

Design and Fabrication of Valve Pulse Jet and Simulation using FEA Technique

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Abstract

Pulse jet works on the principle of Kadenacy effect and produces thrust due to combustion, occurring in pulses. This paper focuses of the construction of small scale valve pulse jet. Air fuel mixture enters through reed valve into the combustion chamber and gets ignited by the sparkplug produces tremendous energy which results in expansion of gases to produce thrust. The above model is generated in Solid works software, and the structural and thermal analysis is carried out using ANSYS Workbench platform, a finite element technique. The results which are obtained are validated with the existing work.

Keywords: Kadenacy Effect, Thrust, Reed Valve, Venturi Effect, Fea, Combustion Chamber

Introduction

Pulse Jet engines are a type of air breathing engines which are capable of being operated statically. It can be made with few or no moving parts and has one of the simplest designs from manufacturing aspects. Pulse Jet engines are easy to build on a small scale as the total cost of construction is much cheaper than a turbine engine. The type of Pulse Jet engine that we aim to build is called Valved Pulse Jet and employs reed valves in the main heart of the engine. These engines can run on most substances that can burn which make them a considerable asset in the alternative fuel area of research. The main characteristics of Pulse Jet Engines are: simplicity, low cost of construction, high noise levels & excellent thrust to weight ratio/ Since Pulse Jet engines emit very high levels of noise, they are mostly used for military and industrial purposes. These are used today in target drone aircrafts, fog generators and industrial drying and heating equipment. Since Pulse Jets are an efficient and an easy way to convert fuel into heat, they are also being introduced in new industrial applications such as bio-mass fuel conversion. Pulse Jet works on the principle of Kadenacy effect and thrust is produced due to combustion occurring in pulses. This thrust produced by the engine can be increased by modifying parts of the engine (Nozzle).

The main components of a pulse jet engine are: the body which is similar to a pipe, combustion chamber and ignition system and valve head. The innovation of the pulse jet can be traced back to World War II. It was used as the propulsion device for the first cruise missile. This was known as the German V-1 "BUZZ-BOMB". It was a valved type of pulse jet and its implementation can be called the first successful application of pulse jet as a propulsion device. The V-1 piqued allied interest into pulsed combustion which further

led project squid and the Hitler Aircraft Corporation (United States) to carrying out the two most noted studies. Due to the research carried out by these projects, valveless pulse jets could be applied to helicopter rotor tips. Development of "pulsation combustion" however was recorded around the 17th century. Christian Huggheens came up with the pulsating engine, which relied on gun powder. The pulsating flame was discovered in 1777 which led to the creation of many theoretical designs that utilized this phenomenon. Advantages of the Pulse Jet Engines are extreme simplicity, low cost of construction and efficient combustion. Engines of considerable size can run on any fuel and the nozzle can be modified in order to maximize thrust. Limitations of the pulse Jet Engines is: thrust grows with flight speed. This can be mistaken for a pro, but since this would require more acceleration, it is taken as a con. Has comparatively low fuel efficiency. The fuel energy is converted to other forms of energy high levels of vibration. Heat resistant materials are necessary for design. Are not suitable for supersonic speeds.

Related Study

It should be noted that there is no specific and palpable law on which the working of a Pulse Jet is based on; therefore, all new innovations relating to the Pulse Jets are done on a trial and error basis. A considerable reason that the earlier Pulse Jets have not fulfilled their expected potential is that it is extremely complex and difficult to come up with a mathematical model, as such the entire theoretical study on the topic of Pulse Jet engines have not been completed till date. This being said, construction of a Pulse Jet engine is a comparatively simple task and so there exists numerous records of Pulse Jet engines being built. However, the lack of complete understanding at the present time hinders prediction and considerable modification/improvement of the engines performance [1]. the purpose of the entire investigation and study of this project was to check if gasoline, propane, military grade JP-8 etc. can be used for

