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Numerical investigation of unsteady detonation waves in combustion chamber using Shchelkin spirals

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Abstract: Pulse Detonation Engine (PDE) is considered to be a propulsive system of future air vehicles. The main objective is to minimizing the Deflagration to Detonation transition run-up distance and time by placing Shchelkin spiral with varying pitch length. Here we have considered blockage-area ratio is 0.5 as optimal value from review of previous studies. In the present study the detonation initiation and propagation is modeled numerically using commercial CFD codes GAMBIT and FLUENT. The unsteady and two-dimensional compressible Reynolds Averaged Navier-Stokes equation is used to simulate the model. Fuel-air mixture of Hydrogen-air is used for better efficiency of PDE. It is very simple straight tube with Shchelkin spirals, one of the methods which is used to initiate detonation is creation of high pressure and temperature chamber region with 0.5cm from closed end of tube where shock will generate and transition into low pressure and temperature region propagates towards end of the tube. Two different zones namely high and low pressure zones are used as interface in modeling and patching has been used to fill the zones with hydrogen and oxygen with different pressure and temperatures hence shock leads to propagate inside the combustion chamber.

Keywords: Deflagration-Detonation Transition (DDT), Shchelkin spiral geometry.

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1 Introduction: The pulse detonation engine (PDE) is a pioneering concept in propulsion system which uses continuous detonations to generate thrust or power. This PDE uses Constant volume propulsive system and it makes huge difference from many other conventional engines, which works on constant pressure process leading to various advantages in PDE. In PDE fuel is ignited as a detonation wave, which propagates through a tube having Shchelkin spirals in it. As this PDE's have a simple geometry with Shchelkin spirals in it, estimation and performance of this can be performed in Computational Fluid Dynamics (CFD) analysis. The computational studies have been processed by placing common obstacles of measured size in the detonation tube, explained in geometry section. In general having many types of obstacles but Shchelkin spiral shape has major role in the detonation tube for propagation of detonation wave.

From past researchers it has been detected that with CFD simulations, accurate and reliable solutions have been the outcome in PDE. From one end of geometry the fuel and air are injected and the other end to keep being open. At closed end fuel gets initiated and promptly transitions to a detonation, or powered shock. This shock wave which is produced near closed end propagates towards open end in very less time (micro seconds) causing detonation and in this process again repeats in multi-cycles within very less time span. Overall performance of PDE, other thrust parameters depends on the time it uses to complete each cycle.

2. Literature survey: In CHIPING LI and K. KAILASANATH "Detonation Transmission and Transition in Channels of Different Sizes" **[1]** major focus was to visualize diffraction to detonation waves in smaller to larger tubes. PDE is a new propulsive concept which uses high pressure here generated by many detonation waves which are repetitive leading to high propulsive efficiency. Three numerical simulations have been performed for 1) both small and large tubes are filled with ethylene oxygen mixture 2) ethylene – air 3) small channel is filled with energetic ethylene – oxygen mixture large channel mixed with ethylene-air mixture. Two domains are created small tube for detonation initiator and this detonation wave diffracts into large domain which represents the detonation tube in PDE.K. KAILASANATH and G. PATNAIK on performance estimates of pulsed detonation engines **[3]** done simulation on A simple tube simulated, the area integrated difference between the pressure at the closed end and ambient gives the thrust from the tube. Thrust would be also different for different cases. The time integral gives the impulse and is different for different cases.. The maximum impulse is found for gradual relaxation at exit of tube and minimum impulse found at closed end which is fast relaxation length.

4. Methodology: GAMBIT was used for geometry modeling and grid generation. Grid independency study has been carried out with increasing the number of elements. Once generating the mesh, the file was then imported into FLUENT, where the modeling equations and boundary conditions were set.

5. Geometry and grid generation: The geometry that is made inside the GAMBIT is a two dimensional geometry. We created two zones first zone is high pressure zone which is 2cm from closed end of the tube and rest of the tube is low pressure region. For the first case we created a straight tube with 3cm diameter and 54cm length, and second case for 3cm main tube diameter we added Shchelkin spiral which is 1.5cm diameter and including block area ratio is 0.5 and the spacing length is 4cm for each spiral. Similarly we have created another Shchelkin spiral tube with 2cm diameter for which we used block area diameter 1cm and spacing 4cm.

Figure (1): Straight detonation tube model.

