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Research paper

Computational Study on Effect of Obstacles in Pulse Detonation Engine

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Abstract

Deflagration to Detonation transition is an important factor in the operation of pulse detonation engine which is basically working on the constant volume cycle. Insertion of obstacles decreases the DDT length. Hydrogen and the oxygen-enriched air was used as fuel and oxidizer respectively. The Purge gas is not required used. K-Ɛ turbulence model is being used for the simulation and for combustion species transport model is being used. Effect of blockage ratio and obstacle spacing is also discussed. A blockage ratio of 0.5 is considered for the Shchelkin spiral. Temperature profile, flame propagation velocity and average peak pressure variation are discussed. Two-dimensional geometry and Shchelkin shape of obstacles are being considered. The comparison is done between straight tube and tube with obstacles. Numerical simulation is done and the results are being compared with those obtained through experimental investigation.

Keywords*: Blockage ratio; Deflagration to Detonation; Flame acceleration; Obstacles; Pulse detonation engine.*

1. Introduction

The Pulse detonation engine has become an important topic over the past few decades as its efficiency is nearly 15% more than that rocket engine. The PDE operates up to Mach 7 i.e. it has the capability of operating both in supersonic and hypersonic range. Also, the specific impulse of pulse detonation engine is greater than that of ramjets, scramjets and other engines. A pulse detonation engine basically works on the constant volume cycle and is different from other as it utilizes unsteady operation. Also, the combustion process which is being used is different from other engines as it uses detonation for combustion which in turn requires very less amount of pressure (200 pounds/inch^2) at the injection of fuel as the mode of operation is pulsed.

Normally a basic pulse detonation engine works on the following process: 1) first detonation tube is filled with fuel and oxidizer mixture in the proper equivalence ratio; 2) mixture is ignited with the spark plug at one end; 3) waves generated through ignition are converted from deflagration to detonation waves; 4) these detonation waves travel towards other end and combustion exhaust occurs through blowdown process; 5) purge gas is used for removing the unwanted wastes and also helps in preventing pre-ignition for next cycle.

