Design and Development of Valveless Pulsejet Engine

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Abstract—Development of Valveless Pulse jet engine requires the careful design of an inlet, combustor, and exhaust pipe. Geometrical design and usage of materials, which primarily affects engine efficiency and performance. The design of an inlet ensures the amount of air allowed to flow towards the combustor. The thrust of the pulse jet engine depends upon the overall length and volume of fluid flowing through the pipe. Thus, the inlet pipe should be wide enough to flow towards the combustor. The design of the combustor should ensure the actual mixture of compressed air with the fuel. The exhaust pipe must be designed to allow enough expansion for the gas to provide power. The exhaust pipe should be significant in length to ensure the creation of strong pressure waves which will continuously run the engine. Aim of this research work is to develop the Valveless Pulse jet engine to operate with Liquefied Petroleum Gas. The significant effort on using the experimental method to attain the whole configuration of the valveless pulse jet engine was focused, and exit temperature for various run was presented.

Index Terms—pulse jet, valveless, combustion, temperature.

I. INTRODUCTION

A Pulse Detonation Engine (PDE) is a kind of propulsion device that can be operated from subsonic to hypersonic speeds effectively. PDE is lightweight, simple in construction, and produce significant thrust. PDE has a high thrust to weight ratio with less moving parts leads more attention and requires a lot of research in this area. Valveless pulse jet engine is similar to PDE, which controls the exhaust flow with its geometrical design as it possesses no moving parts. The gases are expelled out of both intake and tailpipe. However, the significant amount of exhaust should be discharged through the long tailpipe for efficient propulsion. The operation principle of the valveless pulse jet engine is the same except the presence of a valve in case of a valved pulse jet engine. Atomized liquid or gas can be used as fuel and is made to burn with atmospheric air in the combustor [1]. Usually, an ignition source and external compressed air are used to start an engine. Modern manufacturing techniques enable the engine to self-start without external compressor, provided only with air-fuel mixture and ignition source. Combustion will be sustained and continue to operate until the fuel supply. The primary application of a valveless pulse jet engine is to power the model aircraft, preliminary racing-kart, and an aircraft piloted by remote control, i.e., UAV. Nikolai Egorovich Zhukovsky published the original idea of the pulse jet in 1882 [2]. The research of the pulse jet engine was not established again until the late 1920s when German engineer Paul Schmidt again found the pulsed combustion principle to achieve an explosion within an engine. One of the best use of pulse jet engines exists in 1941 with the first test flight of the German V-1 flying bomb [3]. Lockwood and Hiller made a U-shape engine that produced an extremely high T/W ratio. They did several experiments to increase thrust as well for the development of a thin weight engine [4]. The length of the pipe is too small is the major problem was created in a pulse jet engine by Bruce Simpson. If the pipe is too small, then the engine won't work because all of the hot gases will leave the exhaust pipe. Thus there's nothing left to burn the new air-fuel mixture drawn during the inlet phase. If the length pipe is too large, then the exhaust gases will "explode out" and cool down too much, making it unfeasible for them to burn the fresh fuel/air mixture. The worst important thing is that most engines are far more unbiased of a too-large pipe than a too-small one. So, for better designing of the engine, the pipe should be a little larger. If the inlet area is too large of the engine, then it's challenging to suck some of the hot exhaust gases back to compress and burn the fresh fuel/air charge, and it will disappear too early. If the inlet area is too short, then not enough air-fuel mixture will be drawn into the engine to provide sufficient combustion and the engine [5], [6].

II. PRINCIPLE OF OPERATION

When air mixed with fuel and burn in the combustor, the deflagration occurs. This deflagration raises the pressure and creates a compression, which travels towards both the intake and tailpipe at the speed of sound. The air mass starts to expand due to the deflagration. The lower mass of air in the intake accelerated faster outside behind the pressure wave, but the long tailpipe proceeds slowly. The compression waves reflected as low-pressure rarefaction waves at the end of intake and tailpipe. This reflection occurs at intake first, due to the short length compared to the tailpipe. Even though the rarefaction wave is weaker, but it still reverses at the intake due to the lower mass of fluid and loads with fresh air. The combusted product expelled even when the rarefaction