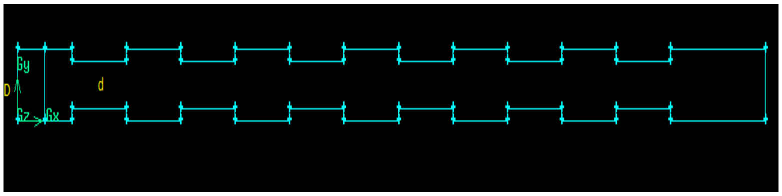


Figure (2): Shchelkin spiral attached detonation tube with 30mm diameter

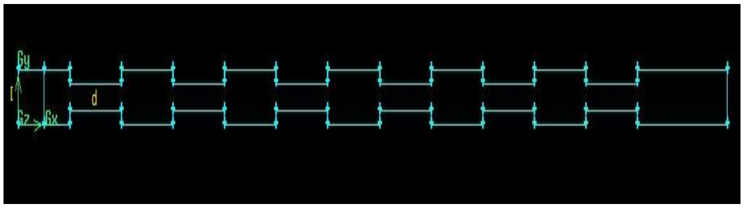


Figure (3): Shchelkin spiral attached detonation tube with 20mm diameter

Mesh also has generated in GAMBIT with help of edge, face and zones command. Here we have done grid independence study with different interval count cells. Two zones have created one high pressure zone which 2cm length in axial direction and second one low pressure zone which remain length of the tube.

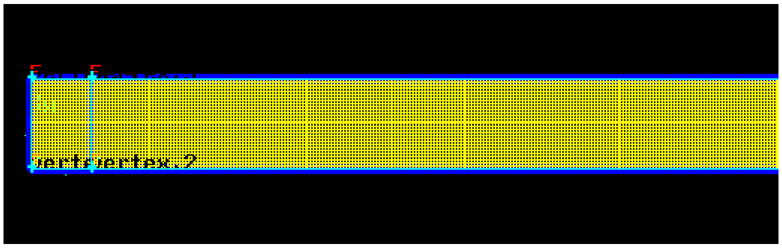


Figure (4): Mesh for straight tube

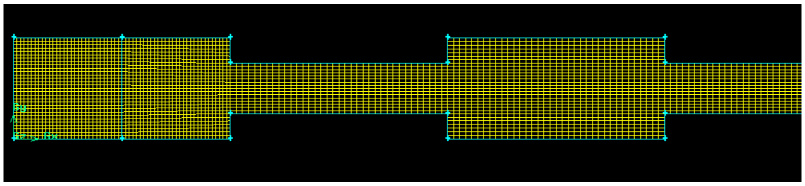


Figure (5): Mesh for 20mm diameter of Shchelkin spiral tube.

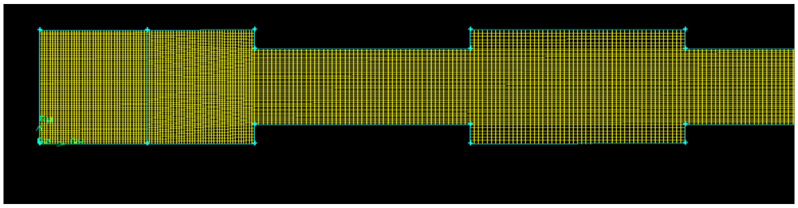


Figure (6): Mesh for 30mm diameter of Shchelkin spiral tube.

6. Numerical Simulation:

The solution of the specified geometrical model is determined from the Numerical simulation. This Numerical Simulation should be done in effectively to visualize and analyze our results. Numerical Simulation is done by using FLUENT 14.5 and animation sequence of the species transport is produced by using the FLUENT only. The various contours have plotted using this numerical simulation in FLUENT and we are going to analyze the results basing up on this simulations. These simulations are nothing but the approximate solutions for the system of equations which are the transport equations by solving the Navier-Stokes equation for the species transport.

The Problem setup will be based on the type of Detonation we are producing. For the system of patching the conditions we will use the **Density** based solver with planar model, and system is unsteady in nature so we enable the **Transient** condition. As the flow is considered to be high speed we make the system as **inviscid** flow model. So, for the flow at high speeds the heat transfer rate will be more so considering the **Energy** equation to be enable for solving the Navier-strokes equation. The fuel-air is made to enter the tube with two different inlets such that the formation of the shock will be based on the release of the energy from the chemical reactants. So, we should have to consider the volumetric combustion system as the model of species transport system. The materials will be defined basing on the fuel we are using, in this model we are going to analyze for the fuel of Hydrogen and oxygen as the oxidizer. For the volumetric combustion of fuel hydrocarbons are best suited for this type of combustions. Density based solver are mostly solved by using the ideal gas condition for defining the properties of the pressure.

