Carbon – Science and Technology

ISSN 0974 – 0546

http://www.applied-science-innovations.com

RESEARCH ARTICLE Received:10/03/2016, Accepted:15/04/2016

Effect of pre-combustion characteristics in pulse detonation engine using shchelkin spiral

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Abstract: Pulse detonation engines are the modern propulsive device which provides high thrust. They are unsteady propulsive devices which has multi cycle operations in it. In this multi cycle process for every cycle fuel and air are initiated and a shock wave is generated in combustion chamber in form of deflagration. Combustion chamber is maintained with high pressure and high temperature which leads to combustion of reactants. This deflagration transmits to detonation with high velocity and increasing Mach number. Deflagration propagates forward by taking all unburned species and products formed after combustion. Propagation of Deflagration – Detonation Transition (DDT) shock wave studies is a pioneering research concept. In the present study, simulation of PDE with Shchelkin spiral geometry is considered with two mass flow inlets has been used in which one is for fuel inlet and other for oxidizer. Geometry and meshing has been done in Gambit. Fuel used is gaseous fuel hydrogen and oxidizer is air mixture of O_2, N_2 work has been performed for different mass flow rates of fuel and oxidizer. Energy equation, Species transport equation to be solved in Fluent. Comparison results of DDT in parameters of mach number, velocity, pressure and temperatures depending on different time steps have been observed.

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

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1 Introduction: Pulse Detonation Engine is advanced technology playing a vital role in combustion engines. It majorly works depending on its performance estimates and considering its thrust outcome. In past decades this technology is getting a pioneering advance in its developments. Few experimental investigations performed for a straight tube and detonation tube with obstacles by past researchers. In this PDE the research of propulsion concept in Deflagration to Detonation (DDT) is considered depending on its wave running length and all other parameters **[1]**. This chemical propulsive system in PDE leads in greater efficiency than compared with other convectional engines. Constant volume combustion is employed in Pulse Detonation Engines which leads in Deflagration Detonation Transition (DDT).This PDE has high propulsive efficiency in outcomes of thrust as this is the main area of research in developments of this engine. In this process of direct initiation of Species into the detonation tube high energy is needed and proper mixtures of fuel and oxidizer is needed **[5]**. These obstacles in detonation tube leads to change in its volume of tube. In this research article, PDE schematic study operating for hydrogen/air as fuel and oxidizer is provided in a wide range for its performance level and thrust generation. Pre combustion characteristics in PDE for hydrogen/air mixture in terms of pressure, Mach and other various parameters are discussed. Computational studies in operating PDE have been performed for different mass fuel inlets of fuel and oxidizer are considered for simulating PDE in commercial software's. An obstacle in detonation tube occurs in various types but the shchelkin spiral obstacles are considered to be best flame acceleration in detonation tube due to its volume deflections. Fast DDT is possible in the obstructed detonation tube as velocity propagates faster **[4]**. Shchelkin spiral blockage ratio of a nominal value leads to decrease in volume sections and fast transmission of shock wave in detonation tube. The effect of pressure drop and increase in Mach number depends on the propulsive system in detonation tube **[3]**. Detonation waves will be used to combust the air fuel mixture in propulsive system of PDE. The propulsive system of PDE operates from sub sonic speeds at closed ends to hyper sonic speeds at open right end of the detonation tube. A high energy at the closed ends is used to ignite the air fuel mixture of deflagration which accelerates towards the open end of the tube leading to detonation. Here design of Shchelkin spiral in the detonation tube leads to creation of eddies which further processes moving of detonation wave with faster acceleration major part of researches going on deflagration to detonation transition at high speed reigns.

2. Chaplam - Jouguet velocity:

CJ velocity is defined as the velocity at which the detonation wave propagates when it reaches to sonic velocity of reacting gases. The CJ velocities of air/fuel mixture in the detonation tube ranges between 1400 - 1800 m/sec. This propagation of detonation wave of CJ velocities reaches to sonic velocities towards the open end of detonation tube **[7]**.

