Numerical Comparison between Two Tailpipe Shapes of Valved Pulsejet Engine

Kadim Karim Mohsen and Zaid Hashim Hussain

Dept. of Mechanical engineering, College of Engineering, Thi-Qar University, Iraq
E-mail: dkadim2020@utq.edu.iq

Abstract. In this article, the valved pulsejet engine has been numerically investigated using Ansys/fluent (CFD) program. The designed model has a 1400 cm length and 17 cm combustion chamber diameter connected with one of two different shapes of exhaust pipe that has the same length (45 cm). The first shape has a 12 cm constant diameter abbreviated by the constant D; the second has a differential diameter in which the near and far ends are having 12 cm and 15 cm, respectively, and also denoted by different D. The conclusion was the maximum velocity is the same value (46 m/s) in the two cases but centered at the beginning of different D case. In the constant D case, the velocity was distributed in the last 45 cm of the exhaust pipe. The maximum pressure generated in the combustion chamber in the constant D case is twice the value compared to the second case. In the case of different D, the pressure curve has a rather strange behavior. The temperature distribution exhibits the same behavior in both cases, but the engine has a different diameter tailpipe generate temperature more significant than the second case by 10%.

Keywords. Pulsejet engine valved pulsejet, Pulsed-combustion, Computer fluid dynamic (CFD), Numerical simulation of pulsejet, Eddy dissipation model, Jet propulsion.

Nomenclature

| x, y, z | Coordinates | u, v, w | Velocity components |
|---|---|---|---|
| t | Time | p | Pressure |
| ρ | Density | $E_T$ | Total energy |
| τ | Stress | q | Heat flux |
| $R_s$ | Reynolds number | Pr | Prandtl number |

1. Introduction

The pulsejet engine is an unsteady propulsion engine, produces discontinues thrust [1]. This engine type has many disadvantages: high vibration, high noise level, and a very high percentage of fuel conception [2]. Despite all these mentioned disadvantages, the pulsejet engine has a unique advantage as a high thrust to weight ratio[1], simple design, and it can be delivered intermittent thrust at zero velocity; therefore, it can be used for take-off vehicle. It is a tube in one end of a valve system (mechanical or aerodynamic valve); the one-way valve allows air to enter the combustion chamber, ignition, and fuel injection systems, and finally, the tailpipe (exhaust)[2]. Pulsejets are classified as a valve, valveless, and pulse detonation engine(PDE) [3]. A Sweden man Martin Wiberg (1826–1905), developed the first pulsejet engine, and Karavodin had got a patent in 1906 while in 1907 completed engine work. Simultaneously, with Karavodin, the valveless was invented in 1907 by Marconnet in
France, which consists of an inlet diffuser, combustion chamber, and long exhaust pipe. In 1939 the significant development was made by a German engineer Paul Schmidt for the most infamous engine Argus V1 then was known as Schmidt Argus V1 pulsejet that used to power the Fieseler Fi 103 V-1 “Buzz Bomb” that used in WWII. After WWII, the usage of the pulsejet engine was limited [3].

1.1. Thermodynamic cycle
Any vehicle equipped with a pulsejet engine. In-flight, the air is forced to enters the combustion chamber (air pressure increase) and mixed with fuel coming from the fuel injection system. The mixture now is ready to react; the ignition system is fire for one time and gets off ultimately. The combustion happens, and gases flow at a velocity higher than its inlet due to kinetic energy gain from combustion, therefore exit from the tailpipe. During discharging burned gases from the exhaust, the combustion chamber pressure is dropped, and part of the flame gases return to the chamber to ignition the second cycle[1].

1.2. Literature survey
Wan et al. (2005) performed a numerical simulation of micro and large pulsejet engines (0.02 m) and (0.5 m) long, respectively, compared to the gas-dynamic behaver in tailpipes. For two different models, minimum pressure is low, the frequency of operation inversely proportional to exhaust pipe length. In the case of the micro pulsejet engine, by the estimation of the thickness of the boundary layer, the researchers approved that the viscosity of gas cannot be neglected [4]. Nakano et al. (2006) these researchers studied the exhaust pipe geometry of the pulsejet engine and its effect on shock wave and also on compression and expansion wave growth. This work was done numerically and experimentally; the first shape has a pipe form with a constant diameter; the second has the same length but has a diffuser shape at the end. Because of the use of flare shape exhaust, the period time for one cycle was shortened, and the vacuum pressure generated inside the engine got lower than the atmospheric pressure in comparison with vacuum from another shape. The conclusion was that the air intake significantly increases when using a divergent (flare) exhaust tube [5]. As pointed out by Joseph Kalyan Raj Isac et al. (2014), using a CD-adapco’s STAR-CCM+CFD package, they concluded from their study that any change in the geometrical parameter affected on the operation of the engine. They also found that the presence of a flare enhances the working of a pulsejet and the close agreement in the frequency of operation [6]. Liu et al. (2016) put a small valved pulsejet engine on an experimental table equipped with all systems it needs for operation and collecting data like (fuel system, ignition system, TR-PIV system, and ITIS system). They found that the fuel flow is inversely proportional to the pulsation period and vertically with pressure and pulse combustion[7]. Finally, Anand et al. (2019) used an actual Argus V1 engine to investigate the pulsejet engine experimentally and to measure the exhaust flame shape, noise, engine body, and exhaust gas temperature, the time between valve open and ignition. They found that the noise produced reach 128 dB. Moreover, the engine behaves like a “Helmholtz resonator,” not as previously known quarter-wave behavior [8]. To this time, there is no law governing the design and operation of pulsejet engines; for this, any additive idea or unique design is subjected to trial and error, and the results are unpredictable [7]. Due to that, and from the preview of research papers, there is a gap in the study the tailpipe geometry and what is the effect of the divergent exhaust pipe on operation phenomena and gas dynamic behaver in the pulsejet engine. Therefore, in this paper, two cases of pulsejet engines have two shapes of the tailpipe are investigate.