7. Boundary conditions:

As discussed after setting up the problem the key factor now is to defining the Boundary conditions for a particular model. Setting the boundary conditions should be done basing on the conditions specified in problem setting up steps. Firstly, in specifying the boundary conditions the walls are considered to be adiabatic such that there will be no heat transfer through out of system or into the system and considered to be isothermal condition as temperature will be constant. So, there will be no heat flux near the walls so the wall be marked as the type wall only. The species travelling at detonation speed will be travelling throughout the length and moves towards the exit of tube with the pressure conditions to be atmospheric conditions. So, the outlet condition which is named as type pressure outlet are given with atmospheric condition 101325pa and the operating condition is termed as 0 (Zero) because of density based solver static and absolute pressure will be equal. The reference values are required to be specified because to take references for the particular flow problem such that basing on the characteristic line theories we will specify the hot zone conditions for the reference values.

8. Results and discussions:

After the Solution iteration the solution should have to analyze whether the solution is in accurate or not have to analyze. So, to analyze as we know the variation of properties across a shockwave the results are to be compared with the theoretical or the standard results by visualizing the various flow contours such as Pressure, Temperature, Velocity, Mach values.

Pressure Contours

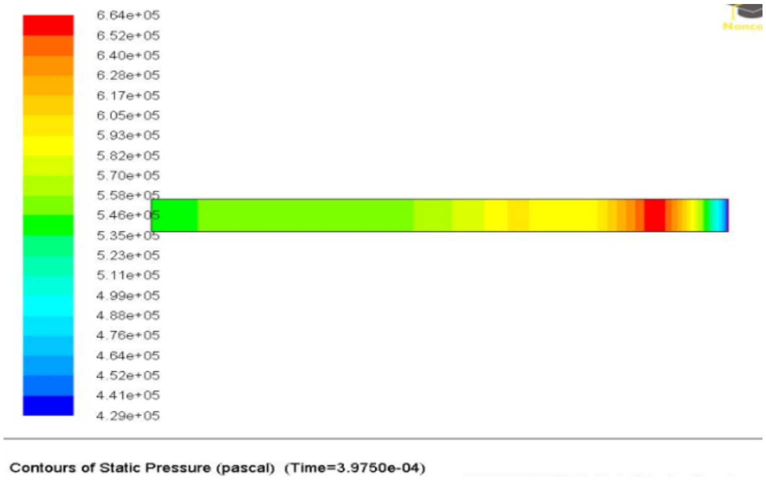


Figure (7): Pressure for straight tube.

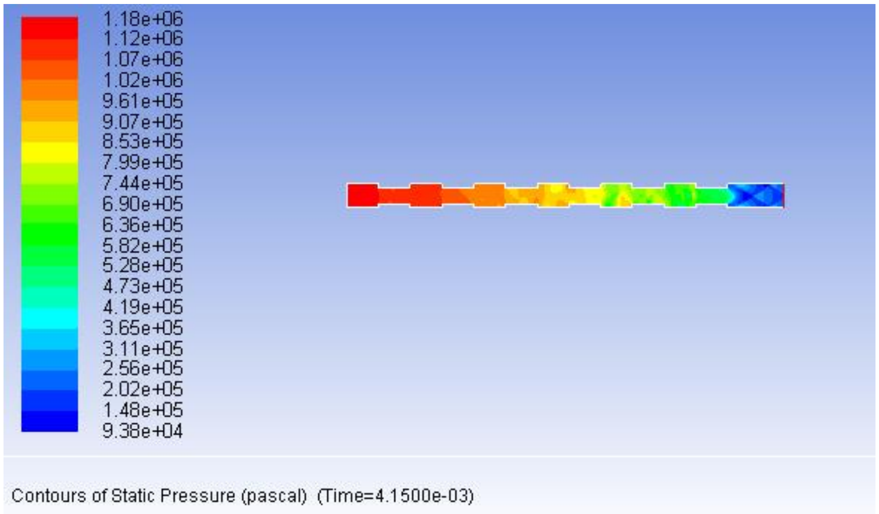


Figure (8): Pressure for 30 mm diameter Shchelkin tube.