UAV (unnamed aerial vehicle) and military purpose. After successful operation, all the data was acquired and the modifications were thoroughly studied and analyzed for optimum understanding. And it was understood that both the hobby scale pulse jets ran smooth upon using kerosene as fuel [2]. One of the experiments that we must note was the work done by the Hiller aircraft Corporation on scaling down the valve less Pulse Jets. The smallest Pulse Jets they were able to operate was recorded to have a combustion chamber diameter of 19cm and its overall length was up to 36 cm. This jet relied on oxygen that were injected separately but at the same time. However, this setup was could not be operated in a consistent manner. Therefore, only the thrust data was recorded [2]. Michael Schoen directed his research towards the miniaturization of valve less pulse jets in order to bridge the gap between hobby-scale and micro-scaled Pulse Jets. This work was done to understand the physical effect that the changes in Jet geometry have on the performance of the engine. It was observed that the tail pipe length is a direct function of inlet length. Furthermore, it was observed that allowing a diverging exit nozzle in the design of the jet allows for the jet to be shortened and operated in a more consistent manner. The highlight among the conclusions drawn from Schoen's work is that the combustion time is challenged by the period of fluid mechanic oscillations, at shorter lengths. Reducing the size of the jets gives way to a rise in its inherent operating frequency. Therefore, a highly reactive fuel must be employed in order for the combustion process to keep up with the acoustic property of the engine [3]. Adam Kiker directed his focus towards developing micro-scale pulse jets. He managed to design and operate a record 8cm long pulse jet fueled by hydrogen. It was observed that the frequency of the jet measures as one over the length. It was also observed that tripling the inlet length had the same effect as increasing the overall length by 50%. Furthermore, it was recorded that although the exhaust diameter did not have any considerable impact on the operating frequency, it did however affect the peak pressure rise in the combustion chamber that is as the exhaust diameter decreased the peak pressure increased. Kiker also recorded that with increase in fuel flow rate, the operating frequency and peak pressure also rise. This experiment was also able to obtain instantaneous thrust data which should not be overlooked even though the method of measuring used was somewhat questionable [4]. Rob Ordon focused on the hobby-scale pulse jet. It had a length of 50cm and worked on either ethanol or propane. One of the highlights of this project was that Ordon had managed to make use of both valved and valve less pulse jets. This work was a significant contribution in further understanding the characteristics of the hobby-scale pulse jets and allowed Schoen and Kiker to complete the respective projects. The contribution of this project also led to the design of an analytical model which could predict the operating frequency of any valve less Pulse Jet. This model paved the way to finding the parameters that govern the design of Pulse Jets [5]. Daniel Paxson from the NASA Glenn research center conducted another noteworthy study which used a hobby-scale pulse jet similar to that of Ordon's (50cm). This Jet however ran on gasoline and was used as a model for unsteady combustion to test thrust augmenters for use in the pulsed detonation engines. Paxson focused on the relationship between the exhaust diameter, pressure of the combustion chamber, and average thrust produced [6]. The work done aims at understanding the working of the pulse jet and employs a numerical approach in doing so. The fluid mechanics and acoustic properties are analyzed in a numerical manner in order to better understand the complete physics involved in the operation of the pulse jet. The study was directed

to improve the already existent model design for valve less pulse jets, obtain the basic data on thrust of the model pulse jets, and also examine how the intake and exhaust lengths affect the thrust produced by the Jets [7]. Hussain Sadig Hussain, from university of Khartoum, under the supervision of DR. Ali Omer Ahmed, conducted a thorough research of the thermodynamic characteristics of conventional pulse jet engines and then a conceptual design and calculations of a pulse jet engine generating 100 lbs. of thrust is formulated, keeping the geometrical aspects (specific fuel consumption, thrust and frequency limitations) in frame. The objective was to estimate the dimensions of each part of the pulse jet in the simplest possible fashion. Important aspects such as inlet diffuser and exhaust nozzles effects that are significant in real applications have not been considered in this research. The primary domain of this research was to study the conventional engine and later design an elementary pulse jet engine with 100 lbs. thrust. While the study focuses on the investigation of geometrical aspects of the engine, continuous work on fuel ignition was required. Further detailed study of the pulse jet engine demanded the design to be built with suitable material and testing in lab to compare the actual thrust with the theoretical, studying the effects of changing dimensions on engine performance, Combustion chamber volume and shape, valve system type [8]. Liu Min directed his experimental research that resulted in providing the practical fundament in order to improve the performance of small jet engines. The research was carried out on an air breathing engine experimental bench that includes the fuel supply system, test collection system, ignition valve type pulse jet engine. In order to measure the characteristics of the engine including wall temperature, the concentration of the combustion products, the gas temperature and the pulse pressure, infrared thermal imaging system along with flue gas analyzer were used. The whole experiment was carried out in experimental education center of aeronautics and astronautics of Nanjing University of science and technology. Although this experimental platform is best suited for a research on small jet engine like pulse jet engine. Liu Min performed his experimental research by focusing more on comprehensive small jet engine test bed. The whole experiment resulted in the change in fuel flow of the pulse pressure, wall temp and combustion products. It was also noted that with the increase of fuel flow, the pulse combustion gets intensified [9]. K. Sainath directed his research on the pulse jet engine which have a few or no moving parts which are capable of running statically. They are light weight form of jet propulsion engines and comprises of small value compression ratio with low specific impulse. He further classified the engine into two parts viz., drafting and construction & the modification in the nozzle at the exhaust section so as to increase the thrust of the pulse jet engine. This modification of the nozzle is done in ANSYS software under Computation Fluid Dynamics (CFD). He further designed the prototype which involves in selection of material that is easy to work with. While putting it at test the compressor pressure was noted around 20-50 psi [10].

