Numerical comparison of Pulse Detonation Engine attached with Divergent Nozzle

Nitin Kukreja
Application Engineer – CFD,
ARK Infosolution- Chennai, India

Repaka Ramesh
M.Tech – CFD Student,
University of Petroleum and Energy Studies – Dehradun, India

Sumit Kumar
Assistant Professor - Department of Mechanical Engineering
KSVCEM, Bijnor, Uttar Pradesh, India

Abstract- Pulse Detonation Engine (PDE), a propulsion system, includes detonation of fuel to produce thrust more efficiently than current engine systems by enlargement of its mechanical simplicity and thermodynamic efficiency. The concept of PDE is old but has a great impact on efficiency of detonation engines. At present due to the behavior of unsteadiness this type of engine's design optimizations are not completed and this leads one to improvise nozzle geometry via qualitative numerical predictions. This paper summarizes the computational behavior of Pulse Detonation Engine attached with the divergent nozzle, with the working medium of kerosene and oxygen mixture. Two different tubes are meshed for four separate angles. In addition, the effects of a transient detonation process and performance of the engine was computationally predicted using a two dimensional grid in a viscous domain and evaluated from subsonic to supersonic operation. Grid independence study is performed to eliminate/reduce the influence of the number of grids/grid size on the computational results. Pressure variation with the several time intervals are pictured for all test cases. Obtain result of this computational investigation provides that as the nozzle length is increased the responsible impulse is also increased. Overall, to find the quality amount of thrust, high divergence angle at the end of the tube are favored.

Keywords – PDE, Detonation engine, Divergent-nozzle, Numerical prediction, Grid independence study.

I. INTRODUCTION

PDE is an efficient and improved unsteady propulsion technology that uses a repetitive cycle to produce effective thrust. 1990 was the time when researcher took this concept again into consideration and started improving its controlling parameters and responding devices. Researcher found much noticeable improvement in thermal efficiency, specific impulse and mechanical simplicity for this system as camper to other air breathing system.

The major development was observed in the papers of Hoffmann, where both liquid and gaseous hydrocarbons are employed and concept of intermittent detonation was successfully discovered. But later on some unsuccessful attempts were also observed to attain optimum cycle frequency [3]. This leads Nicholls and all in 1957 to explore again the concept of detonation waves for propulsion applications. Nicholls and all studied a simple detonation tube open at the other end, which utilizes fuel and oxidizer at the other end and examined specific impulse of 2100 seconds for hydrogen and air mixtures at attainable frequency of 25 Hz but the attempt of initiation form the open end were not successful [3].

Helman and all did successful attempts to achieve the initiation of detonation inside the detonator tube of small diameter with the mixture of oxygen and ethylene. This repetitive fuel injection resulted in intermittent detonation at frequency of 25Hz. Later on numerical simulation were also carried out to check the performance of PDE system by M. Arian and A. M. Tahsini [1]. Their study was done for the 50 cm long main tube attached to a 43 cm long diverging nozzle, quality issues likes mixing, ignition and transition from deflagration to detonation was ignored under this study. But overall performance gave the specific impulse of approx. 6500 seconds at the 667 Hz of operating frequency. Cambier and Tegner [1] computationally investigated the five different shapes of nozzle and their results provide that the presence of nozzle can improve noticeable parameter in the performance of a PDE [1]. Eidelman and Yang adds another conclusion in study by converging and diverging nozzle by re-examining and comparing all the relevant finding. Overall conclusion of these two studies was that the nozzle is truly responsible for the improvement in the efficiency of PDE's system. Another effect of nozzle was investigated by Cooper and Shepherd [2], where the prediction of partial filled model for detonation tube was investigated [2]. Study of convergent and divergent nozzle was experimentally investigated by Cooper and Shepherd and all finding were compared with steady state flow nozzle [2]. Points for the performance of nozzle on PDEs were considered and the whole study is focused to present the effect of divergent nozzle on the pulse detonation engine performances.

PDE allows repetitive ignition, propagation and finally transmission of detonation waves inside detonation tube. Inlet valves, detonation tube and a nozzle at the end are the basic element of our considered propulsion system.