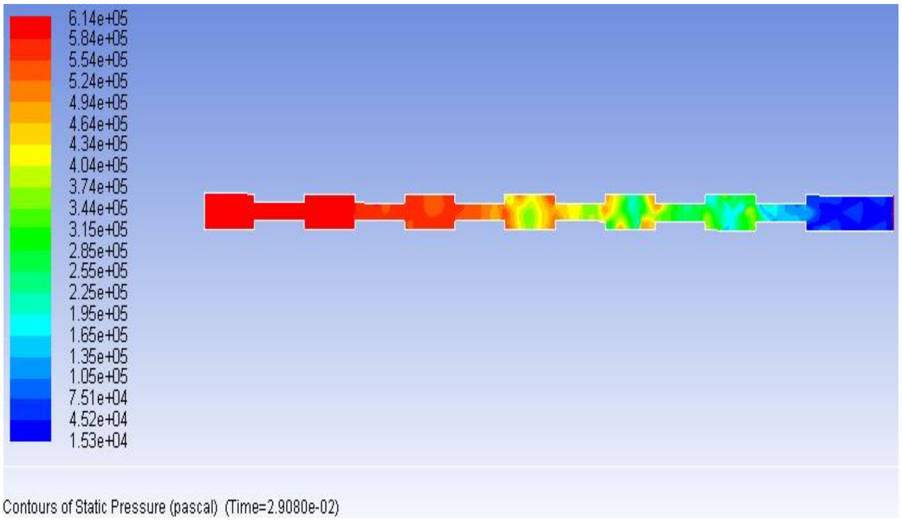


Figure (9): Pressure for 20 mm diameter Shchelkin tube.

The above pressure contours shows the variation of pressure inside the tube with respect to the flow time and the distance of the tube. The maximum value of pressure can be obtained at the end of time step 6.0050e-^{04}s is 8.65e^{+05} Pa for Shchelkin spiral tube with 2cm diameter. From the above the variation of pressure inside the flow has observed with the rarefaction waves which are formed inside the tube which are low relative pressure with respect to the shocks. The effect of using spiral inside detonation tube showed greatest potential in increasing the pressure. High-pressure region at the head end of the tube with combustion products corresponding to CJ condition considered as initial condition. Shock wave which is generated at closed end is coupled with reactants which move the detonation wave towards open end. The energy releases through pressure waves will fluctuate in all directions.

Temperature Contours

The maximum temperature is 3930K rose for Shchelkin spiral tube with 2cm diameter which is 4% more than the straight tube. Expansion waves generated as detonation wave propagating towards open end while transition from head end to open end. Similarly as pressure fluctuations temperature also follows same pattern.

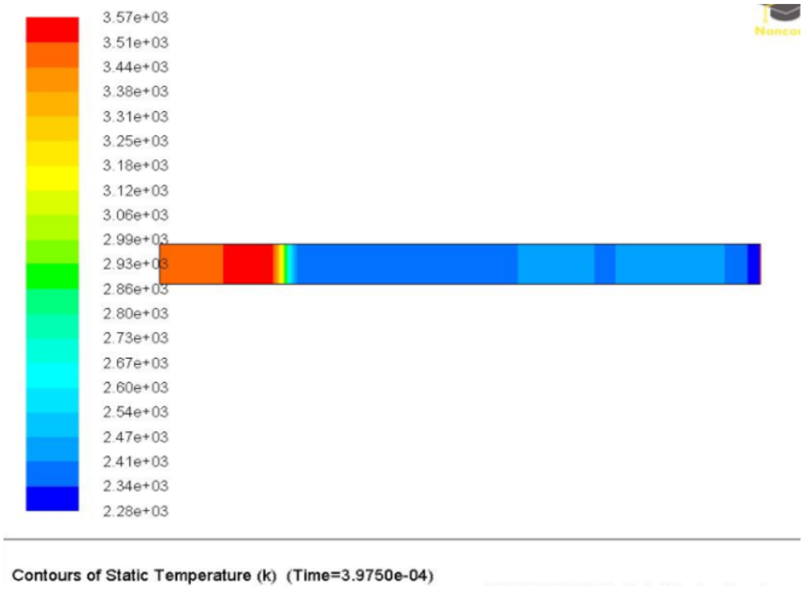


Figure (10): Temperature for straight tube.

