Numerical Modelling of Valveless based Pulse Detonation Engine

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Abstract— **The Pulse Detonation Engine (PDE) is considered to be a propulsion system of next generation air vehicles. Structural simplicity and performance reliability enabled pulsejet to be exemplary for the use in mini aerospace vehicle. The objective of the present study is to model an efficient Pulse Detonation Engine. A number of simulation are done in order to understand the flow field variation and PDE performance. CFD software FLUENT is used to simulate the influence of single and double inlet PDE performance. In the current study, single and double inlet engines are drawn and meshed in GAMBIT and later on imported to FLUENT for analysis. The results of the simulation were discussed using velocity, pressure contours and with various other plots. The preset paper can be used as a reference for future enhancement.**
Keywords—Pulsejet, Valveless pulsejet, k-ε Turbulence Model, Pulsejet Combustor, Pulsejet Combustion.

I. INTRODUCTION

The Wright brothers in 1903 performed the first powered flight, on an aircraft which was driven by a propeller and powered by a reciprocating internal combustion engine. In 1939 the German Heinkel company flew the first turbojet powered aircraft, the HE178. Ever since then, the gas turbine engine has become the pillar for the industry in energizing aircraft, ships, tanks and electric power plants. Larger propelled aircraft and helicopters are powered by turboprop or turbo shaft engines, which are limited to the low to mid subsonic regimes, because the propellers get extremely noisy and lose propulsive efficiency significantly over 550 kmph [6]. After the introduction of the gas turbine engine no major change took place in engine technology that is revolutionary enough to replace the gas turbine engine, while providing better performance in terms of thrust, fuel efficiency, costs and range of Mach number of operation. Only the pulsed detonation engine (PDE) has the capability to offer all the above and more [7-10].

A PDE is a type of propulsion system that can potentially operate from subsonic up to hypersonic speeds. Pulse detonation engines are light weight, simple in construction and produce large thrust. Before the mid 1950’s a lot of significant works on the pulsejet were conducted and researches were abandoned due to its low efficiency. However, due to its great heat capacity intensity, air breathing, simplicity, high thrust to weight ratio, less moving parts and extremely low cost has gained pulsejet enormous research attention over the past two decades. Operating principle of a pulsejet is that of a thermodynamic cycle. Valve less pulsejet, it strictly depends on the dynamics of the pressure waves in the intake and exhaust. When a working cycle of pulsejet is completed, due to the inertia of the exhaust hot gasses an over expansion occurs, which creates a negative pressure on the combustion chamber in turn. And then fresh air and fuel are inhaled into the combustion chamber and are auto ignited by remaining hot products by last working cycle. As to china style pulsejets, inlet of the pulsejets acts as an aerodynamic valve, which helps to ignite fresh air-fuel mixture. Then the cycle repeats itself. [1-5]. The PDE is an internal combustion reaction engine that works in a pulsed cyclic fashion utilizing a constant volume combustion process [9]. In that sense, it is similar to the pulsejet which uses deflagrated combustion and has traditionally only been applied for subsonic applications. PDEs, on the other hand, use periodic detonation waves and can theoretically operate up to about Mach 5, when the total temperature at the inlet becomes higher than the auto-ignition point of most fuels. With appropriate design and control techniques, it has been evaluated that PDEs can be operated up to about Mach 8.

In the current study, Computer simulation software is used to study the flow characteristics of the pulse detonation engine and FLUENT software is used for the simulation. Simulation main objective is to study of flow in the PDE so that any important factor that contributes to total pressure, velocity distribution may be identified.

The volume for the PDE is imported to gambit. Completion of the points to make the sketch as well as meshing is also done on gambit. Hex mesh is chosen to analyze in depth of the air flow inside the PDE. The meshed file is then exported from the gambit and later on imported into FLUENT where analysis is carried out. Based on the result the model is varied.