The use of obstacles in the detonation tube increases the efficiency of pulse detonation engine. Zhang et al. [1] studied the effect of obstacles in detonation tube filled with methane-oxygen mixture. Results show that flow instability was generated which effects the detonation transmission as obstacles were generating large perturbations. It was due to increase in flame surface area and transport of energy and local mass thus increasing burning rate. Effect of the Shchelkin spiral with different degree of roughness was also examined. Valiev et al. [2] observed the flame acceleration in DDT transition of pulse detonation engine. The result showed that obstacles generate stronger turbulence which increases burning rate and hence facilitates flame acceleration. It was also found that axisymmetric obstacle is nearly twice as efficient as planar obstacles. Obstacles having blockage ratio between ¼ and ¾ are found to be causing maximum flame acceleration. Also inserting obstacle is beneficial only when the distance between obstacles is larger than obstacle size. Flame velocity was also found to be increasing with increase in number of obstacles. Sarli et al. [3] used large eddy simulation for analyzing the effect of obstacles on gas explosions with varying blockage ratio. It was observed that sharp–edged obstacles (square, rectangle, diamonds and triangle) were giving more intense flame accelerations than round shaped obstacles (cylinders). Zhang et al. [4] studied the effect of spiral obstacles in the hydrogen-air mixture on the propagation of detonation. Results showed that at the pressure of 10KPa spiral obstacles with roughness 0.4 helps in detonation but as roughness increases to 0.625 detonation quenches. Also, it was observed that turbulence is necessary for increasing the surface area which in turn will help in increasing the detonation rate. Marsi et al. [5] through their research on premixed flame propagation over a different type of obstructions found that volume of the trapped unburned mixture is found to be high when the triangular and square shape of obstacles are being used, while rectangular and circular cross section obstacles have respectively low amount of trapped gas. Also, it was found that flame propagates in the form of hemisphere regardless of the shape of obstacles being used. In rectangular obstacle, flame speed is more as compared to circular and triangular and it increases with increase in blockage ratio. Chen et al. [6] studied the impact of plate slits on the flame acceleration of methane and air premixed mixture and results show that triangular hollow –square plate was giving highest turbulence, flame propagation velocity and explosion overpressure. The above parameters were followed by the hollow square thin plate and circular hollow square plate. Maximum jet flame length decreases with increasing number of slit. Ciccarelli et al. [7] investigated the effect of obstacles size and their spacing on flame acceleration. The result showed that rapid flame acceleration was observed when the ratio of 5 was between spacing and obstacle height. Also, the recirculation zone should be nearly around spacing between the plates. Sorin et al. [8] through their work on optimization of deflagration to detonation transition by reduction of transition time and length observed that direct initiation using high energy initiators were producing detonation waves. Also, orifice plates with different sizes and geometries with blockage ratio between 0.54 and 0.98 were analyzed for the effect. Copper et al. [9] analyzed detonation to deflagration in the closed tube using ballistic pendulum arrangement. The result was with 15% error when compared with the experimental result for internal obstacles on DDT transition. Also, they studied the effect of these obstacles on flame acceleration. Li et al. [10] analyzed effect of detonation area of initiation in DDT chamber. The experiment was performed in detonation tube which was closed at one end and open at the other side. Studies were done for spiral internal grooves like semicircle, square and inversed triangle groove and these were found to enhance DDT transition. Asato et al. [11] studied flame propagation, Shchelkin spiral dimension in flow vortex on deflagration to detonation transition characteristics and as well as rotating velocity. The result showed that deflagration to detonation transition distance in the vortex flows is shortened by 50-57% using Shchelkin spiral. Newet al. [12] studied multi-tube pulse detonation engine having Shchelkin spiral. The effectiveness was studied using propane-oxygen mixture at low energy sourced of ignition. Also, various configurations of blockage ratio along with different length to diameter ratio was studied and it was found that shorter length and highest blockage ratio was successful. Johansen et al. [13] studied the development of unburnt gas flow field for different obstacle height as the blockage ratio of obstacle were changing. Results showed that production of turbulence increases with increase in the number of blockages. Rudy et al. [14] investigated flame acceleration in the channel which is obstructed by obstacles. The study was done using hydrogen-air mixtures in obstacle channel using profiles for pressure, velocity for waves and it was observed that blockage ratio and spacing of the obstacle were significantly affecting the detonation wave. Craig et al. [15] analyzed the effect of blockage ratio of an obstacle on unburnt gas flow with obstacle height. Also, the flame acceleration was examined with the variation of blockage ratio in the obstructed channel of a square shape. The result shows the blockage ratio increases, flame acceleration also increases. Teodorczyk [16] studied flame travel in different channel heights of 0.01, 0.02, 0.04 and 0.08m. Flame propagation velocity in channels with obstacle was analyzed. Results showed that DDT transition increases with obstacles.

The purpose of the present study is to study the temperature contours along the length of detonation tube for a hydrogen-air mixture. Also, the contours of the pressure profile as well as the flame velocity propagation along the detonation tube are being analyzed. Results are being compared with the experimental result and effect of blockage ratio of the obstacle is also been shown. Different type of fuel is being analyzed with the different air-fuel mixture. CFD analysis is done for the present work for analyzing the comparison between different geometry.

2. Problem Statement

In this simulation, we used the hydrogen-air mixture in the combustion chamber which consisted of Shchelkin obstacle. Purge gas (Nitrogen) is not being used. The entire tube is closed and the walls on the inner side are smooth leaving the obstacle section. Two-dimensional geometry is used. The following size of detonation tube was being used:

Diameter of the detonation tube (D) = 3cm
Length of the detonation tube (L) = 52cm
Obstacle width = 4cm
Obstacle spacing (Z) = 4cm
Obstacle blockage ratio (α) =0.5 (1/2 of Radius)

The amount of energy required for combustion decreases by DDT transition process which involves use of the obstacles.

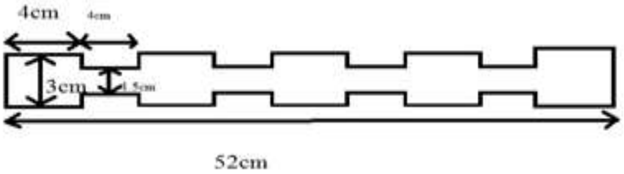

Fig.1:. Schematic diagram of pulse detonation engine

3. Mathematical Model

3.1. Equations and Other Relations

Numerical investigations were performed using the system of equations for the deflagration to detonation transition process. The modified k-ε turbulence model was used. For the combustion process, the species transport model is used. The gas dynamic model consists of the mass balance of components, momentum balance and energy balance. In addition to this species transport equation is also used.