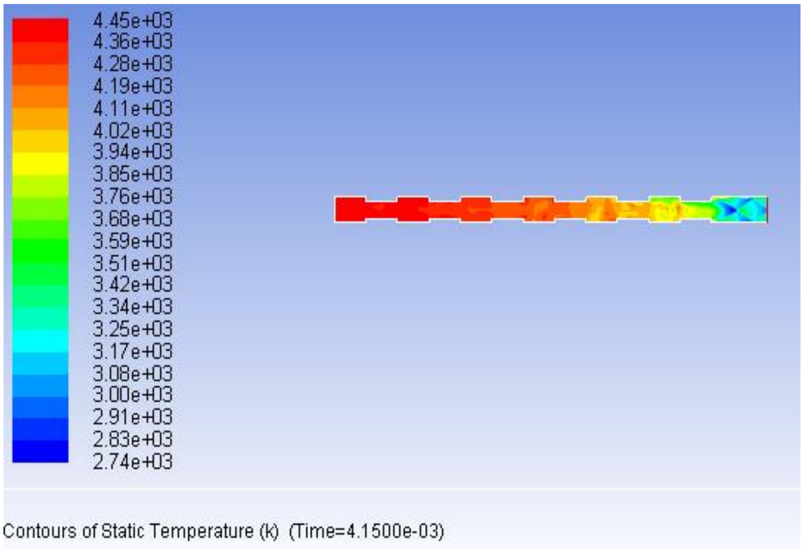


Figure (11): Temperature for 30mm Shchelkin tube.

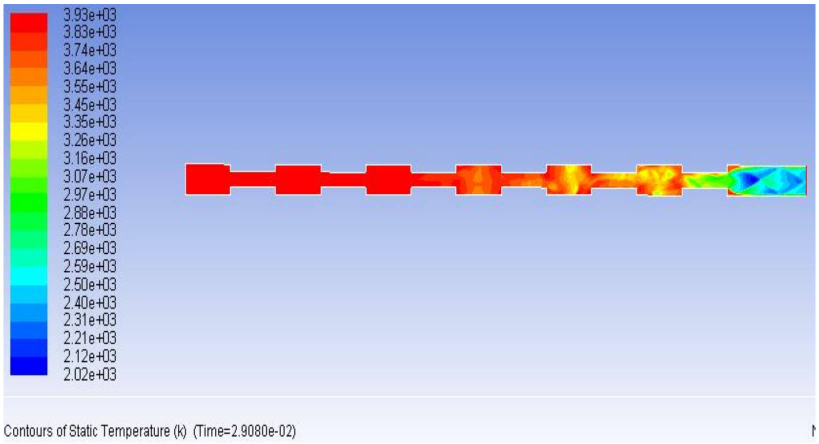


Figure (12): Temperature for 20mm Shchelkin tube.

Velocity Contours

From the velocity contours we can observe the maximum velocity attained for 20mmdiameter Shchelkin spiral detonation tube. We can say that velocity getting increased based on constant volume or decrement in volume. Here Shchelkin spiral detonation tube with diameter 2cm showed 2503m/s which is3times more than the straight tube without spiral.

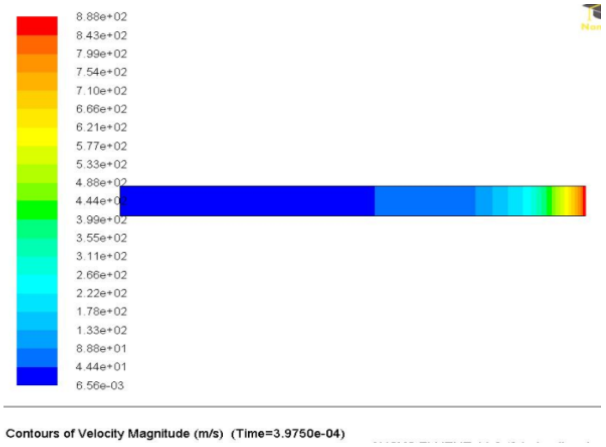


Figure (13): Velocity contour for straight tube.

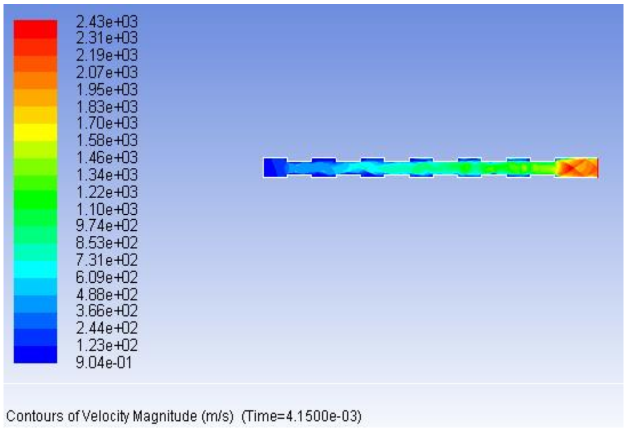


Figure (14): Velocity for 30mm diameter Shchelkin tube.