3. Literature survey:

P. Srihari "Numerical study of pulse detonation engine with one step overall reaction model", this paper presents the basic transient study of compressible, pulse detonation engine with over all reaction model of one step. The study proves reduction of complexity in computational detonation simulations. In this paper work a primary one step chemical reaction model is developed used for ethylene air stoichiometric mixture. The parameters like CJ detonation velocity, head wall pressure are also understandable with the influence of grid sizes in grid independence study for the simulations **[3]**. All the thermo dynamic properties and different mass fractions were calculated theoretically from the chemical equilibrium code by NASA. For the prediction of detonation CJ velocity and wave front profile with accuracy over all one step reaction models is utilized and validations of the numerical studies have been compared with published literatures previously. The theoretical CJ velocities obtained in this work performed is 1823.7 m/sec. all the simulation work have been performed with commercial code FLUENT and NASA CEA code is used to calculate CJ detonation parameters. The main objective of S.M. Frolov "Detonation Initiation Techniques for Pulse Detonation Propulsion" was to ensure fast DDT in PDE tube at the lowest possible ignition energy, at the shortest distance, with lowest pressure loss and using fuel-air mixtures **[1]**.

The shaped obstacles considered in this work were in forms of tube coils as U bends. A concept of fast DDT was applied to reduce the DDT run-up distance and time for air-breathing PDE applications. The approaches used experimentally and computationally, namely as 1) regular orifice plates and shaped obstacles. 2) Tube coils and U-bends **[4]**. The combination of these methods made it potential to achieve fast DDT in kerosene-air mixture in 51 mm diameter with run-up distance and time of about 2 m and 5-6 ms respectively., applying spark ignition energy as low as 5 J.

4. Methodology:

To carry out the present numerical simulation work, commercial software like GAMBIT and FLUENT were employed. FVM approach is used to solve this simulation problem using governing equations of flow like continuity, momentum and energy equations. Geometry is modeled in GAMBIT and mapped meshing of the geometry is also performed in the same tool as it leads to good quality of meshed geometry. FLUENT codes for this combustion problem simulations leads to best accurate results when compared to experimental setups.

5. Geometry and grid generation:

The problem deals with simulating the propulsive parameters inside a pulse detonation engine. Here the necessity of flow domain which creates a detonation forming in normal shock that propagates in the direction of the open end of the detonation tube. The domain has a necessity of shock tube like structure which transfer the adverse pressure generated in the tube to outlet as fast as possible. Shchelkin spiral obstacles in the detonation tube are added advantage because they increase the velocity of the detonation wave. For numerical simulation a flow domain is generated and meshed in GAMBIT which represents the interiors of the pulse detonation engine **[7]**. As the problem mainly deals with the deflagration part of the problem two inlets are modeled where both the fuel and oxidizer are introduced separately into the flow domain.

Successive increment and decrements of area are introduced into the system which replicate the Shchelikin spiral with a

$$\text{Blocking ratio} = \left(1 - \frac{d}{D}\right) \text{-------} \ (1)$$

Where in equation (1) d is the small diameter and D is the bigger diameter and the values motioned as d=1.5 cm and D=3 cm so it leads to blockage ratio value of 0.5. Overall length of the domain is 52 cm with length of each increment and decrement to be 4 cm each and the overall height of the domain is 3 cm.

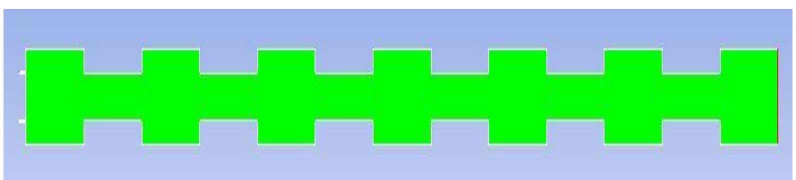


Figure (1): Geometry

A mapped mesh is generated with 49371 nodes and 48060 cells with two inlets, boundary type of mass inlet (for both fuel and oxidizer) at left and pressure outlet at the open end. No mesh stretching is done since the study deals with high Mach number flows where the boundary effects are almost negligible.