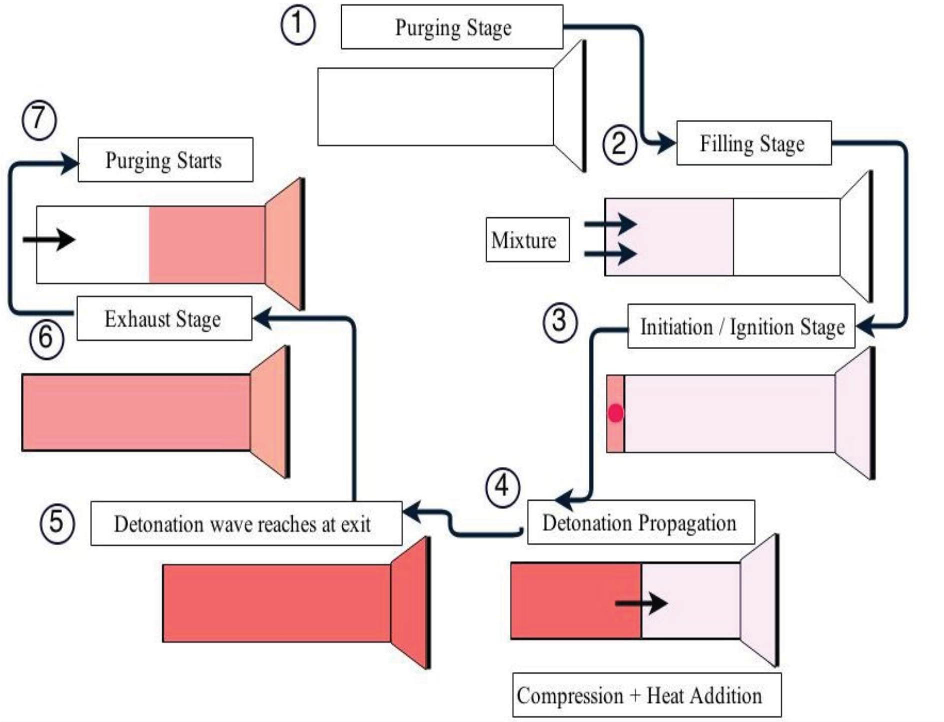


Fig 1: Schematic representation of PDE cycle.

A summary of PDE cycle's process has been clearly explained in figure 1, where part 1 to 3 shows the purging, filling and Ignition stages respectively. Part 4and 5 shows the propagation of detonation inside the complete tube and how effectively it reaches to the exit stage. Simultaneously after a certain period of time a reflection of compressive disturbance is observed, which reflects from the exit wall, and reinitiate of the cycle has been clearly mentioned.

II. GEOMETERY SETUP

In any Computational analysis, the major step is to model the geometry and generate the mesh. Presented numerical work utilizes GAMBIT for creating geometry and mesh. Then mesh file is imported into ANSYS - FLUENT solver, where modeling equations and boundary conditions are set accordingly.

Writing about this investigation, four different test cases with two different types of tubes have been made. First test case was made of straight tube with nozzle at one end; another test case was made for Shckilen spiral with nozzle at one end. Where for both the case cylindrical tube diameter is set to 40 mm, tube length is set to 500 mm and four different nozzles angle 4, 6, 8 and 10 degree respectively are made and meshed in GAMBIT.

Two dimensional representation of straight and shckilen sprial tube with 60 nozzle angle is clearly mentioned respectively in figure 2(a), 2(b), 2(c), 3(a), 3(b) and 3(c). Idea behind this large number of grid study was to find out the best mesh size for the both test cases. Table I and II are showing the different used mesh size for both the cases.

Straight tube	Cells	Faces	Nodes
30 nodes	5700	11620	5921
40 nodes	8000	16240	8241
50 nodes	10200	20220	10362

Table 1: Grid Independence Study for Straight Tube

Shckilen spiral	Cells	Faces	Nodes
30 nodes	8850	18185	9336
40 nodes	16000	32640	16641
50 nodes	25250	51295	26046

Table 2: Grid Independence Study for Shckilen spiral Tube

A large number of grid independence studies were conducted for each nozzle angle. The aim of this study was to find out the influence of the number of grids on the computational results. After testing three different test cases of 60 nozzle angle with different node elements at Y- axis, we have confirmed that the best case which require suitable time to complete the sufficient number of iterations with maximum accuracy is the case with 40 nodes at Y – axis.