Methodology

Problem Definition: Amongst the numerous challenges that surround the project, one of the most vital objectives was to achieve thrust after the fabrication of the model was completed. During the design and analysis phase there were various stresses that needed to be handled so as to not damage the engine. Another crucial aspect of this project was to ensure that the engine cycle manages to sustain itself.

Design & Drafting

The design for this model was made in Solidworks and Creo using the 2-D and 3-D modelling. The analysis of various stresses and temperature was done with the help of ANSYS workbench. The design was subjected to thermal stress analysis, structural analysis, and modal analysis. The results attained from fore mentioned analyses proved the design would be safe and would not falter under the stress.

Construction

The construction of the desired model/engine was done with the help of knowledge gained the past 4 years. The methods employed to fabricate the various parts such as the reed valve, the valve head, combustion chamber & exhaust tube were TIG welding, laser cutting (for precision), and various operations offered by the lathe machine.

Testing Phase

After the construction, the model on hand had to be tested in order to conclude whether or not it would work as expected. The testing would also prove the analysis of the design to be accurate. Testing would also help in discovering if any modifications to the original design were needed.

Validation

Previous knowledge for this project was obtained through various research papers, published on earlier and similar projects. Such papers provided vital information for the design of the engine. Apart from research papers other sources such as books on jet propulsion also played a crucial role.

Documentation

The project is documented in the form of reports that were made at different stages of the project. The reports were used to record the progress made after specific intervals. Apart from reports, this project also has a research paper dedicated to it.

Comparison between Pulsejet and Other Similar Systems

The Pulse Jet, Turbo Jet engine, Ram Jet engine and Scram Jet engine are all air breathing engines using nozzles. The Pulse Jet and Turbo jet can be operated statically, whereas Ram Jet and Scram Jet engines cannot be operated statically. Turbo Jet engines has Moving parts, whereas the Pulse Jet, Ram Jet and Scram Jet engines have no moving parts. The inlet flow of air in Pulse Jet and Turbo Jet engines is subsonic, whereas in Ram Jet and Scram Jet engines are supersonic. The Combustion process in Pulse Jet and Turbo Jet takes place at subsonic flow of air, whereas in Ram Jet and Scram Jet takes place at supersonic flow of air. The Pulse jet and the Turbo Jet engine are IC engines, whereas the Ram Jet and Scram Jet engines don't require enclosed combustion. The Pulse Jet engine inlet consists of a valve, whereas Turbo Jet, Ram Jet and Scram Jet engine doesn't consist of valve. The Mach number for pulse jet is less than 1, whereas for turbo jet (<3.5), ram jet (<6) it is greater than 1.

Governing Principle & Working

Pulse Jet Engine works on Newton's 3rd law of motion that is forces of action and reaction between two bodies are equal and in opposite direction. It generally works on two cycles namely; Lenoir cycle and Humphrey cycle.