TABLE I
INITIAL CONDITIONS TO OPERATE THE PULSE JET ENGINE

Area of Inlet	0.2676 m²
Initial Velocity at Inlet	102.08 m/s
Initial Pressure at Inlet	101325 pa
Initial Temperature at Inlet	288.16 K
Mass Flow rate at Inlet	22.46 kg/sec
Initial Mach number at Inlet	0.3
Initial Density at Inlet	1.225 kg/m3
Specific Heat at constant pressure	1004 J/kg.K
Specific Calorific Value of LPG	46.1 MJ/kg
Air-fuel ratio	110 : 1

waves move towards the combustor. The pressure drops at the combustor below ambient due to the drop in heat addition at the combustor end and oncoming of rarefaction waves from the tailpipe. At the same time, the fresh air is entering from the intake towards the combustor. The exhaust gases are expelled out even when the fresh air entering inside the intake due to inertial effect. The partially reflected rarefaction waves at the combustor end and moving back to the tailpipe and stays as rarefaction wave. The rarefaction wave creates a complete flow reversal at the intake with fresh air beyond the exhaust gases. Weak compression wave is then reflected back towards the exhaust outlet as a rarefaction wave. The fresh air is slowed substantially as the compression wave reaches the combustor to aid the combustion of gases that are now moving back into the combustor [7]–[10].

III. DESIGN CALCULATION

The calculation of Valveless Pulse jet Engine depends upon pressure, temperature, density , velocity , mass flow rate,and mach number. Initial parameters were given in table I.

A. Inlet section (0-1)

Standard sea level values are assumed for inlet Temperature and Pressure and inlet Mach number $M_0 = 0.3$.

Inlet Area is

$$A_0 = \frac{\pi \times d^2}{4} \qquad (1)$$
$$= 0.2676 \text{ m}^2$$

where (d) is the diameter of the inlet = 0.01846 m. Velocity of the inlet is

$$v_0 = M_0\sqrt{\gamma \times R \times T} \qquad (2)$$
$$= 102.08 \text{ m/s}$$

The velocity remains constant for constant area duct flow as per continuity equation , so $v_0 = v_1$. Now, Mass flow rate

$$\dot{m} = \rho_0 \times A_0 \times v_0 \qquad (3)$$
$$= 33.46 \text{ kg/s}$$

Now, pressure and temperature,

$$p_0 = \left(1 + \frac{\gamma - 1}{2}M_0^2\right)^{\frac{\gamma}{\gamma - 1}} \times p_1 \qquad (4)$$

Thus,

$$p_1 = 98.19 \text{ kpa}$$

and,

$$T_0 = \left(1 + \frac{\gamma - 1}{2}M_0^2\right) \times T_1 \qquad (5)$$

Thus,

$$T_1 = 283.06 \text{ K}$$

B. Diffuser section (1-2)

Using steady flow energy equation for diffuser section, we have

$$T_2 = T_1 + \frac{v_1^2}{2c_p} \qquad (6)$$
$$= 288.24 \text{ K}$$

Now,

$$p_2 = p_1 \times \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma - 1}} \qquad (7)$$
$$= 101.42 \text{ kpa}$$

Velocity can be obtained using Steady Flow Energy Equation, if the temperature is known. Thus, we can get

$$v_2 = 101.98 \text{ m/s}$$

The Mach number can obtained as

$$M_2 = \frac{v_2}{a} = 0.299$$

C. Combustor (Section 2-3)

Rayleigh's flow equations can be used to obtain velocity, temperature and pressure at exit of combustor. The air-fuel ratio of pulse jet engine is 9 gm/sec to 11 gm/sec. Thus, we get , $\dot{m}_f = 0.009 \, \dot{m}_a$.

Now,

$$T_{02} = \left(1 + \frac{\gamma - 1}{2}M_2^2\right) \times T_2 \qquad (8)$$
$$= 293.39 \text{ K}$$

Now, the heating value of LPG fuel is 46.1 MJ/kg. Thus,

$$Q = 0.009 \times 46.1$$
$$= 0.4149 \text{ MJ/kg}$$

Now,

$$T_{03} = T_{02} \left[1 + \frac{q}{c_p \times T_{02}} \right] \quad (9)$$
$$= 706.42 \text{ K}$$

and,

$$\frac{T_{03}}{T_0^*} = \frac{T_{03}}{T_{02}} \times \frac{T_{02}}{T_0^*} \quad (10)$$
$$= 0.8352$$

Thus, from the Rayleigh's flow table, we get the Mach number at exit of combustor i.e., $M_3 = 0.62$. The exit temperature of combustor will be

$$T_3 = \frac{T_{03}}{\left(1 + \left(\frac{\gamma-1}{2} \right) M_3^2 \right)} \quad (11)$$
$$= 656.46 \text{ K}$$