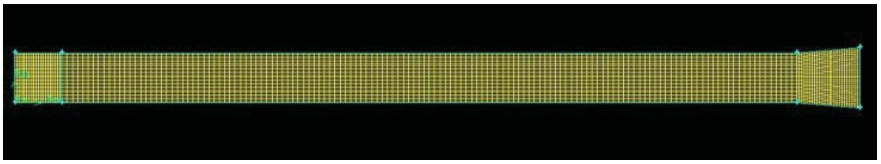


Fig 2 (a): 2-D view of structured mesh with 30 nodes for straight tube with 60 nozzle angle

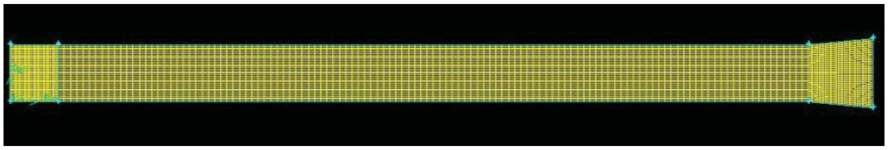


Fig 2 (b): 2-D view of structured mesh with 40 nodes for straight tube with 60 nozzle angle

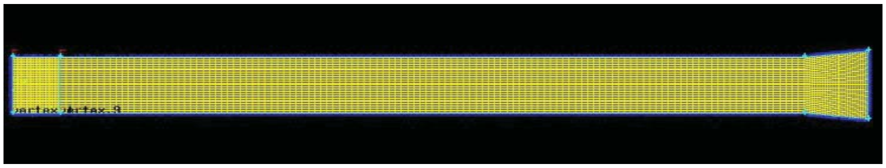


Fig 2 (c): 2-D view of structured mesh with 50 modes for straight tube with 60 nozzle angle

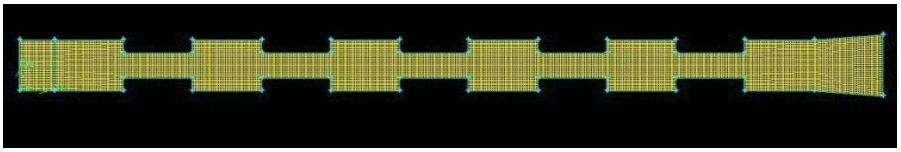


Fig 3 (a): 2-D view of structured mesh with 30 modes for Shckilen spiral tube with 60 nozzle angle

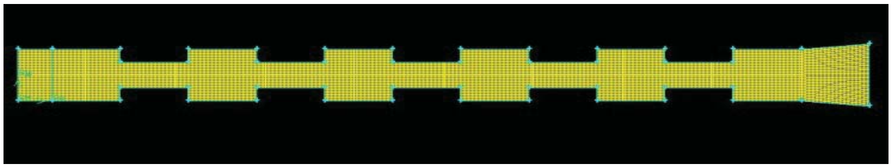


Fig 3 (b): 2-D view of structured mesh with 40 modes for Shckilen spiral tube with 60 nozzle angle

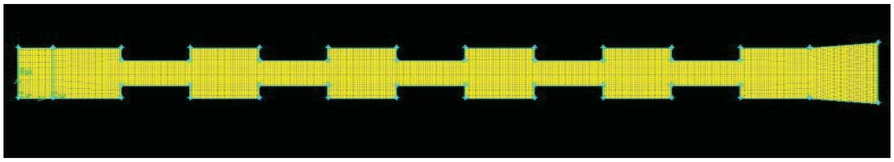


Fig 3 (c): 2-D view of structured mesh with 50 modes for Shckilen spiral tube with 60 nozzle angle

III. SOLUTION METHODOLOGY

In this investigation, liquid hydrogen and gaseous oxygen as fuel and oxidizer are considered. The reactants combination is ignited via patching and detonation is accomplished via deflagration to detonation transition (DDT) process in straight tube which is attach with four different nozzle of 4^0, 6^0, 8^0 and 10^0 (one can refer to figure 2(a), 2(b) and 2(c) to understand more).