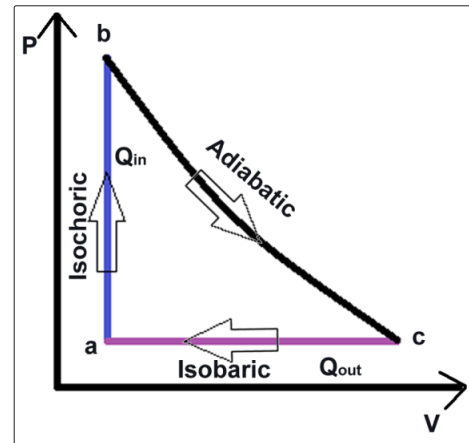


Figure 1: Lenoir Cycle [16]

- The Lenoir Cycle which consists of isentropic compression followed by constant volume heat addition and then adiabatic expansion. It consists of the intake of air and fuel at point a, isochoric combustion from a to b, and an adiabatic expansion to c.

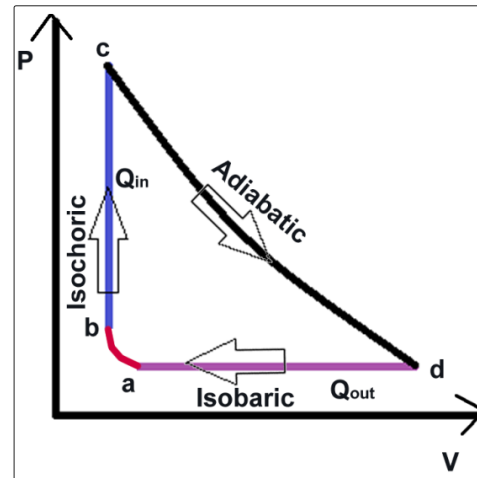


Figure 2: Humphrey Cycle [16]

- The Humphrey Cycle, which operates similarly but has an isentropic compression added to the cycle. Here small amount of compression before combustion, step a to b is added.

Fuel systems

Pulse jet engines are known for their flexibility in the fuel that they use, whether it be combustible liquid or gas. In addition to that, coal dust has also been used as a fuel occasionally. Germans were believed to have attempted to run the Argus V1 on coal dust when they were running out of options at the end of WW2. In fact, some of their pulsed combustors were specifically designed for this type of fuel. According to the summary provided by Princeton University of a lot of researches on pulse jet engines concluded that the pulsating jet engine of contemporary design experienced zero to no difference in performance regardless of the fuel used. The only drawback was regarding the obvious differences in the degree of body heating and how quick the valve was prone to total damage.

Atomization

Atomization is carried out at the front of the engine when the intake air is forced through a comparatively smaller venturi. In atomization, a very crude form of carburetor was used to produce a spray of roughly atomized fuel droplets with the intake air in engines such as Dynajet. The intake air is squeezed by a venturi that travels through a narrow entrance. This, however, results in deficiency in energy for the suction of fuel as the pressure drops when the air is squeezed. Another drawback is that the fuel droplets failed to vaporize properly because of their large size produced. But this problem is eventually solved with the help of the temperature inside the engine that helps in vaporizing the remaining's of the large droplets.

One should be extremely careful in regards to wear the fuel tank is placed due to the fact that small pulse jets are highly sensitive. The suction of the fuel will not be carried out properly if the tank is too low and conversely, if the tank is too high, the gravitational force will disrupt the flow of the fuel hence flooding the engine.

Fuel

Initially the fuel used was RC nitro fuel but due to its low combustion rate and the amount of oil mixed in it, it proved to not be appropriate for the engine. Zippo lighter fuel (naphtha) was found to be a suitable replacement due to its comparatively higher combustibility and rate of atomization. Gasoline was also given due consideration and tested with but the risks involved were found to be of serious consequences, hence further testing with gasoline was discontinued.

