Performance Evaluation of a Pulse Detonation Engine using Vortex Generators as obstacles in the combustion chamber

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Abstract
Propulsion based engines have been known for their exemplary thrust but also for lower fuel efficiency and speed of operation which is limited to subsonic and the level of intermittent vibrations produced. Pulse Detonation Engine (PDE) is similar to a Pulse Jet Engine (PJE) except for the fact that the flame formed inside the combustion chamber of PDE travels at supersonic speed, whereas in PJE, it is subsonic. The supersonic speed of flame front in PDE is because of the detonation wave formed during the combustion of the fuel mixture which is in the order of 2000 m/s and is based on constant volume combustion. A process called Deflagration to Detonation Transition (DDT) can be used for which turbulence has to be created inside the combustion chamber. The obstacles used in this study were vortex generators and the CAD model of the engine and the obstacles assembly was made in SOLIDWORKS 19.0 software. ANSYS (FLUENT) 16.0 was used for the simulation of the combustion inside the combustion chamber using the Species Transport Model for the performance evaluation.

Keywords: Pulse Detonation Engine, Ansys Fluent, DDT, Supersonic combustion

Nomenclature

1-D One Dimensional
PDE Pulse Detonation Engine
CJ Chapman Jouget
ZND Zeldovich-von Neumann-Doring
PDRE Pulse Detonation Rocket Engine
SFC Specific Fuel Consumption
T/W Thrust-to-Weight
DDT Deflagration to Detonation Transition
Dt Diameter
VG Vortex Generator

INTRODUCTION
The Pulse Detonation Engine (PDE) is a propulsion system that uses a very high rate of release of energy to produce thrust from the detonation waves [1] [24]. To get higher efficiency results than the current steady-state detonation engines, the use of simple detonation physics of combustion is done which helps in eliminating the use of high-pressure pumps or compressors leading to a major
improvement over the propulsion systems which are air-borne [6]. Any engine having the ability to be operated over a range of flight velocity such as Mach 0- Mach 5 does not exist currently [23].

There are many shortcomings of using PDE and for this reason; many studies have been performed by multiple organizations and various research facilities to overcome them [7]. The University of Michigan and US Naval Ordnance Test station carried out various experiments in the 1960s but were not able to perform a successful detonation because of the unsuitable implementation of the augmentation device of DDT leading to a halt of PDEs considering no future of such engine for in-flight applications. However, Helman in 1986 performed various experiments at the US Naval Postgraduate School which again brought the attention back to the PDEs. He focused on improving the frequency and the specific impulse on which the engine operates. The use of ethylene-air mixture was done, and from the results obtained, high operating frequencies of 150Hz with a high specification range of 1000-1400 seconds were observed.

Many single-pulse and multi-pulse detonation experiments were conducted. In the single pulse detonation, only the detonation wave initiation and their propagation with blowdown process are done [4]. Whereas, in the initiation of multi-cycle experiments, the requirement of additional purging with multiple filling processes was required. The use of single-pulse was done to find out the required mixture of fuel and oxidizer alongside to validate the various concepts used in the combustion process such as it would provide the insight of the more complex initiation of the multi-cycle process [5] [27].

The measurement of the performance of PDE is done based on the impulse generated by the process involved in the detonation initiation. However, it is observed that these methods fail as they are not accurate for the inlet conditions of the engine, and also the purging and the refilling are ignored. Either direct detonation or DDT can be used to attain detonation [28]. It was observed through various attempts that the detonation was limited to only the single pulse experiments due to which most experiments conducted in PDE use the DDT process. There is a correlation on the usage of fuel mixture, dimensions, and the roughness of the surface of the tube for a detonation to be achieved properly [24].

Sinibaldi [8] carried out an experimental study revealing that the ignitor should be used from the head end of the tube along with the equivalence ratio for the C2H4-O2-N2 mixture which greatly affects the length of DDT. A 7.5 cm of the tube length was found to be minimum for the mixture and an equivalence ratio of 1.2 was obtained. DDT length was increased significantly with the decrease of the equivalence ratio of .75 which proved that DDT length can be more than the length of the detonation tube. Hinkey[9] conducted various tests with H2-O2 mixtures which showed that various devices which could augment the DDT process with a shorter length.

To augment the DDT process, obstacles such as the Shchelkin spiral [10] [29] device was used, introduced by Kirill Ivanovich Shchelkin, a Russian physicist. The results obtained after the use of the obstacle showed that the DDT length was reduced by almost three times [30]. This led to the study and discovery of other obstacles as well. The drawback of using such obstacles was that there was a loss in the total pressure with a decrease in propulsive efficiency. Cooper [11] found out that there was a decrease of 65% length of DDT with a 25% decrease in the impulse.

![General PDE experimental setup with Shchelkin spiral](image)
The use of a nozzle is done at the end of the detonation tube for the improvement of the performance of the engine because it utilizes the internal energy of the products of the detonation exhausts, but it is a very challenging step as PDE is very unsteady [2] [11].