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

Navier-Stokes equation: -
x- momentum equation

$$\rho\left[u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right]=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

y- momentum equation

$$\rho\left[u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right]=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

Energy equation

(4)

Species transport equation

$$\frac{\partial}{\partial t}(\rho Y_{\mathrm{i}}) + \nabla.(\rho\vec{v}Y_{\mathrm{i}}) = -\nabla.\vec{J}_{\mathrm{i}}+ \mathrm{R}_{\mathrm{i}} + \mathrm{S}_{\mathrm{i}} \tag{5}$$

Here u, v is the component of velocity in x and y-direction respectively, ρ is density of the species, p is pressure, ʋ is kinematic viscosity, t is temperature, α is thermal diffusivity, c_p is specific heat at constant pressure, γ is specific heat ratio, Y_i is local mass fraction, J_i is diffusion flux, R_i is rate of production of species, S_i is source term.

Turbulence model includes two equations one for turbulent kinetic energy and other for turbulent dissipation rate of kinetic energy respectively. The equations are as follows-

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho kui)}{\partial xi}=\frac{\partial}{\partial xj}\left[\frac{\mu t}{\sigma k}\frac{\partial k}{\partial xj}\right]+2\mu tEijEij-\rho\in \tag{6}$$

$$\frac{\partial(\rho\in)}{\partial t}+\frac{\partial(\rho\in ui)}{\partial xi}=\frac{\partial}{\partial xj}\left[\frac{\mu t}{\sigma\in}\frac{\partial\in}{\partial xj}\right]+C\in\frac{\in}{k}2\mu tEijEij-C2\in\rho\frac{\in 2}{k} \quad (7)$$

k is kinetic energy, μ_t is turbulent viscosity of the mixture, E is energy, C_1 and C_2 are constants and ε is turbulent dissipation rate of kinetic energy. Eddy dissipation model is used as in this reaction rates are controlled by turbulence and hence Arrhenius chemical kinetics is ignored.

The chemical reaction equation between hydrogen-air helps in determining the correct air-fuel ratio for the combustion process to take place.

3.2. Geometry and Mesh Generation

Computational simulation has now become an important part of the research as one can first test a simulation model and then implement the same technique in experimental field of research. In this research, a 2-D model of the pulse detonation engine with and without Shchelkin obstacles is being considered. The length of the detonation tube is 52cm and diameter 3cm. The geometry as well as meshing both are done on ANSYS14.0. The blockage ratio used is 0.5 for the Shchelkin spiral. Blockage ratio is the ratio of obstacle height to the diameter of the tube.

Fig.2:. Geometry for straight detonation tube without obstacles

Fig.3.: Geometry for detonation tube of 0.5 blockage ratio with Shchelkin spiral obstacles

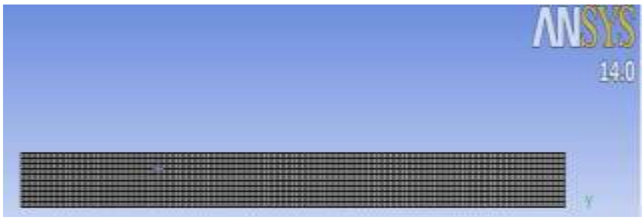

Fig.4:. Mesh for straight detonation tube without obstacles

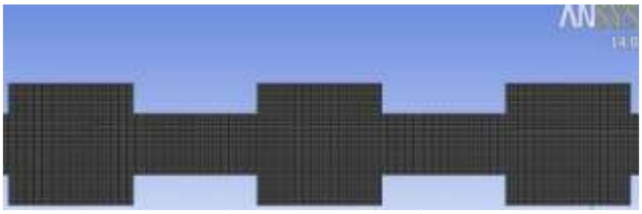

Fig.5:. Mesh generation for detonation tube of 0.5 blockage ratio with Shchelkin spiral obstacles

4. Numerical Simulation

Numerical simulation is done on ANSYS 14.0. The density-based model is used for the incompressible gas. The transient model is used for the analysis as detonation phenomenon is an unsteady process. Also, planar type of geometry is used. As we are using inviscid mode, therefore, heat transfer will be more and hence energy equation is considered. Fuel-air mixture i.e. hydrogen-oxygen enrich mixture is injected through two different inlets such that these two mixes properly and the chemical reaction takes place. So, for the species transport model volumetric criteria is considered. Also for the density based solver, we have to use ideal gas condition. Second order upwind scheme is used to get the better convergence. Reference values are needed to be specified and for initialization, we are using standard initialization technique.

