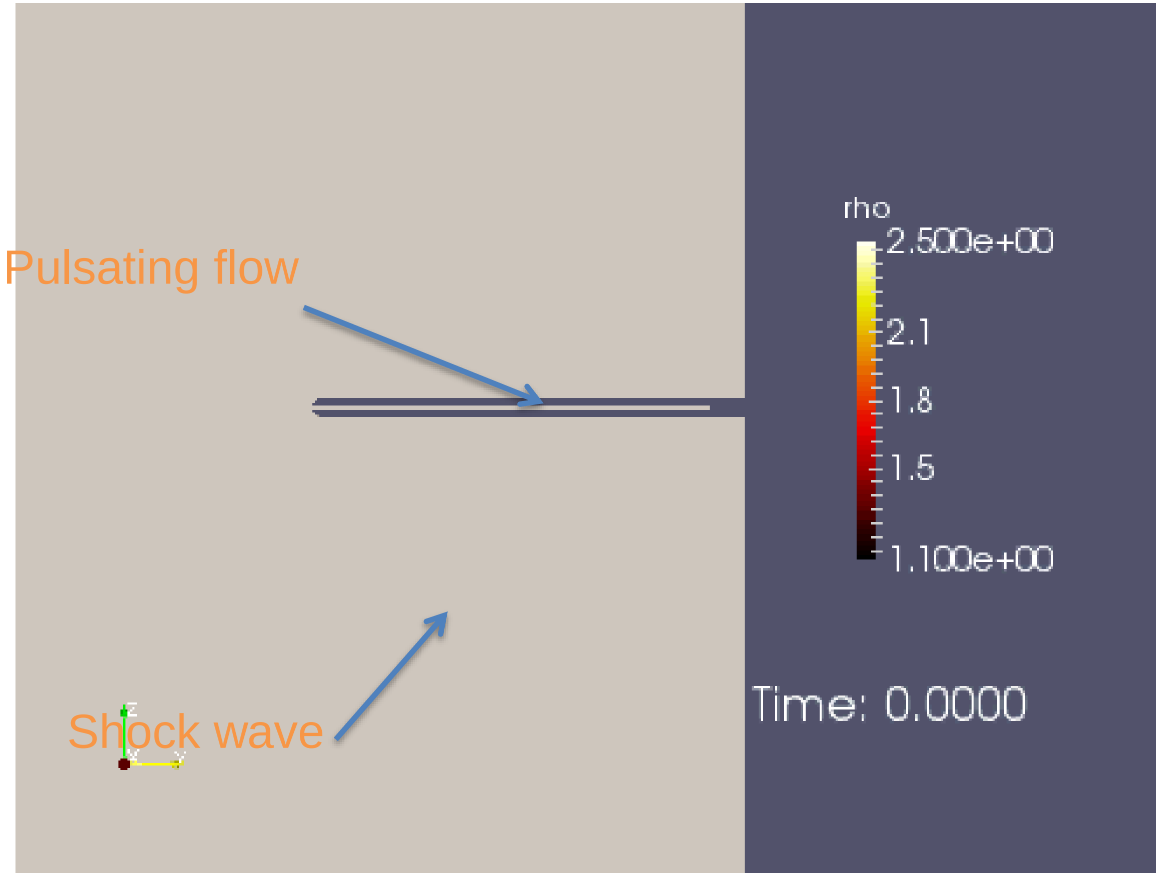
Fig 6: 100 m/s alpha.mercury

- To calculate Δh for multiphase simulation, alpha.mercury were plotted in paraview over lines passing through mid of left and right manometer columns.
- Difference between arc length were calculated corresponding to last point where alpha.mercury=1