II. GOVERNING EQUATIONS

The inlet mass flow relations are governed by the equations of continuity, momentum equation, energy equation and equation of state in conservation (2.1).

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The mass flow rate at the inlet can be determined using the continuity equation:

$$\dot{m} = \rho U_1 A_1 = \rho U_2 A_2 \tag{2.1}$$

Bernoulli equation:

$$p_{01} = p_1 + \frac{\rho U_1^{\,2}}{2} = p_2 + \frac{\rho U_2^2}{2} + \Delta p_{1-2} \tag{2.2}$$

Continuity equation in conservation form

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \vec{v}) = 0 \tag{2.3}$$

Momentum equation in conservation form

$$\frac{\partial(\rho u)}{\partial t} + \nabla.(\rho u \vec{V}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \tag{2.4}$$

Energy equation in conservation form

$$\rho \frac{\partial}{\partial t}\left[\left(e + \frac{V^2}{2}\right)\right] + \nabla.\left[\rho\left(e + \frac{V^2}{2}\right)\vec{V}\right] = \rho\dot{q} - \frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \rho\vec{f}.\vec{V} \tag{2.5}$$

Equation of state

$$P = \rho R T \tag{2.6}$$

Turbulent kinetic energy k

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + 2\mu_t E_{ij} E_{ij} - \rho\epsilon \tag{2.7}$$

Turbulent dissipation rate ϵ

$$\frac{\partial(\rho\epsilon)}{\partial t} + \frac{\partial(\rho\epsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\epsilon}\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k} 2\mu_t E_{ij} E_{ij} - C_{2\epsilon}\rho\frac{\epsilon^2}{k} \tag{2.8}$$

III. NUMERICAL ANALYSIS

A. Geometry

The design is done by the Gambit in a 2 dimensional aspect. The purpose of these was to determine the pressure and velocity variation. The proper dimensions are collected and implemented.

Table 1 Co-ordinate for single inlet pulse detonation engine

X axis	Y axis
0	80
0	40
2.5	77.5
2.5	42.5
370	77.5
370	42.5
520	120
520	0
455	60
451.78	100.67
418.16	91.13
411.965	132.514
390.4	105.445
335.505	132.514
335.505	105.445
333.005	135.014
333.005	102.945

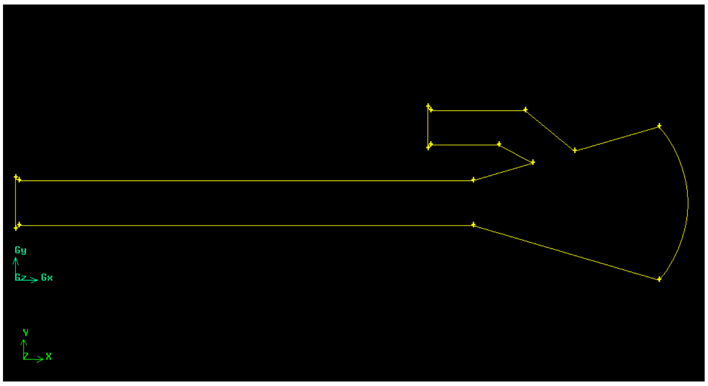

Figure I : Design of one inlet Pulse detonation engine

Table 2 Co-ordinate for two inlet pulse detonation engine

X axis	Y axis
0	80
0	40
2.5	77.5
2.5	42.5
370	77.5
370	42.5
520	120
520	0
455	60
451.78	100.67
418.16	91.13
411.965	132.514
390.4	105.445
335.505	132.514
335.505	105.445

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333.005	135.014
333.005	102.945
418.106	28.87
451.781	19.329
390.4	14.555
411.965	-12.514
335.505	14.555
335.505	-12.514
333.005	17.055
333.005	-15.014