ANSYS Results

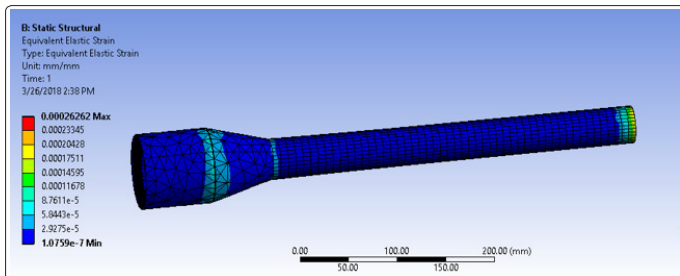


Figure 3: Elastic Strain

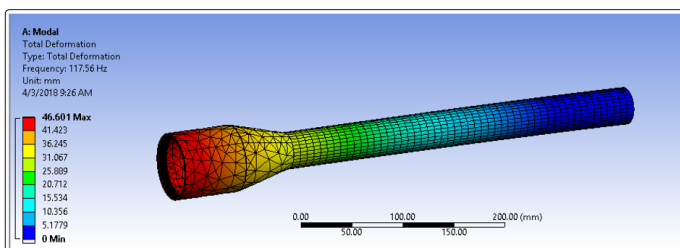


Figure 4: Modal Analysis

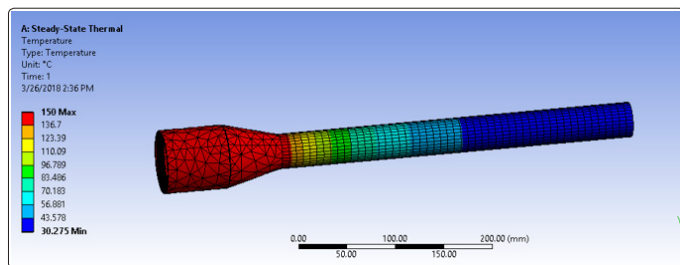


Figure 5: Temperature Distribution

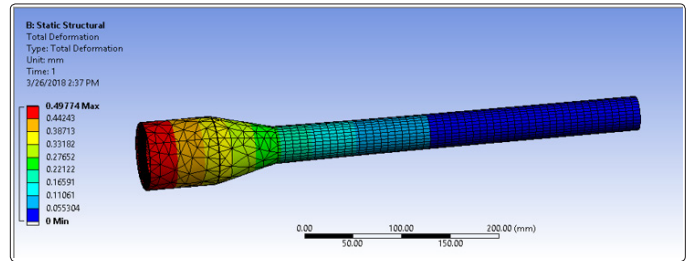


Figure 6: Total Deformation

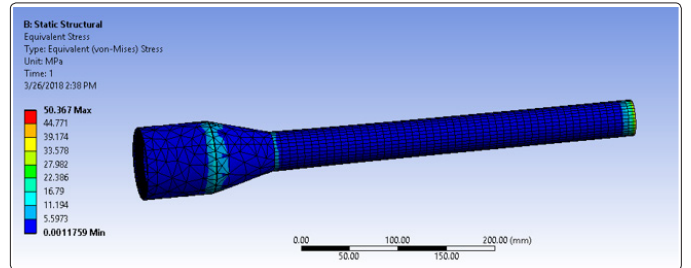


Figure 7: Equivalent Stress

Boundary condition is fixed at one end. And mesh used was fine mesh. Under these conditions total deformation was minimal (0.49 mm). Equivalent stress was 50.36 MPa which is less than the yield stress. Max temperature was 150 °C at the combustion chamber. And the vibration was 117.56 Hz. Factor of Safety = Yield Stress/ Working Stress = 4.11. In conclusion, the design is safe.

Fabrication and Construction

After the initial calculations performed at the Pulsejet Conceptual Design chapter, the final dimensions of the pulsejet are shown in the following schematics: To join the pieces together there were two welding options available: Metal Inert Gas (MIG) Welding or Tungsten Inert Gas (TIG) Welding. The former uses a consumable wire attached to an electrode; this would heat the metal sheets and join them by melting. The former, on the other hand, uses tungsten, which is non-consumable. For the project, TIG was chosen to weld the pieces together as it would more precise due to less contamination and welding shops visited only offered the use of TIG.

Reed valve

The material used for reed valve is spring steel also known as C1095. A thin sheet of this material of thickness 0.5mm was reduced to 0.01mm and cut into the desired shape by a CNC laser cutter.



Figure 8: Reed Valve

Retainer

This is spun from 0.5mm stainless steel to form a dished circle. After spinning it is polished to remove any sharp edges that could damage the valves.