2. Numerical simulation

2.1. Assumption
The three-dimension model is unsteady, viscose, and compressible flow, with heat transfer and neglect the radiation. The first shape has a 17cm diameter and 25cm length combustion chamber connected with a 12cm constant diameter (Constant D) and 90 cm long tailpipe as shown in Figure 1a; the second is very similar to case one, but the exhaust pipe has a differential diameter (Different D) in the last 45cm, the diameter started with 12 cm then gradually increase to 15cm as shown in Figure 1b.
The 3D model was drawn by SOLIDWORKS 2019; the drawing files are forwarded to Ansys/Fluent 19.2 program to complete simulation progress, starting from adding material to the meshing step, which is considered very important because of the direct proportion between element number and solution accuracy. There is no heat loss from the engine wall. Table 1 shows the initial and boundary conditions used to simulate the valved pulse jet engine for 3.3 sec.

Table 1. Important settings in simulation.

| Settings             | Value                                      |
|----------------------|--------------------------------------------|
| Element size         | 10 mm                                      |
| Element number       | 614000                                     |
| Time step size       | 0.01 sec                                   |
| Engine material      | stainless steel 316                        |
| Fuel                 | propane-air                                |
| Boundary condition   | Pressure outlet                            |
| pressure             |                                             |
| Fuel inlet           | 40 m/s                                     |
| Air inlet            | velocity = 5 + sin 6.28 t                  |
The one-way mechanical valve of this engine is a controller for the flow of fresh air to the combustion chamber and completely close when combustion happens; therefore, has been used sinusoidal equation \( v = 5 + \sin 6.28 t \) to simulate the flow of air to the combustion chamber in order to achieve intermittent combustion as shown in Figure 2, which represents the drawing of air inlet equation for one second, the positive velocity axis represents the valve is open and the negative axis the valve is close.

\[ v = 5 + \sin 6.28 t \]

**Figure 2.** Velocity profile of air inlet.

The suitable combustion model in Fluent program settings for pulsejet engine operation was the single step eddy dissipation in the fluent program, the single-step eddy dissipation model has been used to simulate the chemical interaction of propane-air inside the combustion chamber of a valved pulsejet engine. The important settings are shown in Figure 3; the viscous model is k-epsilon to simulate the turbulent flow.

**Figure 3.** Viscous model settings.
2.2. Governing Equation[9]

Continuity equation:

\[
\frac{\partial p}{\partial t} + \frac{\partial (pu)}{\partial x} + \frac{\partial (pv)}{\partial y} + \frac{\partial (pw)}{\partial z} = 0
\]  

(1)

Momentum equation:

\[X - \text{momentum:} \quad \frac{\partial (pu)}{\partial t} + \frac{\partial (pu^2)}{\partial x} + \frac{\partial (puv)}{\partial y} + \frac{\partial (puw)}{\partial z} = - \frac{\partial p}{\partial x} + \frac{1}{Re_1} \left[ \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} \right]
\]

(2)

\[Y - \text{momentum:} \quad \frac{\partial (pv)}{\partial t} + \frac{\partial (puv)}{\partial x} + \frac{\partial (pv^2)}{\partial y} + \frac{\partial (pww)}{\partial z} = - \frac{\partial p}{\partial y} + \frac{1}{Re_1} \left[ \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} \right]
\]

(3)

\[Z - \text{momentum:} \quad \frac{\partial (pw)}{\partial t} + \frac{\partial (puw)}{\partial x} + \frac{\partial (pww)}{\partial y} + \frac{\partial (pw^2)}{\partial z} = - \frac{\partial p}{\partial z} + \frac{1}{Re_1} \left[ \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right]
\]

(4)

Energy equation:

\[
\frac{\partial (E_r)}{\partial t} + \frac{\partial (uE_r)}{\partial x} + \frac{\partial (vE_r)}{\partial y} + \frac{\partial (wE_r)}{\partial z} = - \frac{\partial (up)}{\partial x} - \frac{\partial (vp)}{\partial y} - \frac{\partial (wp)}{\partial z} - \frac{1}{Re_1Pr_1} \left[ \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right] + \ldots
\]

\[\frac{1}{Re_1} \left[ \frac{\partial}{\partial x} (u \tau_{xx} + v \tau_{xy} + w \tau_{xz}) + \frac{\partial}{\partial y} (u \tau_{xy} + v \tau_{yy} + w \tau_{yz}) + \frac{\partial}{\partial z} (u \tau_{xz} + v \tau_{yz} + w \tau_{zz}) \right]\]