The SIMPLEC finite volume technique is utilized to solve the partial differential equations. An unsteady solver was selected to detect the circulation of the reactants towards the inside during filling phase. Material properties of flowing fluid, boundary conditions and k- ε model are preferred. The general form of conservation equations, neglecting the body force is given and considered.

Continuity: $$\frac{\partial \rho}{\partial t} + div(\rho v) = 0$$

X-momentum: $$\frac{\partial \rho u}{\partial t} + div(\rho u V) = -\frac{\partial p}{\partial x} + div(\mu grad(u))$$

Y-momentum: $$\frac{\partial \rho v}{\partial t} + div(\rho v V) = -\frac{\partial p}{\partial y} + div(\mu grad(v))$$

Energy: $$\frac{\partial \rho e}{\partial t} + div(\rho e V) = -div(V) + div(kgrad(T)) + \varphi$$

In mentioned equations, all scientific terms have general meaning. Models constants are found from experimental investigation of turbulent shear flows with air and water, including homogenous shear flows. They have been found to work properly for a wide range of wall – bounded and free shear flows.

As mentioned about patching of two zones; this provides the propagation of shock wave inside the combustion chamber. Inside the tube flow is highly turbulent with changes in density of mixture; therefore density based type solver is used and as the detonation in the combustion chamber is changing instantaneously with the time, transient type of solver is used.

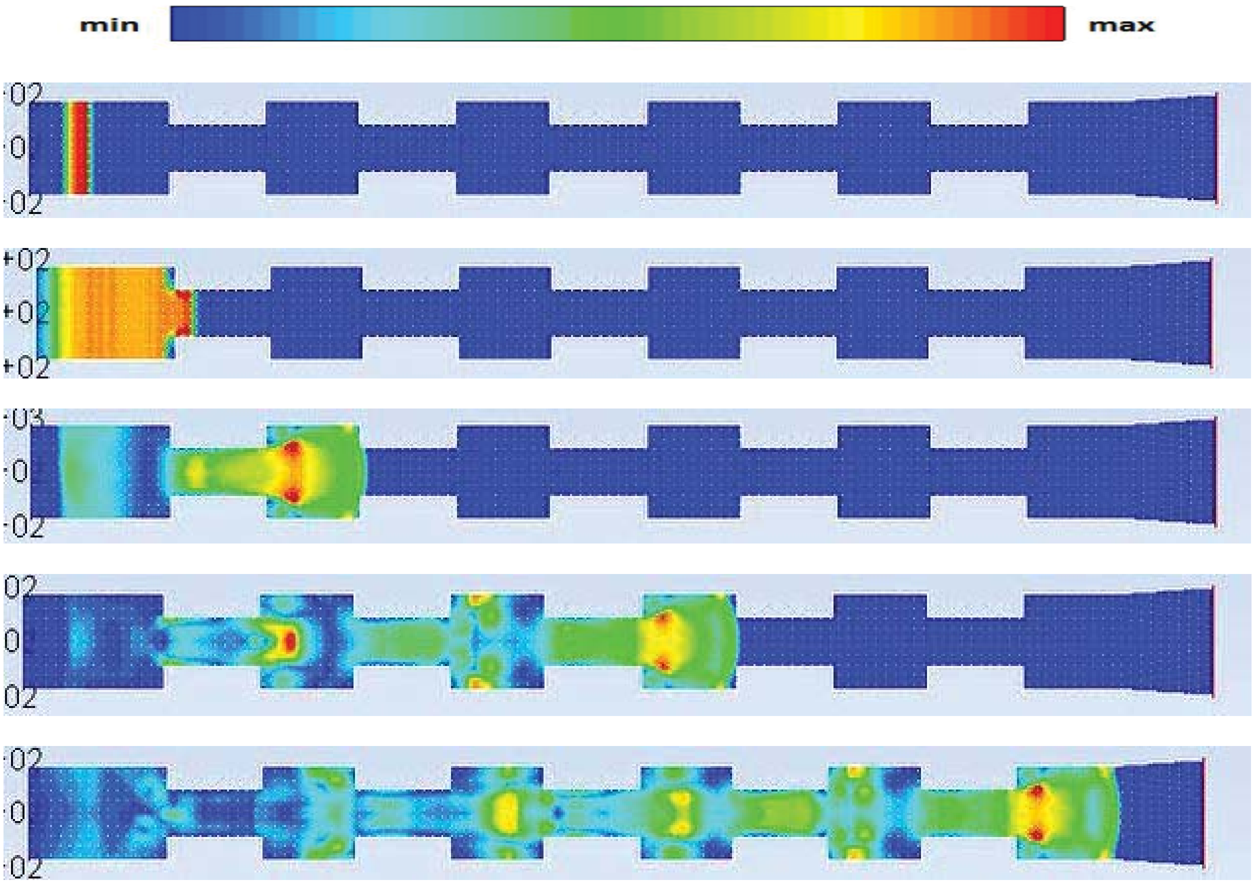
The discretization scheme is chosen to be second order upwind for all flow and the convergence criteria has been fixed to 1e-06 for momentum, energy and continuity equations.