4.1. Boundary Conditions and Assumptions

Boundary conditions need to be specified properly because they are the most important step in getting the proper result. The following boundary conditions are being implemented while performing the simulation. No slip boundary condition at the tube wall i.e. n.u = 0. At the tube wall, adiabatic condition is to be assumed i.e. $n.\nabla T=0$. So there will be no heat flux. At the end, non-reflecting boundary condition is used i.e. primary wave direction is normal to the boundary. Operating condition is zero because of density based solver static and absolute pressure will be equal. At the exit, pressure outlet is atmospheric. At inlet, mass flow rate and pressure of oxidizer and that of fuel are specified. Also, the values of turbulent kinetic energy and turbulent dissipation rate are needed to be specified.

5. Results and Discussions

After the numerical simulation is done, when the iteration is completed for the given time step various contours were plotted to analyze whether the results were within the accepted range. For this various contour have been plotted for the straight as well as the tube having Shchelkin spiral obstacles. These contours included pressure, velocity and temperature plots. After getting these contours, graphs have been plotted for pressure as well as velocity to study the variation with those from the experimental results.

5.1. Pressure Contours

The below contours of pressure are showing the pressure variation inside the detonation tube with respect to time for flow and the distance of the detonation tube. The maximum pressure is obtained for the tube having Shchelkin spiral with blockage ratio of 0.5 and tube diameter of 3cm i.e. more than the tube having no obstacles. The value of maximum pressure obtained for the tube is 2.1e+06 Pa for obstacle-laden tube at the end of the flow time. Thus, the use of obstacle shows great potential in increasing the pressure. The region of high pressure at heat end with products of combustion corresponding to Chapman-Jouguet condition which is the required for the detonation processes to occur. The shock wave generated is coupled with reactants which propagate the detonation wave towards the open end. Fig.6 and Fig.7 show the variation of pressure in the detonation tube without and with obstacles respectively.

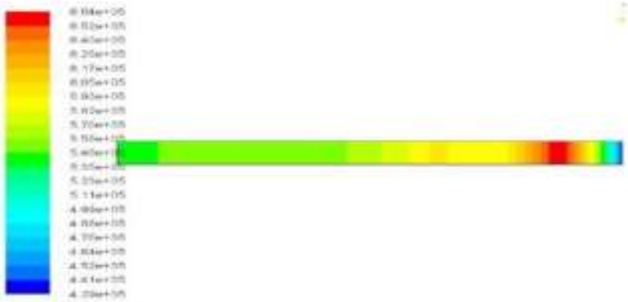

Fig.6:. Pressure contour for straight detonation tube

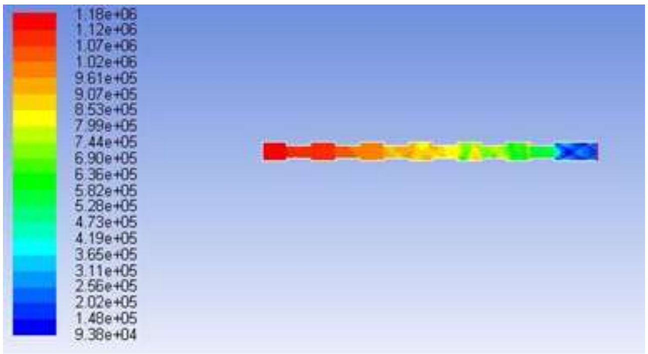

Fig.7:. Pressure contour for detonation tube of 0.5 blockage ratio with Shchelkin spiral

5.2. Velocity Contours

The velocity contours below are showing the variation of velocity along the length of detonation tube. Maximum velocity is observed for the tube having Shchelkin spiral as these will increases the turbulence in the tube. Velocity increases with increase in the number of obstacles. Velocity reaches a maximum value of 2401m/s for obstacle-laden tube. Thus, flame propagation velocity increases drastically with the insertion of obstacles because without obstacle the velocity was 873m/s.

