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PERFORMANCE ESTIMATION AND ANALYSIS OF PULSE DETONATION ENGINE WITH DIFFERENT BLOCKAGE RATIOS FOR HYDROGEN-AIR MIXTURE

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***Abstract* -- This paper provides an introduction to the concept of Detonation waves in the application of Pulse Detonation Engine (PDE) which includes the Detonation initiation and propagation of wave. A review of previous computational studies of Pulse Detonation Engine shows a wide variation in the performance of system. We present the results of systematic study of Pulse Detonation Engine operating with Hydrogen-Air mixture with different blockage ratios to attain high Detonation velocities. We use these results to provide an explanation for the wide variation in a system performance. The system contains the single tube with one end closed and other end opened, which is maintained at two different temperatures and pressure values. Results are computed and analyzed using Computational Fluid Dynamics (CFD) modelling.**

***Keywords*--Blockage Ratio, C-J Velocity, DDT, Detonation, Shchelkin Spiral, Fuel-Air Mixture, Rarefaction Waves.**

1.0 INTRODUCTION

1.1 AIR BREATHING ENGINES

Air Breathing Engines can be classified according to the type of combustion process employed in the device. The combustion process can be characterized as either steady or unsteady, propulsion system may be further classified according to whether a deflagration or detonative mode of combustion is utilized.

1.2 DEFLAGRATION

Deflagration is the propagation of wave at low speeds that is subsonic which is said to be governed by laminar. The thermodynamic property in the deflagration undergoes constant pressure process. i.e., at isobaric stage. This shows the small variations in of pressure in deflagration.

1.3 DETONATION

Detonation is the propagation of wave at high speeds which consists of supersonic speeds with large pressure differences. And it operates at constant pressure cycle which is much more efficient at the constant pressure cycle. The material conversion rate is typically tens of thousands of times faster than any flame can lead to several advantages for propulsion such as more compact and efficient systems.

1.4 PULSE DETONATION ENGINE

The pulse Detonation engine is a new idea propulsion system using repeating explosions to produce thrust or power. Pulse detonation engine typically consists of a sufficiently long tube which is filled with fresh fuel oxidizer mixtures and ignited by sufficiently strong energy source. Flame initiated by ignition must be in relatively shorten to accelerate the detonation velocity. So, the transition from deflagration to detonation must happen in relatively small distance. Detonative combustion produces high pressure which is converted to thrust. PDE can operate in wide Mach number ranging from 0 to 4 with engine operating in the pulsed mode. So the thrust is varying in time and the detonation must be initiated each time. Pulse Detonation Engine is operating in the stoichiometric condition (due to necessity of fast initiation of detonation and frequencies relatively low). PDE system is more advantageous because of its less complexity and weight.

1.5 PULSE DETONATION ENGINE APPLICATIONS AND ISSUES

- PDE applications in rocket engines and missiles and UAV's.
- The flow in a pulse detonation engine is a challenging research problem because it involves compressible, chemically reactive flows in complex geometry configurations with moving boundaries.

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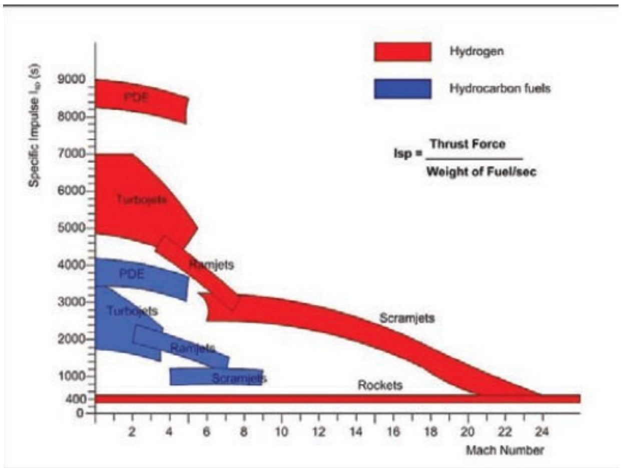

Fig.1 Comparison between different values for Specific Impulse [1]

2.0 RESEARCH REVIEW

Lee et al [4] conducted a parametric study on blockage ratio, spacing between the obstacles and its length, they conducted the experiments with ethylene-air mixture. They found effective blockage ratio between 0.3 and 0.6 to accelerate the flame relative to C-J speed. Lindstedt and Michels [5] found that the optimal blockage ratio is 0.44.