US Naval Postgraduate School carried out experiments focusing on increasing the overall efficiency from the conversion of thermal energy into kinetic energy [16] [18]. This process was conducted with a variable area of nozzle and various tests were conducted on flow rates to observe the characteristics of the flow. There was a great effect on the pressure with the injection at a variable flow rate of mass. Kailash Nath [12] later performed experiments on nozzle effects with various shapes and calculated their effects in inlet pressure along with the thrust of multi-cycle PDE. Thrust was found to be better in diverging, converging, and straight nozzles rather than a converging-diverging nozzle. From the experiments, it was also seen that the acceleration of flame and DDT along with the propagation of detonation is also affected by the structure as well as the roughness of the wall inside the detonation tube. There is a reduction of the velocity inside the detonation tube as compared to the smooth walls [12] [13]. Various experimental data suggest the effect of the composition of various mixtures of fuels on PDE performance. High detonation velocity is achieved for the heterogeneous mixture which has a high ratio of equivalence [12] [13].

The propagation of the wave is also affected by the diameter of the tube. From the computational as well as the experimental analysis and simulation, it was found that the size of the detonation cell is dependent on the initial pressure, composition of the mixture, temperature, and the diameter of the tube which is also called critical diameter [14]. Detonation waves transform from the ignition tube towards the main tube if the critical diameter is more than the tube diameter [24] [5] [11] [15]. There are many experimental studies that show the effects of the varying cross-sectional areas of the tube. From the studies, the prediction of the shock of the propagating wave and its flow characteristics were predicted.

**METHODOLOGY**

In this study, the computational analysis of a Pulse Detonation engine is carried out. In the initial step, the model of the engine, along with the obstacles, is made in the SOLIDWORKS 19.0 software. For the simulation of the engine, the CAD model of the setup was then imported in ANSYS 16.0 software. The setup was simulated considering a one-step chemical reaction model for the hydrogen-air mixture.

It has been observed that, if only deflagration based initiation is done, the achievement of constant propagation of flame is difficult since the self-propagation of deflagration flame tends to accelerate unceasingly thus becoming very unstable. But, with the help of suitable boundary conditions, a velocity of supersonic speed causing detonation phenomenon can be achieved from the subsonic speed of deflagration [19]. This can be done with the help of the long tube of the combustion chamber as it takes a certain time to change from deflagration to detonation phase.

For this reason, the detonation will be achieved through Deflagration to Detonation Transition (DDT) in this work.

**CFD SOLVER**

ANSYS FLUENT is used as the solver for the CFD where the convergence of the solution is obtained after defining the physics associated with the problem.

Since we need to solve the governing equations for energy, mass, momentum, and species transport with the help of a finite volume discretization method, a density-based solver is used as it is the most compatible for solving the required equation. To converge the solution, there need to be several iterations performed [20].

**ONE DIMENSIONAL PROPAGATION OF WAVE IN CONSTANT AREA TUBE**

A tube length of 2m and a diameter of .076m is selected after a thorough literature review study[17]. At a distance of 0.5 m from the tube head end, DDT initiation is placed.
A grid size of 0.1 m is used to get the best estimation of the properties such as flow inside the PDE tube as shown in Figure 2.

![Figure 2. A two-dimensional mesh of an ideal PDE tube](image)

Tables 1 and 2 show the condition for the unburned gas and ignition region respectively. [3] [21] [22] [25].

### Table 1 Properties of the unburned gas mixture initially

| Input Parameters       | Values       |
|------------------------|--------------|
| Original Pressure      | 1 atm        |
| Original Temperature   | 300 K        |
| Mass Fraction of H2    | 2.852 %      |
| Mass Fraction of O2    | 22.635 %     |
| Mass Fraction of N2    | 74.512 %     |
| Mass Fraction of H20   | 0.000%       |

### Table 2 Properties for the ignition region

| Input Parameters       | Values       |
|------------------------|--------------|
| Original Pressure      | 30 atm       |
| Original Temperature   | 2500 K       |
| Mass Fraction of H2    | 0.000 %      |
| Mass Fraction of O2    | 0.000 %      |
| Mass Fraction of N2    | 73.42 %      |
| Mass Fraction of H20   | 25.238 %     |

### Table 3 Specifications of the PDE engine

| The dimension of the PDE tube |
|-------------------------------|
| Inner Dia.                    | 68mm         |
| Length                        | 2000mm       |
Designing the Vortex Generator

Vortex generator acts as a passive flow control device by delaying flow separation point on the flow surface thereby leading to efficient lift and power characteristics. VGs help to control and alter the boundary layer over a surface. Vortex generator produces a swirl in between the high energy flow and low energy flow, filling the low energy level with high energy flow, hence delaying the flow separation. The increment in output parameters such as lift coefficient and electrical power is dependent on the geometry of the vortex generator, angle of incidence (ψ) i.e. the angle between the wedge and the incoming flow, the angle between pairs of generators (έ), spacing between a pair of generators(s), the distance between generators (a), chordwise position(x/c) along the airfoil (or) blade and arrangement of the generator for creating vortices.