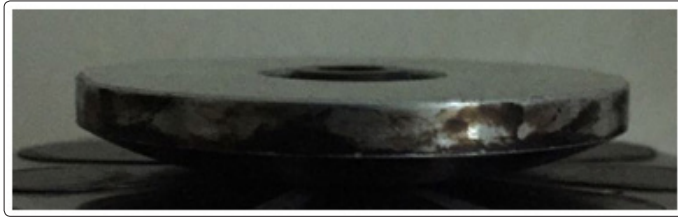


Figure 9: Valve Retainer

Straight Tube: Two sheets of stainless steel were heated and shaped against a mold and welded together. Then rolling operation, grinding the excess weld and polishing the surface for a smoother finish.

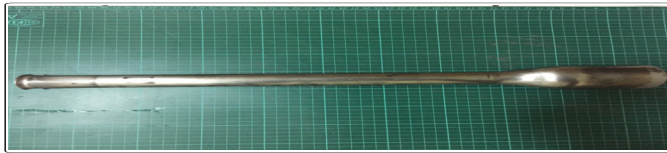


Figure 10: Straight Tube

Valve Head

The nose cone is constructed from a large, solid rod of stainless steel. It was then shaped to the stated dimensions by inputting its computer-aided design onto a Computer Numerical Controlled (CNC) lathe. The process of lathing involves, attacking a work piece onto a platform. And have it rotate about an axis. It then comes into contact with a shaping tool to cut, file or drill the piece with symmetry about the rotational axis.



Figure 11: Valve Head

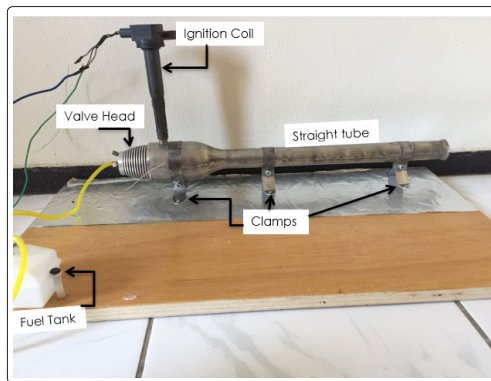


Figure 12: Assembled Pulse Jet

Results & Discussions

We know that

$$\dot{m} = \rho AV$$

Using continuity equation

$$\dot{m} = \rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

($p_1 = p_2 = p_{air}$) (Density of Fuel is not considered since air is in higher ratio)

$$\dot{m} = \rho_1 A_1 V_1 = 1.225 * 0.002827 * 10 = 0.034 \text{ kg/m}^3$$

Calculating V_2 (exit velocity)

$$\Rightarrow 0.034 = 1.225 \text{ kg/m}^3 * 0.007 \text{ m}^2 * V_2$$

$$\Rightarrow V_2 = 39.26 \text{ m/sec}$$

Calculating discharge (Q)

$$\dot{m} = \rho Q$$

$$Q = \frac{\dot{m}}{\rho} = \frac{0.034}{1.225} = 0.027 \text{ m}^3/\text{sec}$$

$$\vartheta = \frac{1}{\rho} = \frac{1}{1.225} = 0.81 \text{ m}^3/\text{kg}$$

Table 1: Experimental results of pulse jet engine

Serial No.	Inlet Velocity V_1 (m/s)	Mass flow rate (\dot{m})	Exit Velocity V_2 (m/s)	Discharge Q (m ³ /s)	Velocity Ratio (V_2/V_1)
1.	10	0.034	39.26	0.029	3.926
2.	11	0.038	44.31	0.031	4.028
3.	12	0.041	47.81	0.033	3.984
4.	13	0.045	52.47	0.036	4.036
5.	14	0.048	55.97	0.039	3.997
6.	15	0.051	59.47	0.041	3.964
7.	16	0.055	64.13	0.044	4.008
8.	17	0.058	67.63	0.047	3.978
					Avg. Velocity ratio= 3.993