Cooper et al [6] shows the detonation transition time will be reduced by using the obstacles with the blockage ratio of 0.43 for propane and ethylene-oxygen-nitrogen mixtures. Eidelman and Yang [7] shows the parameters affecting the Detonation with the parameter length of the tube. The performance was not affected as the detonation occurred within the tube. Desbordes [8] observed the transition analysis in the tube is due to blockages.

3.0 PDE CYCLE OPERATION

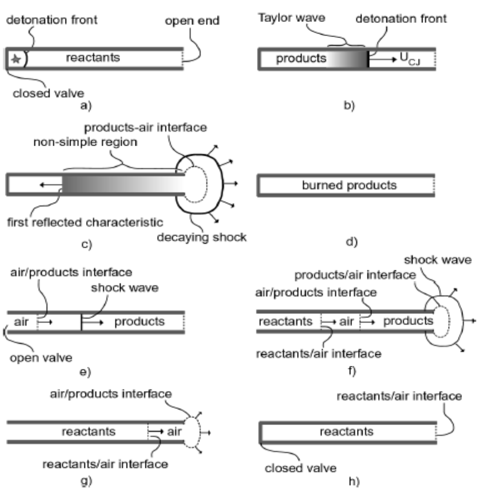

Fig.2 PDE Cycle Operation [2]

3.1 DETONABLE MIXTURE FILLS COMBUSTOR

Detonation tube consists of an open and closed end to start the detonation engine cycle. The fuel-air injection process can impact the net thrust generated by the engine, high combustor inlet Mach numbers decrease thrust performance because of the low static pressures generated in de-accelerating the combustor inlet flow when the wall closes. Low fuel-air injection Mach numbers will also degrade performance by increasing the time required to fill the chamber.

3.2 DETONATION INITIATION AT CLOSED END

After the fuel-air mixture enters the chamber, a valve at the beginning of the combustion chamber is closed in preparation for detonation initiation. Detonation wave can be initiated through deposition of a large amount of energy at a given spatial location. The wall seals the combustion when the downstream fuel - air mixture is still at some finite distance from the open end of the chamber. Detonation tube is filled with fuel-air is calculated from the overall length of the tube and the relative velocities of the injected fuel-air mixture in detonation wave.A detonation wave is initiated immediately in the fuel-air mixture region near the closed end of the chamber. An expansion zone is created between the closed end and the detonation wave. Rarefaction waves are generated at the closed end of the detonation chamber and proceed towards the exit.

The rarefaction waves originate at the closed end and maintains the constraint of zero axial fluid velocity normal to the wall [3]. The strength of the expansion region is the function of the axial velocity of the burned gases behind the detonation wave which must be de-accelerated to satisfy the closed end boundary conditions. The detonation wave is a self-propagating wave which makes the burned gases moves at C-J velocity conditions (Speed of sound). The velocity of this burned wave depends on the velocity produced by the detonation wave and the initial fuel-air mixture and propagates towards the open end of the tube.

3.2.1 CHAPMAN-JOUGET CONDITION FOR DETONATION

- The solution to the conservation equations is only determined with some additional considerations, for detonations gas dynamic considerations are sufficient to determine the solution. Chapman (1899) and Jougete (1902) proposed that detonations travel at one particular velocity which is minimum velocity for all the solutions on the detonation.
- At the solution point (C-J Detonation point) the Hugoniot, Rayleigh line and isentropic are tangent. The Fig.3 represents the flow behind the C-J detonation point is sonic relative to the wave.

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- Most detonations travel at the C-J Velocities.

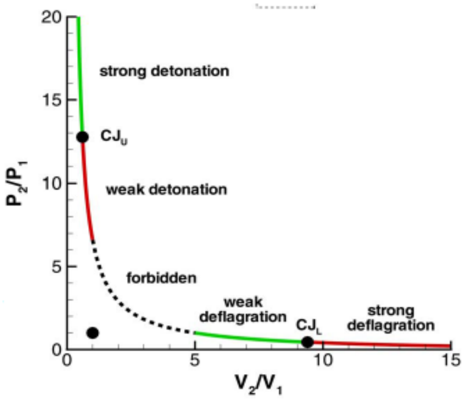

Fig.3 Theoretical regions of Hugonoit curve[2]