Determining the shape of Vortex Generators

From various studies conducted on VGs and their shapes, at various angles of attacks, we found out that Gothic VGs are well suited for generating an optimal amount of thrust. At 10° Angle of Attack, there are some changes in the drag value where the rectangular vortex generator gives the small reduction in drag coefficient and gothic VGs give high drag.
**Determining the Reynolds Number of flow**

Before designing the VGs, we needed to determine what Reynolds Number will we be operating at. For this, we had to approximate or know the speed of airflow in the PDE. Equation 1 below shows how to calculate this value.

\[
Re = \frac{\rho V x}{\mu}
\]

| Variable Meaning | Value at Sea Level |
|------------------|--------------------|
| \(\rho\)         | Air density [kg/m\(^3\)] | 1.205 |
| \(V\)            | Stall speed [m/s]     | -     |
| \(x\)            | Chord length [m]      | -     |
| \(\mu\)          | dynamic viscosity [kg/m-s] | 1.983*10^-5 |

*Figure 4. The equation for the Reynolds Number Calculation*

**Determining the length of VGs**

As per the various research works published, the length of your VGs should be around 5-8% of the chord length of the flow surface. In our case, the flow surface was the entire detonation chamber which was 1200mm in length. Hence, we decided to select an optimal value of 75mm.

The VGs should be placed just in front of the laminar to the turbulent transition of the boundary layer on the flow surface. But, our case did not match with other conditions where the flow is over a wing or an airfoil. Hence, we decided to place VGs at an even distance to one another in a spiral fashion throughout the detonation chamber.

**Determining the height of your VGs**

The shape and size of PDE are similar to a narrow tube and theoretically, the height of the boundary layer in a narrow tube is equal to the thickness of the narrow tube. Hence, we decided to use the height of VGs at 68mm. Each of these small elements creates a swirling wake that places energy in the boundary layer of the wing.

**RESULTS**

**CAD MODELS**

*Figure. 5(a) Isometric View of the combustion chamber with Shchelkin Spiral (b) Isometric View of Shchelkin Spiral*
SIMULATION

ANSYS FLUENT software was used to carry out the simulation with the $k$-$\varepsilon$ model used. The use of the Species transport model was done. The number of iterations performed was 300 to initialize the solution as shown in Figure 7.

*Figure 7. Total number of Iterations*
PRESSURE

It is observed that the initial detonation pressure rise occurred at .2m in the tube from the front end which shows the highest rate of the reaction being occurred at that location.

TEMPERATURE

The sharp increase in the temperature can be seen to be 2270K initially which afterward takes a constant value of 2200K similar to the pressure distribution. The temperature is observed at .350m in the tube from the head as shown in the figure below.

This verifies that the hydrogen-mixture can be used with just a one-step chemical reaction to emulate the ZND behavior of the model.

CJ VELOCITY

To calculate the CJ velocity, the average wave velocity is done at different locations inside the tube by using the formula of displacement to the total time elapsed. The displacement values at the peak pressure waves were taken from the distance of .25m to .6m inside the tube from the head end which was calculated to be approximately 2246 m/s and is similar to the results obtained by Vizcaino[22].
Figure 11. Wave velocity profile

Table 4 Wave Velocity Measurement

| Distance [m] | Flow Time [s] | Velocity [m/s] |
|--------------|---------------|----------------|
| 0.1          | 0.000045      | 2020           |
| 0.2          | 0.00007       | 2190           |
| 0.3          | 0.00015       | 2100           |
| 0.4          | 0.00018       | 2410           |
| 0.6          | 0.00030       | 2510           |
| Average      | 0.00030       | 2246 m/s       |

CONCLUSION AND FUTURE RECOMMENDATIONS

The use of a two-dimensional pulse detonation engine was done in the work to simulate one-dimensional wave propagation. A lean hydrogen-air mixture was used as the fuel species in the species transport model. The verification of C-J and the ZND model was done which showed that they could be simulated even with the use of a vortex generator as the obstacle. From the results, it was seen that
DDT happened around 0.6 m in the chamber, proving the Vortex generator as a suitable turbulence inducer inside the chamber. The Optimum Blockage ratio of 54.9% is achieved in single pulse detonation. On introducing Blockage Ratio, there is a successful coupling of flame and shock fronts to produce a detonation wave.

For future works, it is recommended to use other designs of the chamber to study their effects in the combustion and the detonation. Also, multiple cycle detonations can be performed for accurate and real-time visualization of the combustion.

ACKNOWLEDGEMENTS

The authors would like to thank Prof. BB Arora for providing workspace and the necessary equipments to carry out the research.

AUTHOR'S CONTRIBUTION

The contribution of the authors to this work is equivalent. All authors have read and approved the final manuscript.

FUNDING

Not applicable

AVAILABILITY OF DATA AND MATERIALS

All data generated or analyzed during this study are included in this published article with appropriated citations.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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