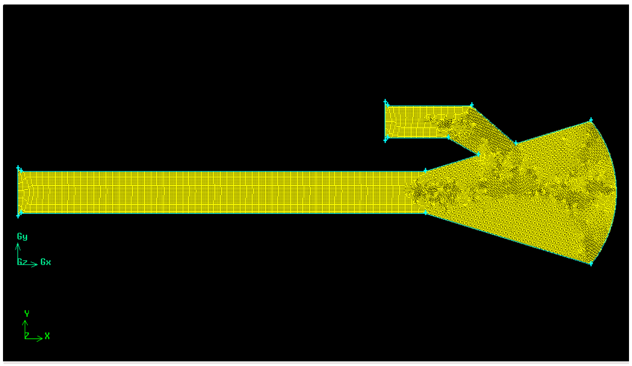

Figure 2 : Design of two inlet pulse detonation engine

B. *Meshing*

In the meshing of the 2D model, the element chosen is Quad/Tri and the type is Map. The Quad/Tri element is chosen because GAMBIT will automatically mesh the entire face and cover more comprehensively the sharp corner of the geometry.

Figure 3 Meshing in one inlet PDE

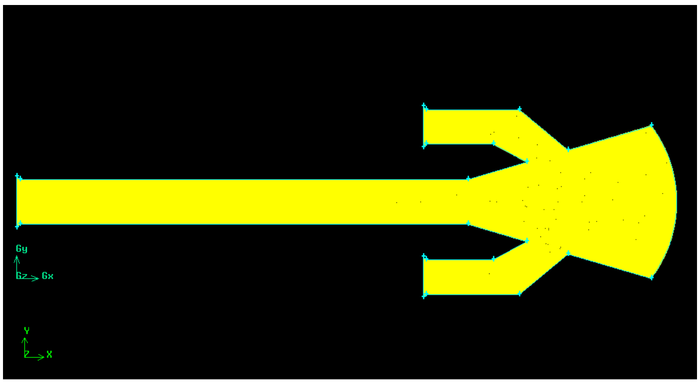

Figure 4 Meshing in two inlet PDE

C. *Boundary condition*

Solver	Pressure based
Space	2D
Velocity Formulation	Absolute
Gradient Option	Green-Gauss Cell Based
Formulation	Implicit
Time	Steady
Porous Formulation	Superficial Velocity
Viscous Model	k-ε model
Material	air
Density	1.225
Viscosity	$1.7895e^{-05}$
Operating Pressure	101325
Velocity Magnitude	100m/s

D. *Performance Measures Used*

Table 3 Case 1: Pulse detonation engine with 1 inlet

quadrilateral cells	29222
2D pressure-outlet faces	40
2D wall faces	1374
2D velocity-inlet faces	32
2D interior faces	57721
nodes	29946

Table 5 Case 2: Pulse detonation engine with 2 inlet

quadrilateral cells	231197
2D pressure-outlet faces	107
2D wall faces	4143
2D velocity-inlet faces	172
2D interior faces	57721
nodes	233409

E. *Results and Discussions*

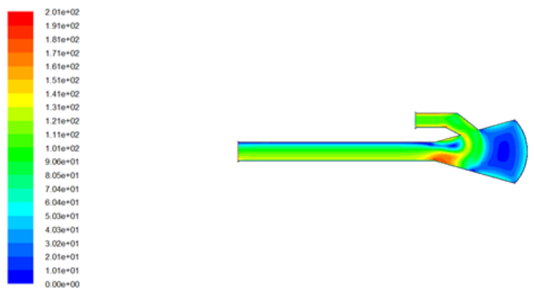

Figure 5: Contours of Velocity Magnitude for 1 inlet PDE

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Figure 6: Contours of Total Pressure for 1 inlet PDE