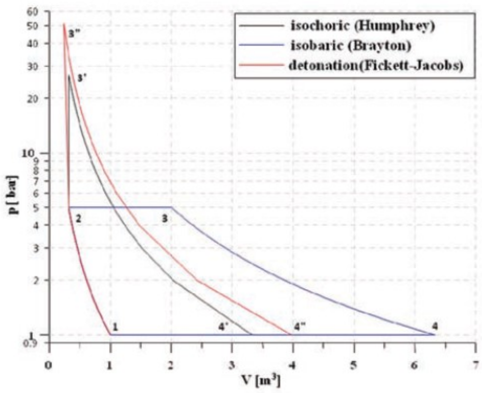

Fig.4 Comparison between constant volume and constant pressure cycles [1]

3.3 DETONATION WAVE CHARACTERISTICS

The detonation wave can be modelled as a strong shock wave which makes combustion and thin flame front in which heat addition occurs behind the shock. The shock moves at the detonation velocity related to the gas which increases the pressure and temperature of the gas from its previous values.

The region of the burned gas just behind the shock is a high pressure region known as the Von Neumann spike. Rarefaction waves will be generated near the closed end of the tube behind the detonation tube, because of this rarefaction waves the low pressure region will be created than the pressure just behind the detonation wave.

4.0 COMPUTATIONAL FLUID DYNAMICS MODEL

4.1 DESIGN CONSIDERATION OF PDE

In the analysis, we will consider the liquid hydrogen and gaseous oxygen as fuel and oxidizer separately. The reactants combination was ignited by direct initiation and the detonation was achieved by deflagration to detonation transition (DDT) process with Shchelkin-type spirals.

Fig.5 Isometric view of the Straight tube

Our model with a 40 mm inner diameter also a total length of 540 mm is used. It consists of two different sections where the first section which is from the closed end having more pressure and temperature values, the second section is having ambient conditions.

Fig.6 Isometric View of the Pre Detonator with Shchelkin Spiral

The blockage ratio of the Shchelkin spiral welded inside the DDT chamber was 0.5 and the length of the DDT chamber was 480 mm.

4.2 GEOMETRIC MODELLING

We have created a cylindrical tube of diameter 40 mm, length 540 mm with blockage ratio 0.5. The pre detonator tube of diameter reduced to 20 mm, and length between each spiral is 40 mm. By using commercial tools we analyzed the model and the results were discussed in performance estimation.

5.0 PERFORMANCE ESTIMATION

The research in PDE is mainly based on performance estimation. PDE consists of a straight tube with a thrust wall at the closed end and other is opened [10]. To avoid the premature ignition [9], buffer gas is needed between consecutive fillings so that it will reduce the frequency of operation and thrust. Another way to minimize frequency of operation is to have multiple tubes in that some tubes are filled while other tubes are detonated or evacuated.

Daniau et al experimentally investigated the nozzles with different shapes and by varying length. This nozzle maintains high frequency by conversion of unsteady to steady so that the thrust can be increased. So, the effects of the nozzles are considered basing on the fuel filling the tube that is partial fulfill effects have been discussed in their results. The effects of partially filling the thrust tube with detonable mixture and filling the rest with air is interpreted as straight nozzle [4]. The fuel based straight nozzle has indicated specific impulse (I_{SP}) will be more.