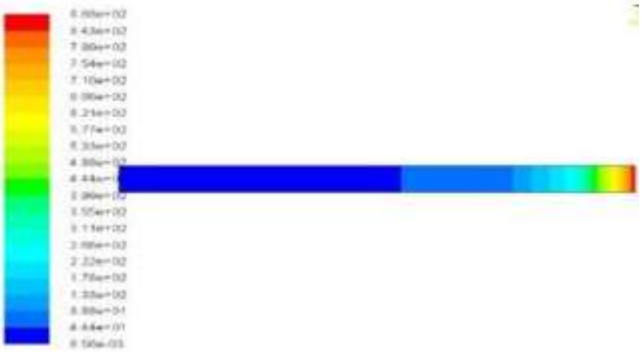

Fig.8:. Velocity contour for straight detonation tube

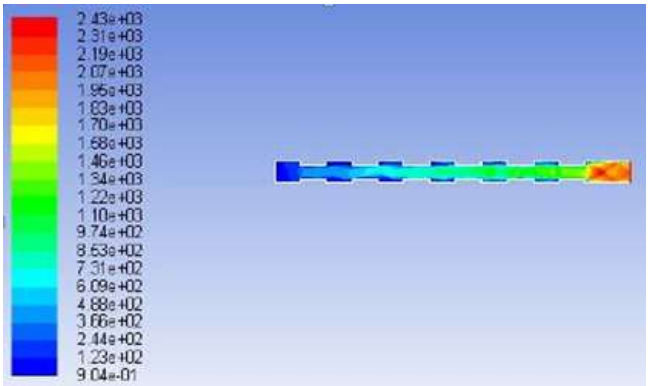

Fig.9:. Velocity contour for detonation tube of 0.5 blockage ratio with Shchelkin spiral

5.3. Temperature Contours

From the below temperature contours, it is found out that maximum temperature of 4407 K was when the Shchelkin spiral was being used. Maximum temperature was found near the obstacles. Contour of straight tube shows temperature of 3542 K. Temperature is found to be maximum for the tube at the staring end and it starts to gradually decrease with the increases in length of the tube.

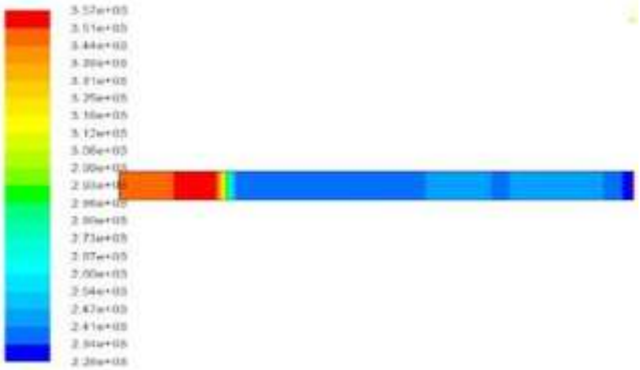

Fig.10:. Temperature contour for straight detonation tube

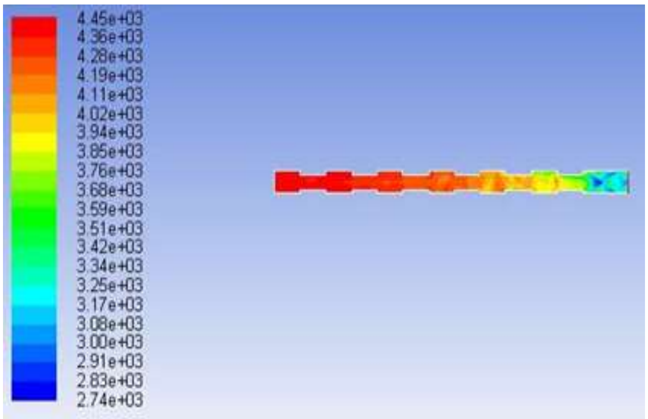

Fig.11:. Temperature contour detonation tube of 0.5 blockage ratio with Shchelkin spiral