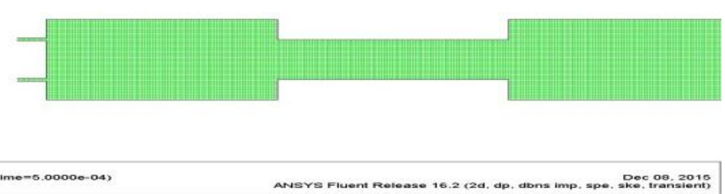


Figure (2): Mapped mesh geometry

6. Numerical model:

For this specific propulsive numerical simulation problem commercial code ANYSIS FLUENT is used to simulate and obtain accurate results. The outcome results obtain in the form of plots have been observed and validated with previous literature published. All the results obtained here are approximate solutions gained by solving numerical equations like species transport for combustion and general governing transport equations like Navier-Stokes equations.

7. Choice of models:

In this numerical simulations the problem is of unsteady case so, simulations have been performed time dependent i.e. transient analysis have been chosen and density based solver is used for solving this case. K-Ɛ (epsilon) turbulence model have been used for the fast combustion process. Enable energy equation as temperature is the major factor in combustion problems. Species transport equation has been enabled for hydrogen/air mixture.

8. Boundary conditions:

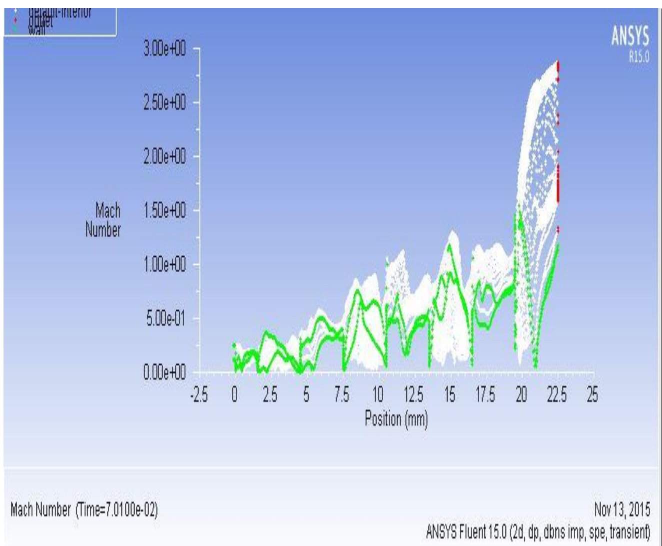
Adiabatic heat conditions are applied for walls as there is no heat transfer in the system. Mass flow rate of fuel inlet is of 0.3 kg/sec with 10 bar pressure direction normal to the boundary with 2000 k temperature. Similarly mass flow rate of air inlet is 0.8 kg/sec with same pressure and temperature values. And outlet pressure is maintained at ambient value and same in case of temperature. An implicit formulation is considered and second order upwind is used. Standard initialization has been done before starting the calculations.

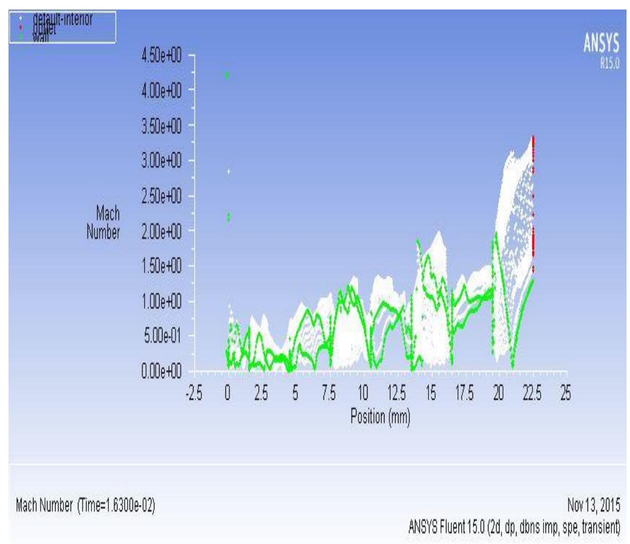
9. Results and discussions:

After running the iterations using the time step size is 1e-04 using seconds for 15000 time steps checking, solution got converged for each time step

9.1 Mach Plots:

Mach number plots have been compared at 2 time step size as shown in plots below:

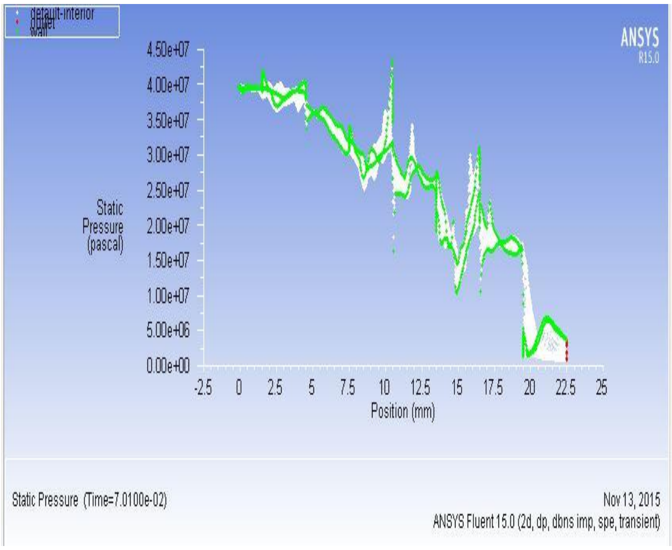


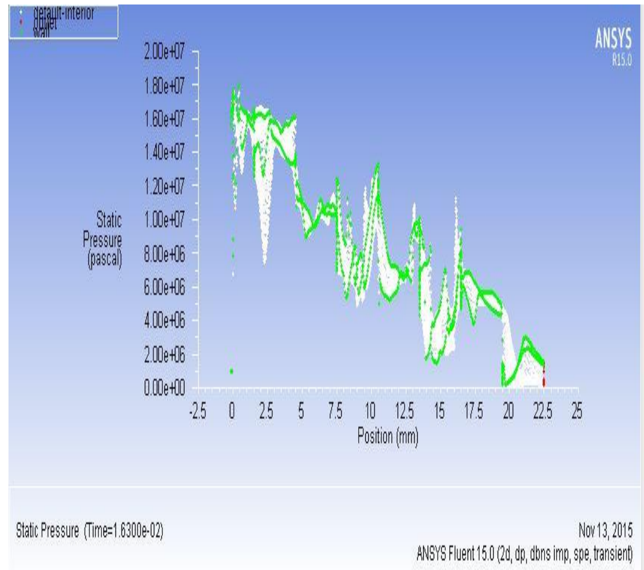


Plot (1): Mach number at 0.07 sec. Plot (2): Mach number at 0.0163 sec.

This plot has been considered at 0.07 sec and 0.0163 sec in the above graphs. It shows the range of Mach number leading from subsonic values to supersonic value at this time step. At the closed end of the detonation tube Mach number is at subsonic range below 0.8 and at open end of the detonation tube Mach number accelerates to supersonic value M > 2.5. Depending on time the Mach number and velocities in the detonation tube varies, as the time increases the Mach number increases as shown at time step 0.0163 sec. And the velocities obtained here are at the range of 2200 m/sec. As in general validation of the results with other previous literature has been successful with the obtained numerical simulation plots of this Mach number.

9.2 Pressure plots: Pressure plots have been compared at 2 time step size as shown in plots below:





Plot 3: Static Pressure at 0.07 sec.

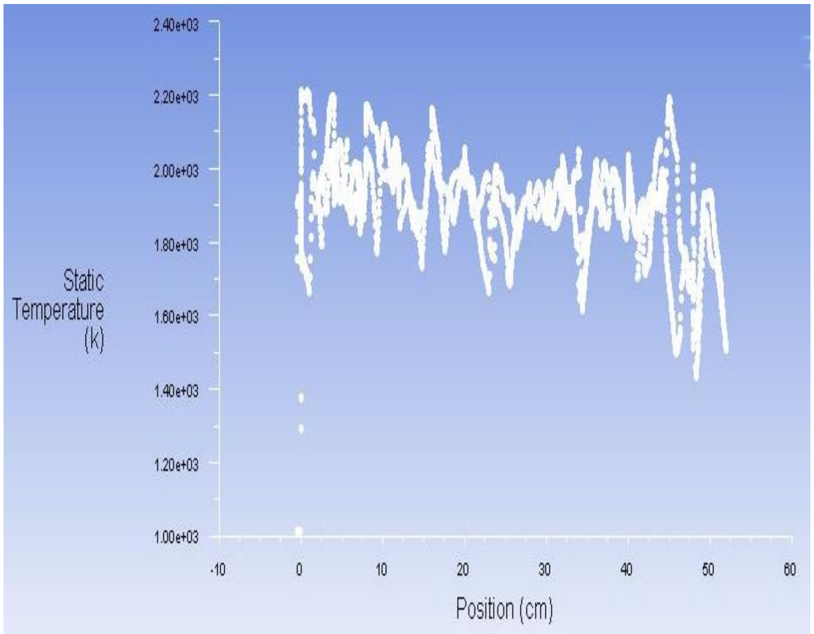
Plot 4: Static Pressure at 0.0163 sec.