III. RESULTS AND CONCLUSION

Gaseous mixture of hydrogen and air was analyzed in this study. Comparisons between two different tubes of four different nozzle angles were performed. Mentioned results and solving considerations can be very useful for the further development of pulse detonation engine (PDE).

Phenomenon of patching, of two different zones named as hot and cold zone are utilized to achieve detonation. In numerical simulations, velocity and pressure contours were studied to make sure the generation and propagation of detonation wave.

Observing the pressure contours one can notice the enlargement of detonation wave inside the tube. In the starting reactant destruction happens at their boundary because of hot and cold zone interaction. High temperatures in hot zone originated combustion of hydrogen air mixture. Fig 4.1 clearly demonstrates shock wave transition into detonation wave after a definite distance; rush in energy release from the chemical reaction is answerable for development of this detonation wave. Figure 4.1 provides the complete development of high velocity wave as propagating detonation wave with wide range of time step.



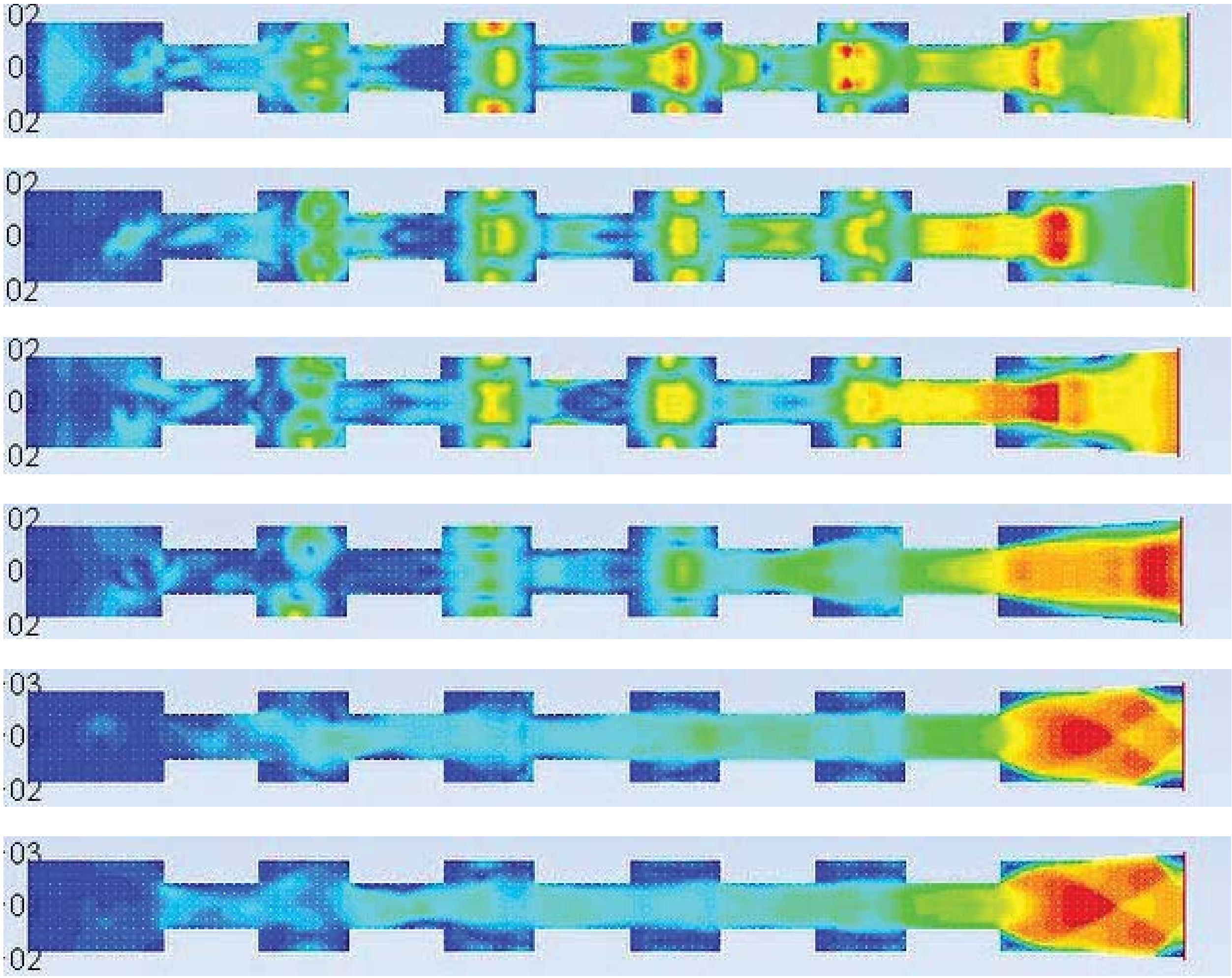


Figure 4.1 Propagating detonation wave with wide range of time step.

Figure 4.2 clearly mentioned the variation of pressure with a very short time step. This is done in order to achieve the best possible variation wave of pressure wave inside the limited length of tube.

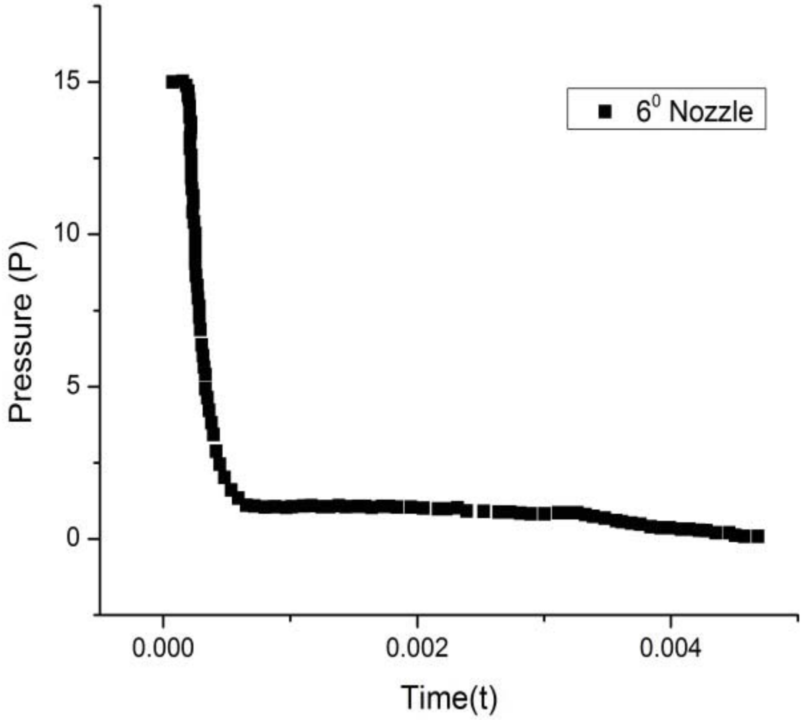


Figure 4.2 Pressure variation for 6^0 nozzle angle

IV. CONCLUSION

The Following are main conclusion of this study:

1. A diverging nozzle is beneficial to increase the cycle impulse. We observed that as the nozzle length is increased the responsible impulse is also increased.
2. By considering four different angles 4^0, 6^0, 8^0 and 10^0 we observed that the greater the divergence angle, the greater will be velocity. Moreover at the maximum angle the flow becomes supersonic in the nozzle.
3. Overall, to find the quality amount of thrust, high divergence angle at the end of the tube are favored.

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