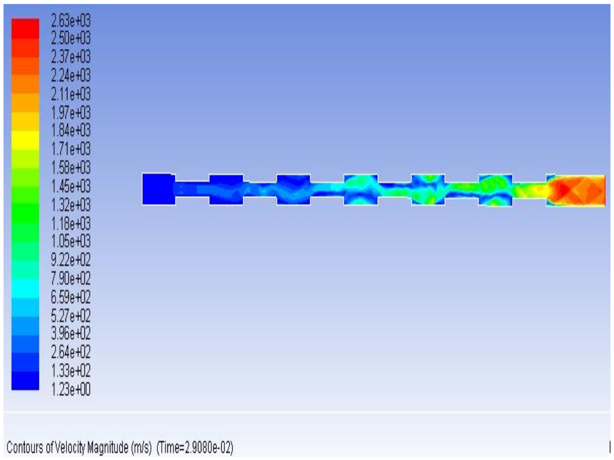


Figure (15): Velocity for 20mm diameter Shchelkin tube.

9. Pressure X-Y Plot

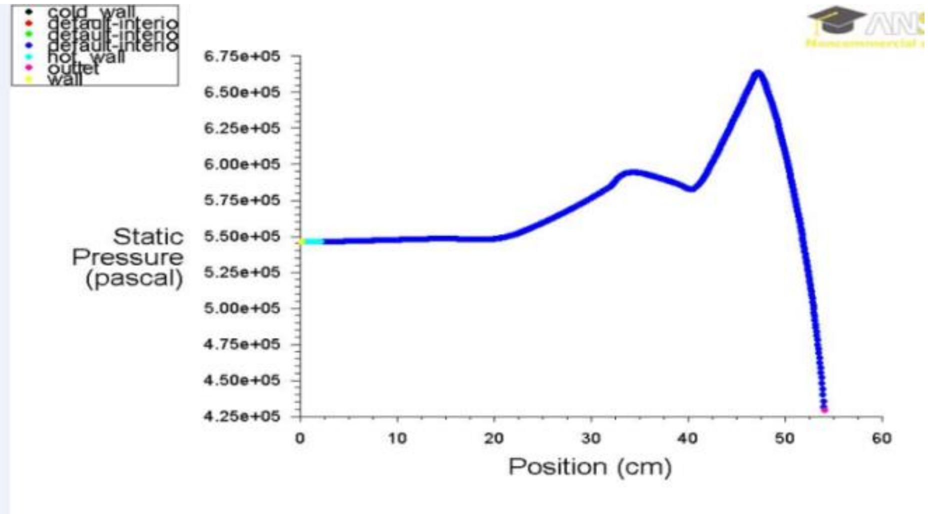


Figure (16): Straight tube pressure X-Y plot.

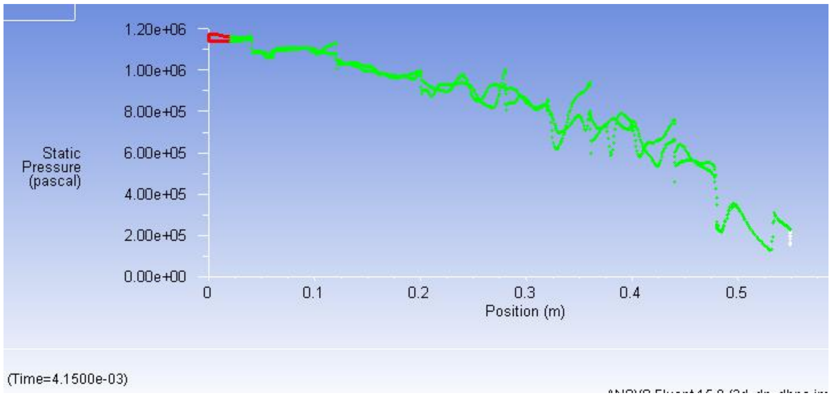


Figure (17): X-Y pressure plot for 30mm diameter Shchelkin tube.

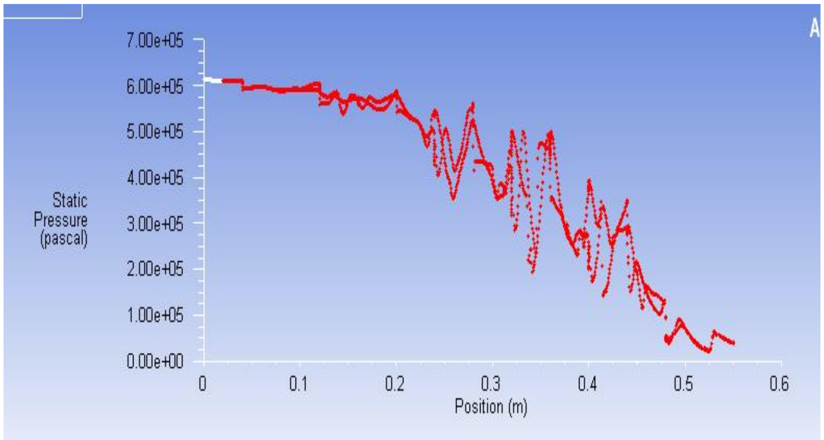


Figure (18): X-Y pressure plot for 20 mm diameter Shchelkin tube.