This plot has been considered at 0.07 sec and 0.0163 sec in the above graphs .it shows the range of pressures decreasing from closed end inlet to open end outlet values. At the inlet the pressure values are high and as the combustion happen and the wave propagates in the detonation tube the pressure get decreases towards the open end. The pressure drop in the detonation tube leads to flow simulation and propagation of detonation wave. Pressure plots are compared at this two time steps are observed to be at different ranges at detonation tube. At the outlet open end of the detonation tube the pressure to be ambient value of 1atm.

9.3 Temperature plot:

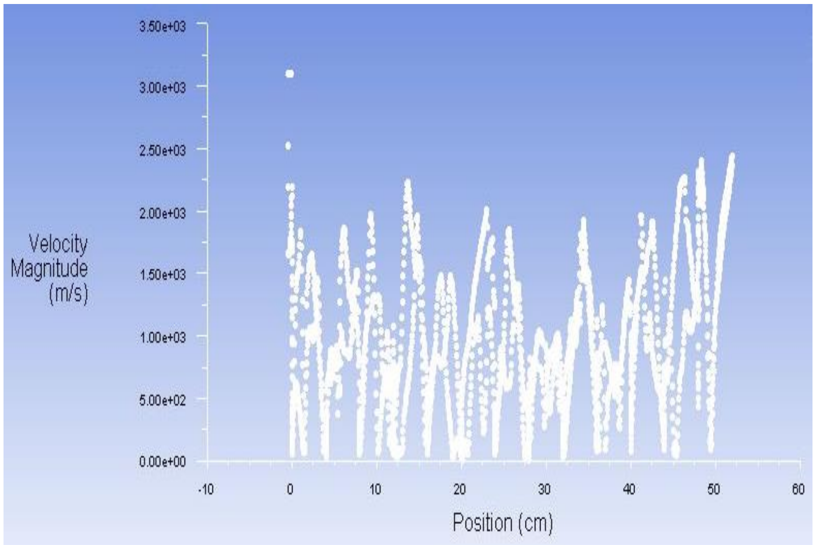
At the closed end of the detonation tube with different mass flow rate at inlet temperatures the combustion happen leading to high temperature values in this zone, propagation of temperature ranges with the shock wave leads to decrease in temperature value of 1600k. so, it clearly shows the high temperature at the open end where the combustion process have been occurred for hydrogen/ air reactants and the products formed are propagated towards the open end with slight decrease in its temperature values as shown in the below graph.

Temperature values has been considered from the below graph.



Plot (5): Temperature plot

9.4 Velocity magnitude: The below graph shows the velocity plots in the detonation tube with shchelkin spiral obstacles.



Plot (6): Velocity plot

The outlet velocity is obtained as 2300 m/sec at the open end detonation tube as the graph shows the deflection in CJ velocities ranges while passing through the obstacles in the working detonation tube. The default interior of the detonation tube from position 5 cm to 45 cm ranges with CJ velocity of 1800 m/sec. so as this velocity occurred leads to the higher thrust results of pulse detonation engine.

10. Conclusion: In this current article numerical simulation of pulse detonation engine with 2D geometry having Shchelkin spiral obstacles have been carried out in the commercial codes available. This simulation has been performed for different mass flow rates of hydrogen/air composition. Hydrogen which acts fuel and air as the oxidizer leads to the high overall performance efficiency compared with parameters like Mach number, pressure and velocity plots. As it is an unsteady flow analysis, parameters like Mach number and pressure are compared at two different time steps where Mach number leads from subsonic to supersonic range and pressure drop in the detonation tube has been observed. The overall performance and the thrust values are high depending on velocity value obtained as 2300m/sec.

11. Future scope: Simulations can be carried out for different liquid and solid fuels such as kerosene-air, methane-air, and propane-air.

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