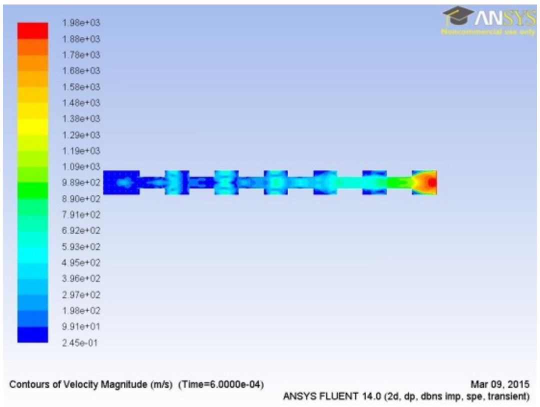

Fig.7 Velocity contour for Shchelkin Spiral

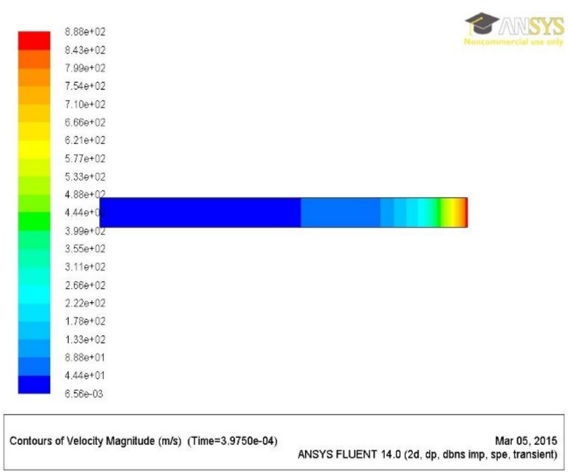

Fig.8 Velocity Contour Straight Tube

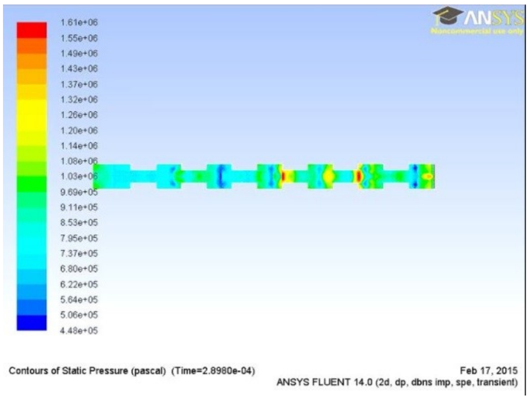

Fig.9 Pressure Contour for Shchelkin Spiral

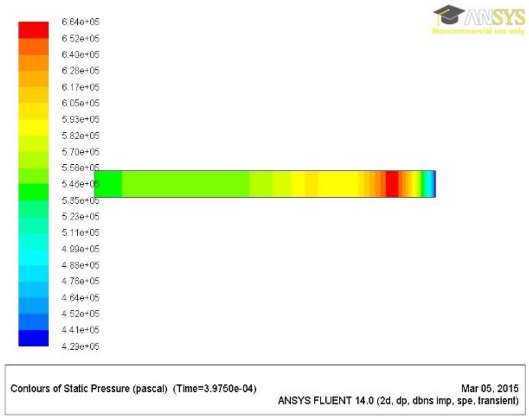

Fig.10 Pressure Contour for Straight Tube

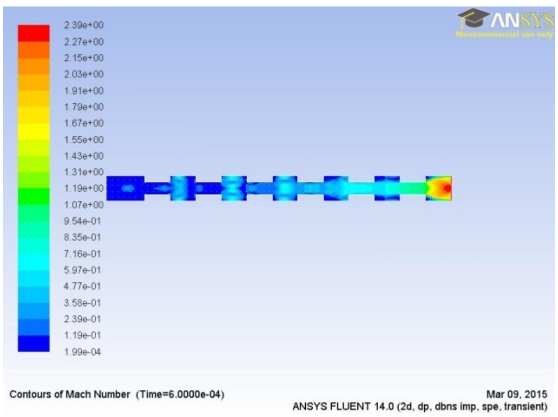

Fig.11 Mach number contour for Shchelkin Spiral

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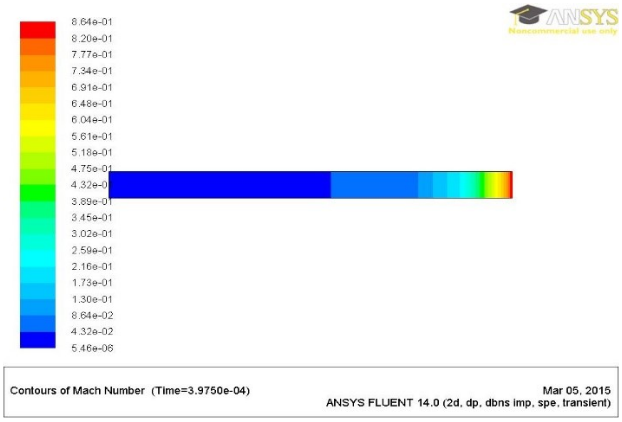