Considering the ambient value at outlet pressure is important boundary condition. The pressure inside the tube is suddenly raised high value when detonation passes at the exit. This leads to greatest lost in pressure at the exit of the tube since flow agrees well with ambient value. The pressure at the closed end reaches with ambient value because of high velocities.

Table (1): Performance comparison for all detonation tubes.

TUBE	P (Pa)	V (m/s)	Mach	T (K)	FLOW TIME (m/s)
Straight Tube	6.64e+05	888	0.86	3573	3.97e-04
Spherical tube (30mm diameter)	9.83e+05	2310	2.13	4323	4e-03
Spherical tube 20mm diameter	11.8e+05	2503	2.56	4583	2.2e-02

10. Velocity X-Y Plot

Considering the ambient value at outlet pressure is important boundary condition. The pressure inside the tube is suddenly raised high value when detonation passes at the exit. This leads to greatest lost in pressure at the exit of the tube since flow agrees well with ambient value. The pressure at the closed end reaches with ambient value because of high velocities

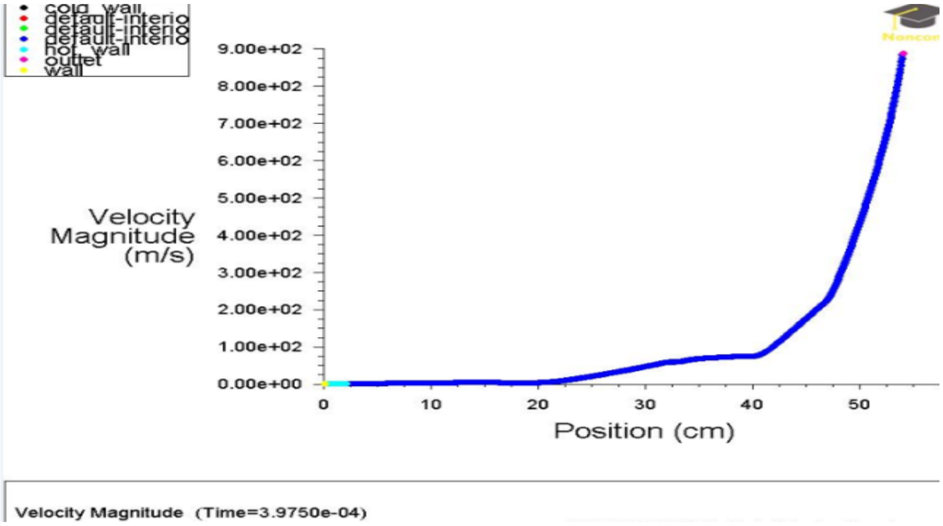


Figure (19): Straight tube velocity X-Y plot.

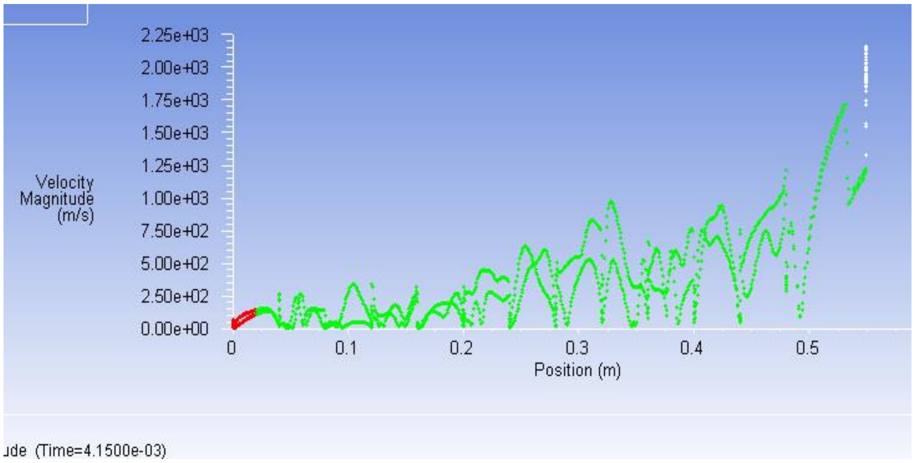


Figure (18): X-Y velocity plot for 30mm diameter Shchelkin tube.