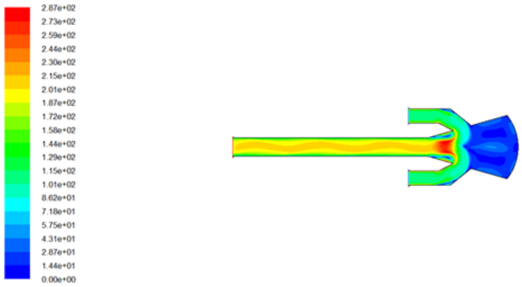

Figure 7: Contours of Velocity Magnitude for 2 inlet PDE

Figure 8: Contours of Total Pressure for 2 inlet PDE

From analysis it has been found out that the one inlet PDE will provide a maximum velocity of 120-130 m/s while two inlet PDE provides a maximum velocity up to 200 m/s. Velocity steeply decreases in the one inlet PDE plot when compared to the two inlet where the velocity gradually increases at the beginning and stay at the maximum velocity over a period of time and gradually decreases towards the end.

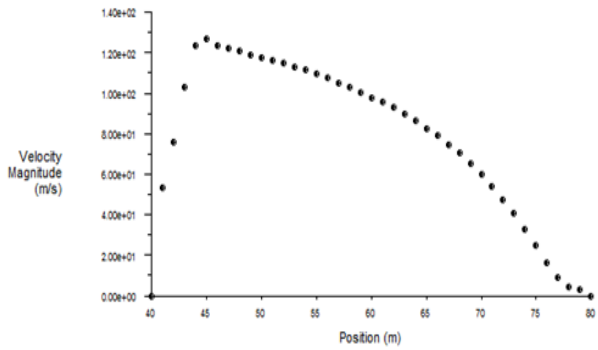

Figure 9: Velocity magnitude of one inlet at the exhaust

In one inlet PDE, contours of velocity magnitude gives no velocity at the upper side of exhaust outlet. Velocity is maximum between the region towards the end of the combustion chamber and starting of the exhaust section.

In two inlet PDE, Velocity is almost uniform in the exhaust section. The high velocity region is found where mass from two inlets meet, which is almost exactly at the middle. The velocity at the mid-section of the exhaust tube is having the highest velocity and it gradually decreases towards the sides which is even higher than the one inlet PDE.

The tight corners in the inlet section of the PDE has to be smoothened to a curved surface since a region of no velocity is formed at the tight corners of the inlet section.

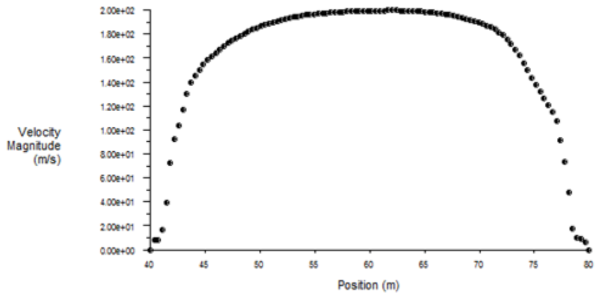

Figure 10: Velocity magnitude of two inlet at the exhaust

F. *Conclusion*

The work on valveless pulse detonation engines presents an interesting view on how the flow inside the PDE takes place. This also leads to future work that can be done to experimentally test these jets based on the CFD presented. Several conclusions that can be drawn from the work presented above are:

1. PDE with one inlet shows velocity 120-130 m/s while two inlet PDE provides a maximum velocity up to 200 m/s at the exhaust.
2. CFD analysis of the model shows the flow pattern that can be used as a great benefit for the future work.
3. This experiment proves that inside of having a single inlet for a pulsejet, a multiple number inlet gives more efficiency and advantage.
4. Regions near the inlet where there are tight corners needs to be blended in order to smoothen the air flow thereby increasing the velocity at the exhaust.
5. Contour images of velocity and pressure identifies where the changes in the system has to be made to improve the model.
6. Model can be used as a reference and reengineering in it will further enhance the efficiency of the model.
7. From the computational investigation, it has been analyzed that two inlet is more efficient than a single inlet in the above design.

G. *Acknowledgment*

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