Fig.12 Mach number contour for Straight Tube

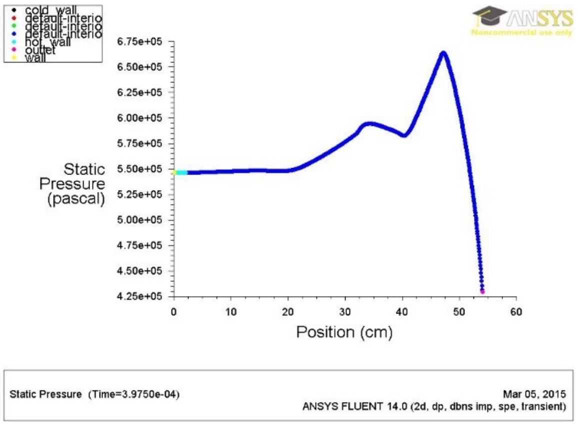

Fig.14 Pressure plot for Straight Tube

*Values at Tube End				
Type of Tube	**Velocity (m/sec)**	**Mach Number**	**Pressure (Bar)**	**Flow Time (S)**
Straight Tube	888	0.86	6.6	0.00039
Shchelkin Spiral	1980	2.39	16	0.0006

Table.1 Values for Straight Tube and Shchelkin Spiral

In the pressure plot at the maximum velocity, pressure value reached to 25 bar. At the end of the tube we got 16 bar when flow time is 0.0006 s where as in straight tube, pressure value reached to 6.6 bar when flow time is 0.00039 s. When wave reaches to spiral region, pressure value decreases.

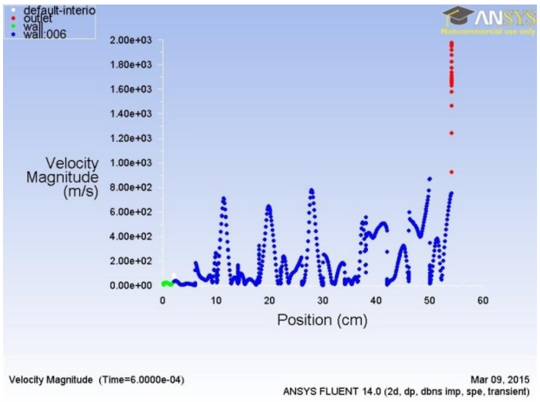

Fig.15 Velocity plot for Shchelkin Spiral

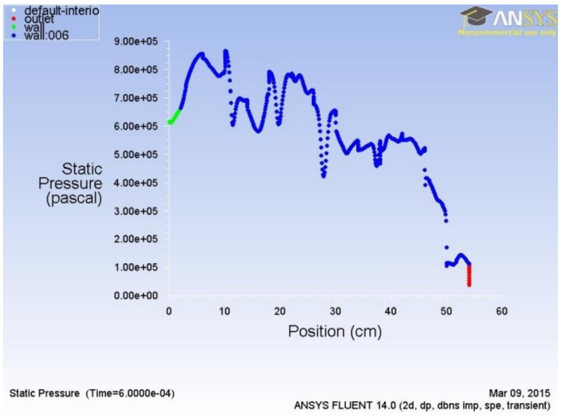

Fig.13 Pressure plot for Shchelkin Spiral

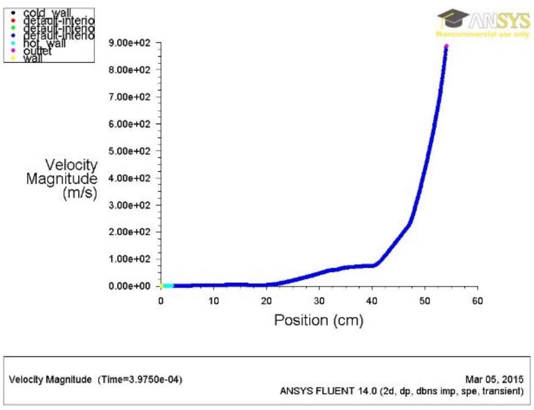

Fig.16 Velocity plot for Straight Tube

In the velocity plot, the detonation wave started from 900 m/s as subsonic speed, at the end of tube velocity reaches to 1980 m/s. when flow time is 0.0006 s, whereas for straight tube velocity reached to 880 m/s when flow time is 0.00039 s. During the propagation of wave, Detonation velocity reaches to 2050 m/s in the Shchelkin spiral tube.

6.0 CONCLUSION

Performance estimation of Pulse Detonation Engine towards the research development, concludes that the detonation tube with Shchelkin Spirals will produce more detonation velocity with effective Mach number compared to straight tube because of generation of turbulence caused by the hot spots which are responsible for formation of DDT at the surface of obstacles. So, the performance of the engine will get increased by producing high thrust and effective Specific Impulse.

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