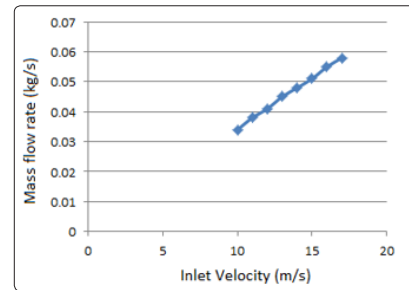


Figure 13: Graph of Mass flow Rate vs. Inlet Velocity

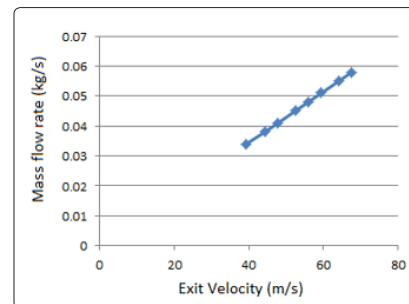


Figure 14: Graph of Mass flow Rate vs. Exit Velocity

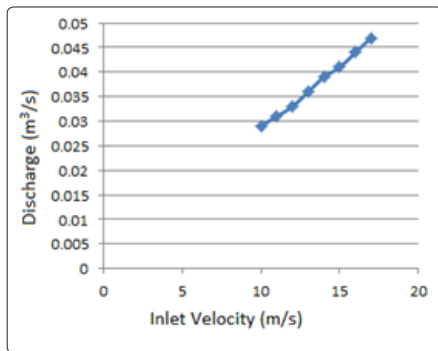


Figure 15: Graph of Discharge vs. Inlet Velocity

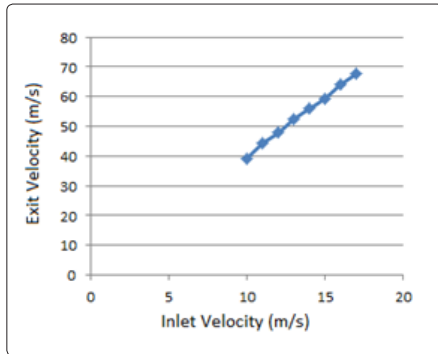


Figure 16: Graph of Exit Velocity vs. Inlet Velocity

Scope

The engine can be improved more in the future by putting it on wheels which could show the movements of the engine due to the thrust produced. Gauges could be attached to the engines which could specify the various parameters such as inlet velocity, engine temperatures (inlet and outlet), exit velocity (thrust) and the speed generated by the engine. The spark plug ignition system can be automated to make it more safe, efficient and effective. Experimenting with different fuels in order to maximize efficiency and achieve low carbon emission.

Conclusions

A model of the pulse jet was created using the Solid works software and Creo, which was then, analyzed using finite elements technique via the ANSYS workbench platform. The designed model was subjected to thermal stress analysis, structural analysis, and modal analysis. These tests help establish the integrity and safety of the model and the results proved the design would not fail under the various stressed that would occur during the operation of the pulse jet. Upon completion of the design and research about the pulse jet engine, the materials to be used for the fabrication were known. Most of the components are made using stainless steel except for the Reed valve, which is made of spring steel. The spring steel was cut into the desired shape using a CNC laser cutter. The Fabrication of valve head employed the use of a CNC lathe machine. For the straight tube; two sheets of stainless steel were heated and shaped against a mould and welded together. The straight tube and the retainer were also made of stainless steel and required manual operations. The method of TIG (Tungsten inert gas) welding was chosen to weld the pieces together as it would be more precise due to less contamination as compared to electrode arc welding. Due to low air pressure in the fuel and air injector, fuel was dripping inside

the combustion chamber instead of being atomized and sprayed. But with proper regulation of pressure, this problem was resolved to get a sustainable supply of atomized fuel. The testing phase started soon after the completion of fabrication and assembly. Initially the fuel used was RC nitro fuel but due to its low combustion rate and the amount of oil mixed in it, it proved to not be appropriate for the engine. Zippo lighter fuel (naphtha) was found to be a suitable replacement due to its comparatively higher combustibility and rate of atomization. Gasoline was also given due consideration and tested with but the risks involved were found to be of serious consequences, hence further testing with gasoline was discontinued. Instead of a conventional ignition system, an individual ignition coil (Honda F20 engine) was used to provide the spark for combustion but the spark was delivered manually instead of using a timed delivery setup. The ignition coil was placed on the spark plug and connected to a portable 12 V battery. An air compressor was initially used to pump the fuel and open the valves for the initial start-up. A portable air compressor (usually used for re-inflating tyres) was chosen for this purpose.

Nomenclature

ρ = Density [kg / m³]
 F = Force [N]
 m = Mass [kg]
 a = Acceleration [m/s²]
 \dot{m} = Mass flow rate [kg/m³]
 V = Velocity [m/s]
 Q = Discharge [m³/s]
 ϑ = Specific volume [m³/kg]
 P = Power [W]

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