5.4. Pressure Plots

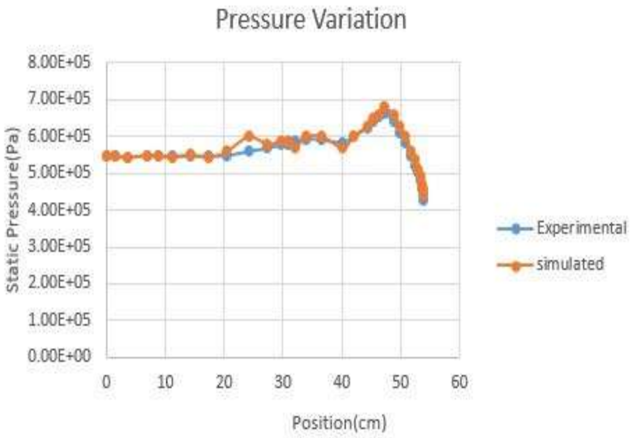

Fig.12:. Pressure vs. Position variation plot for Straight tube

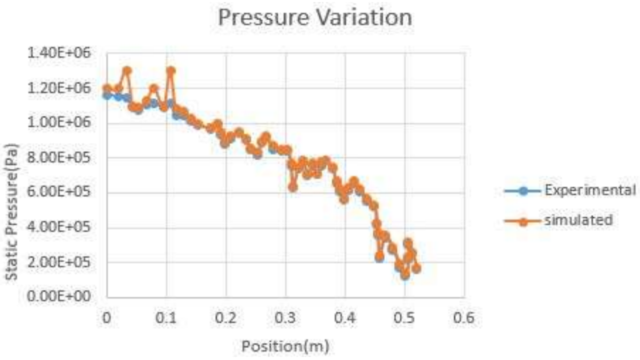

Fig.13:. Pressure vs. Position variation plot for Shchelkin spiral tube

5.5. Velocity Plots

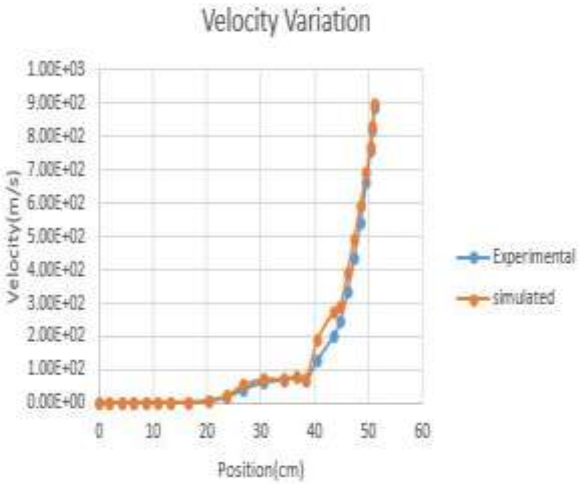

Fig.14.: Velocity vs. Position variation plot for Straight tube

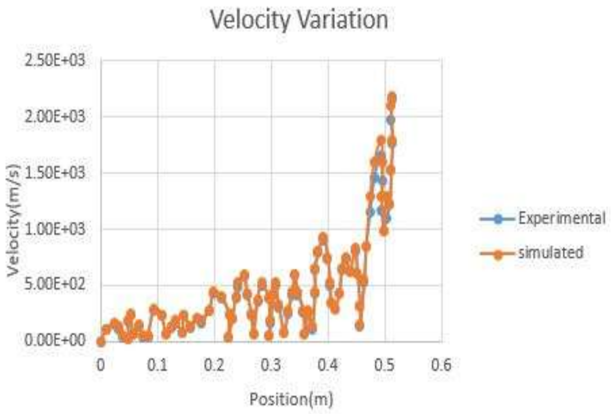

Fig.15:. Velocity vs. Position variation plot for Shchelkin spiral tube

The above pressure and velocity plots are for detonation tube with and without obstacles. From the Fig.12 i.e. pressure vs. position variation for a straight tube, the error obtained between experimental and simulated result is 2.26% while for the Fig.13 the error obtained is 4.26%. Similarly, the error is calculated for the velocity variation and the error obtained is 12.60% (Fig.14) for the straight tube and 5.64% (Fig.15) for the Shchelkin spiral tube. The simulated value is found to have increment with respect to experimental results [17].

6. Conclusion

Through numerical simulation of the straight tube without having obstacles and tube with obstacles, it is found that Shchelkin spiral was found to increase the efficiency of the pulse detonation engine as compared to that of the normal pulse detonation engine without the obstacles. The blockage ratio is an important parameter which affects the performance. Also, obstacle spacing is an important parameter. Velocity obtained with use of Shchelkin spiral is nearly 3 times that obtained from the tube without having obstacles. Also, the maximum pressure obtained is more in Shchelkin spiral laden tube. Thus, it is found that obstacles were increasing the deflagration to detonation transition faster which in turn increases the efficiency of pulse detonation engine.

7. Future Scope

Simulations can be carried out for different air-fuel ratio. Also, different blockage ratio can be considered. In place of the hydrogen-air mixture, propane-air and acetylene air mixture can be used.

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