Animation Video: 570 m/s



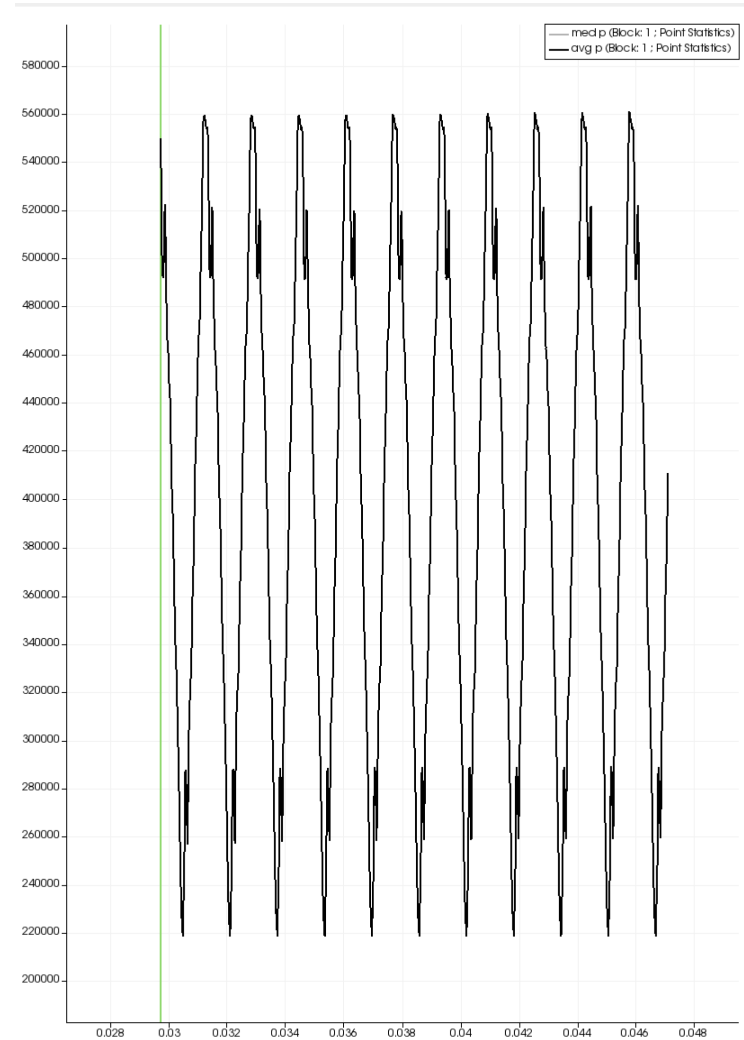


Fig 7a: 67 m/s alpha.mercury

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Fig 7b:Pressure in Pulsating flow

- Average of Max and Min pressure at various points inside inner tube has been extracted from CFD simulation and used in formula (4) to calculate velocity of air for given velocity of sound at same temperature.

Some Colorful Pictures

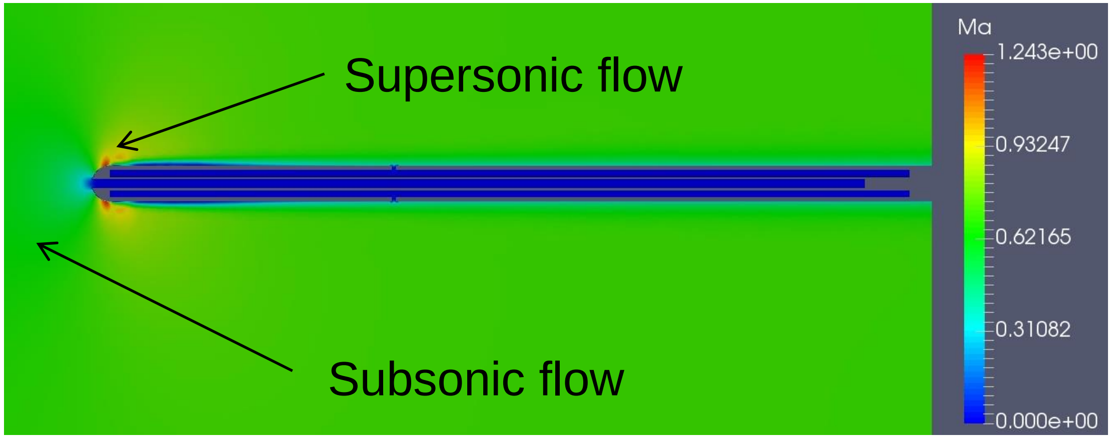

Fig 8a : Mach Number for 240 m/s

Fig 8b : Pressure contour for 240 m/s

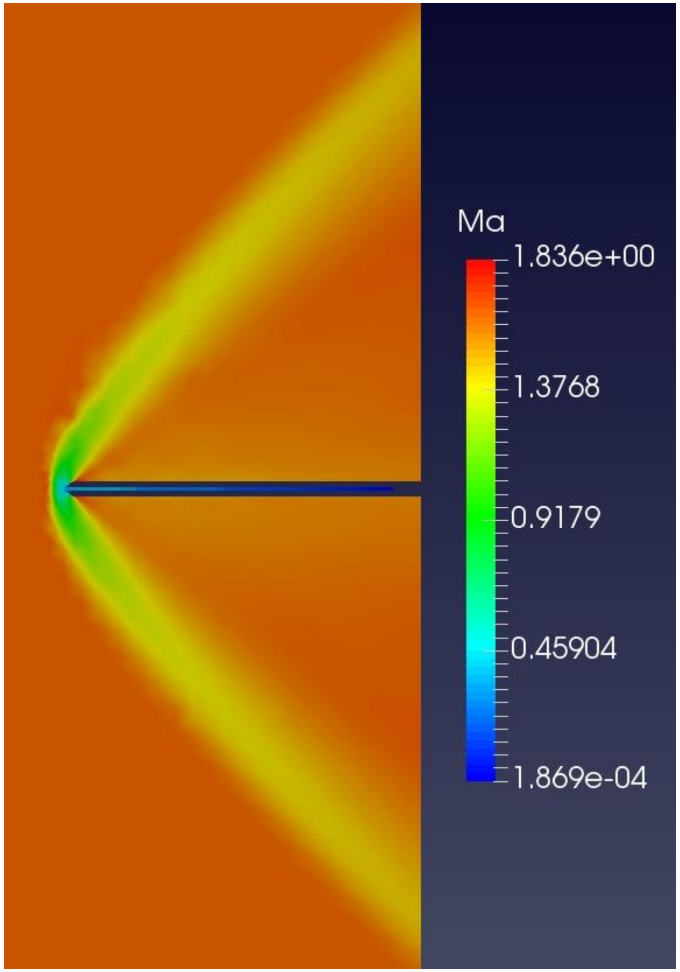

Fig 9 : Mach Number for 570 m/s