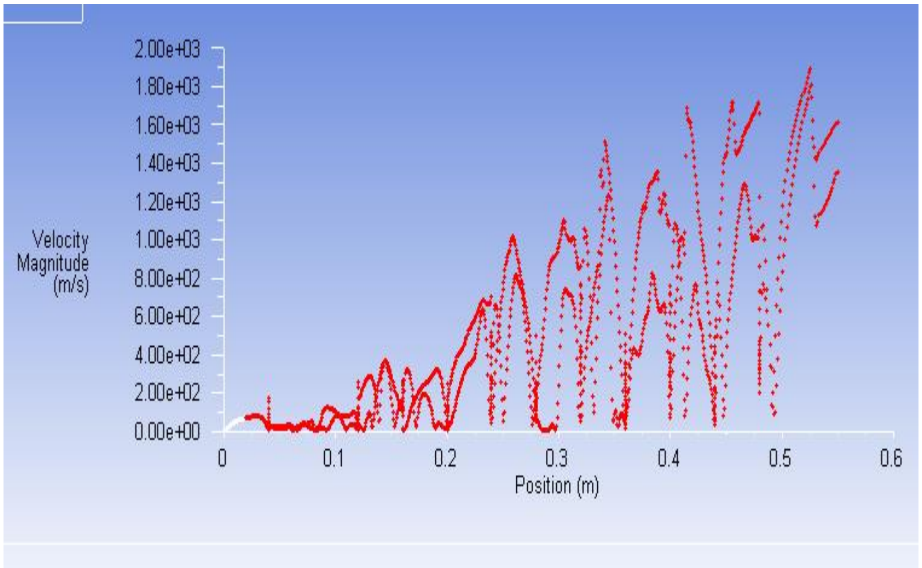
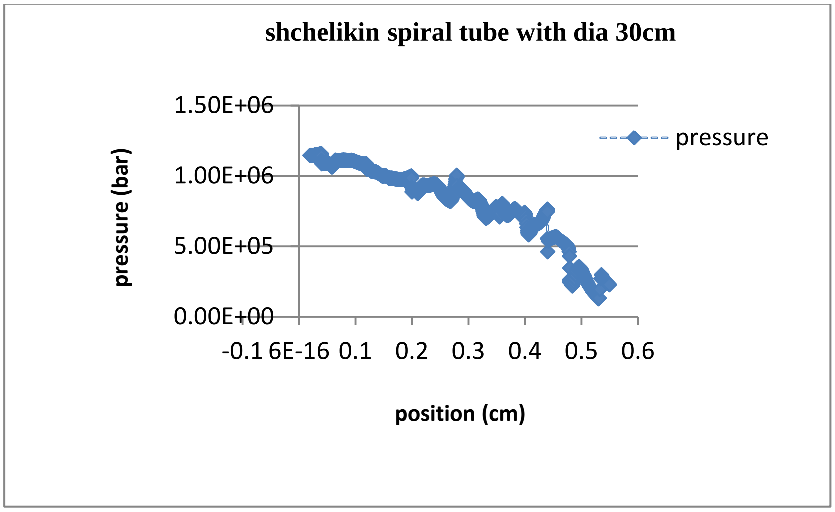


Figure (19): X-Y velocity plot for 20mm diameter Shchelkin tube.

Because of the significant differences in pressure histories observed from pressure plots the thrust also would be different for different for different cases. The maximum impulse attained at the exit of the tube as larger relaxation length. . The pressure inside the tube is suddenly raised high value when detonation passes at the exit. This leads to greatest lost in pressure at the exit of the tube since flow agrees well with ambient value. The pressure at the closed end reaches with ambient value because of high velocities.

11. Solver Validation

Solver validation is done for the simple straight tube numerically with the reference **[3].** The values for straight tube as obtained from X-Y plot of pressure and temperature have shown decent increment in comparison of **[3]**. The velocity and Mach values for regular Shchelkin spirals also compared with **[1]**. Beside the validation, grid independency study also carried out. The increased in number of grids have not shown any variation in results.



12. Conclussions

Numerical simulations have been carried out for straight tube, Shchelkin spiral tube with 30mm and 20mm main tube diameters respectively. We can see the potential of placing Shchelkin spiral from velocity and Mach values which are nearly 3times more than the straight tube. It also has shown favorable to achieve fast detonation. Considering the volume of the tube as important parameter we can say 30mm diameter with Shchelkin spiral is optimal where it achieved nearly pressure 10bar.

13. References

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