(5)

3. Result and discussion

The two curves below (Figure 4) show essential values. First, the maximum pressure generated in the combustion chamber in the Constant D case is twice the value compared to the second case; this makes the engine with Constant D tailpipe more efficient because of its higher compression ratio. The second is the divergent shape in Different D case did not let the combustion chamber pressure reach to its maximum value in the moment of an explosion.
Figure 4. Pressure curves along with engine body (a) Different D , (b) Constant D

Figure 4 shows the profile of pressure in general, but figure 5 explains the distribution of pressure on the engine body has been shown.
Due to the combustion presented in Figure 6b and 7b, the velocities (velocity and the velocity component in the x-direction) values increase gradually after the combustion chamber until reaches its greatest value at the last 45cm of the exhaust. In the second case, as shown in Figures 6a and 7a, the matter is so different, the velocities are decreases once it enters into the diffuser section of the exhaust pipe. The difference in maximum velocity concentration between the two cases is due to the effect of divergent shape on the behavior of exhaust gas flow.
Figure 6. Velocity contour (a) Different D (b) Constant D.

Figure 7. u-velocity (in X -direction) contour (a) Different D (b) Constant D.
The cross-section contour for u-velocity in the exit zone has been shown in Figure 8. In the Different D case (Figure 8a), the velocity grows from 16.9 m/s to 22.8 m/s, then to 28.8 m/s, finally reach to fully developed velocity at 34.7 m/s. This linear increase in the wide boundary layer of the flow field is terrible, especially in the exit zone of the jet engine. The Constant D case (Figure 8b) has a relatively small boundary layer thickness, and the flow reaches to fully developed velocity of 41.8 m/s. The difference in the value of fully development velocities and boundary layer thickness in the two cases return to the different the centering of maximum velocity along the tailpipe.

Figure 8. Boundary layer and U velocity (in X-direction) at the exit plain (a) Different D (b) Constant D.

Figure 9 explains the velocity profile in the two cases and explains that in Different D cases how the velocity suddenly decreases when exhaust gases inter to the last 45 cm of the engine.
Temperature degree was somewhat similar in the two cases; only the different D case temperature is greater by 10% from the other case, Figure 10.
4. Conclusions

- The divergent shape in Different D case did not let the combustion chamber pressure reach to its maximum value in the moment of the explosion; therefore, the magnitude of pressure in the engine with constant diameter exhaust pipe was greater by twice from the other case, also make the pressure curve of different D case was simply rather strange.
- The maximum velocity was the same in the two cases but centered in the mid-length of the tailpipe of Different D case and distributed in the last 45 cm of the second case.
- The temperature distribution almost the same in the two cases, but the engine has a different diameter tailpipe generate temperature greater than the second case by 10%.
- The boundary layer in the pulsejet engine is variable and cannot be negligible.
- When flow inside the engine is subsonic, the pulsejet engine that has a constant diameter exhaust pipe was having better compression ratio and gas dynamic than the different D case.

**Figure 10.** Temperature distribution at the wall (a) Different D (b) Constant D.
5. References

[1] T Geng, M A Schoen, A V Kuznetsov and W L Roberts 2007 Combined Numerical and Experimental Investigation of A 15-Cm Valveless Pulsejet (Flow, Turbul. Combust) vol 78 no 1 pp 17–33

[2] A L Kay 2002 German Jet Engine and Gas Turbine Development 1930-45 (Airlife)

[3] A F El-Sayed 2016 Fundamentals of Aircraft and Rocket Propulsion (Springer)

[4] Q Wan, W L Roberts and A V Kuznetsov 2005 Computational Analysis of the Feasibility of a Micro-Pulsejet (International Communications in Heat and Mass Transfer) vol 32 no 1–2 pp 19–26

[5] K T Toshihiro NAKANO and Shigeru MATSUO 2006 Effect of Exit Geometry of Tail Pipe on the Performance of Pulse Jet Engines (Therm. Sci.) vol 15 no 3

[6] V K K Joseph Kalyan Raj Isaac, Logu Mohanraj and Enumula Srikar Sai 2014 Numerical Simulation of a Hydrocarbon Fuelled Valveless Pulsejet (Propuls. Power Res.) vol 3 no 2 pp 90–95

[7] M Liu, L Yu and W X Cai 2016 Experiment Analysis of Combustion Performance in Pulse Jet Engine (Energy Procedia) vol 100 pp 248–252

[8] V Anand et al 2019 Revisiting the Argus Pulsejet Engine of V-1 Buzz Bombs: an Experimental Investigation of the First Mass-Produced Pressure Gain Combustion Device (Exp. Therm. Fluid Sci.) vol 109 p 109910

[9] NASA Naver stock equation, https://www.grc.nasa.gov/www/k-12/airplane/nseqs.h