Now, for the exit pressure

$$\frac{p_{03}}{p_{02}} = \frac{p_{03}}{p_0^*} \times \frac{p_0^*}{p_{02}} \quad (12)$$
$$= 0.8089$$

where,

$$p_{02} = \left(1 + \frac{\gamma-1}{2} M^2 \right)^{\frac{\gamma}{\gamma-1}} \times p_2 \quad (13)$$
$$= 95.32 \text{ kpa}$$

Therefore,

$$p_{03} = 0.8089 \times 95.32$$
$$= 84.92 \text{ kpa}$$

Thus, the pressure at the exit of combustor will be

$$p_3 = \frac{p_{03}}{\left(1 + \left(\frac{\gamma-1}{2} \right) M_3^2 \right)^{\frac{-\gamma}{\gamma-1}}} \quad (14)$$
$$= 110.05 \text{ kpa}$$

Now, the density at exit of combustor will be

$$\rho_3 = \frac{p_3}{R \times T_3} = 0.5841 \text{ kg/m}^3$$

The diameter of combustor =43.75 mm. Hence Area of the combustor will be

$$A_3 = \frac{\pi \times d_3^2}{4} = 1.5033 \text{ m}^2$$

From the continuity equation, the mass flow rate = $\rho \times A \times v$. Since the combustor having constant area, $\rho_2 \times \rho_3 = v_2 \times v_3$. Thus, $v_3 = 213.87$ m/s. Therefore, the mass flow rate = 187.75 kg/s.

D. *Convergent section (3-4)*

Using steady flow energy equation for diffuser section, we have

$$T_{04} = T_3 + \frac{v_3^2}{2c_p} \quad (15)$$
$$= 679.23 \text{ K}$$

Now,

$$p_{04} = p_3 \times \left(\frac{T_{04}}{T_3} \right)^{\frac{\gamma}{\gamma-1}} \quad (16)$$
$$= 123.99 \text{ kpa}$$

For convergent section, the stagnation condition is $T_0 = T_{04}$ and $p_0 = p_{04}$. Thus, from isentropic table at M=0.62, we get

Velocity can be obtained using Steady Flow Energy Equation, if the temperature is known. Thus, we can get

$$T_4 = 0.9286 \times 679.23$$
$$= 630.73 \text{ K}$$

and,

$$p_4 = 0.7716 \times 123.99 = 95.67 \text{ kpa}$$

Velocity can be calculated as,

$$v_4 = \sqrt{2c_p (T_3 - T_4)} \quad (17)$$
$$= 227.30 \text{ m/s}$$

Also,

$$\rho_3 = \frac{p_4}{R \times T_4} = 0.5285 \text{ kg/m}^3$$

The diameter of convergent section =12 mm. Hence Area of the convergent section will be

$$A_4 = \frac{\pi \times d_4^2}{4} = 0.113 \text{ m}^2$$

The following relation can be used to find the Mach number at station 4,

$$\frac{M_3}{M_4} = \frac{v_3 \sqrt{T_3}}{v_4 \sqrt{T_4}} \quad (18)$$

Thus,

$$M_4 = 0.65$$

E. C pipe (4-5)

Here, as there is a C-shaped curved pipe with constant cross sectional area, there will be no significant change in flow flow field.

F. Exhaust pipe (5-6)

Using steady flow energy equation for diffuser section, we have

$$T_6 = T_5 + \frac{v_5^2}{2c_p} \qquad (19)$$
$$= 656.45 \text{ K}$$

Now,

$$p_6 = p_5 \times \left(\frac{T_6}{T_5}\right)^{\frac{\gamma}{\gamma-1}} \qquad (20)$$
$$= 110.20 \text{ kpa}$$

Also,

$$\rho_6 = \frac{p_6}{R \times T_6} = 0.5849 \text{ kg/m}^3$$

Now, by using Bernoulli's theorem,

$$p_5 - p_6 = \left(\frac{1}{2} \times \rho_5 \times v_5\right) - \left(\frac{1}{2} \times \rho_6 \times v_6\right)$$

Thus,

$$v_6 = 215.94 \text{ m/s}$$

The diameter of exhaust section =29.90 mm. Hence Area of the exhaust section will be

$$A_6 = \frac{\pi \times d_6^2}{4} = 0.702 \text{ m}^2$$

The mass flow rate at exhaust section $= \rho_6 \times A_6 \times v_6 = 88.60$ kg/s.

The following relation can be used to find the Mach number at station 6,

$$\frac{M_5}{M_6} = \frac{v_5\sqrt{T_5}}{v_6\sqrt{T_6}} \qquad (21)$$

Thus,

$$M_6 = 0.629$$

G. CAD design and calculated parameters

The CAD design is presented in Fig.1 depicting various stations and drafting of the same were presented in Fig.2 and Fig.3.
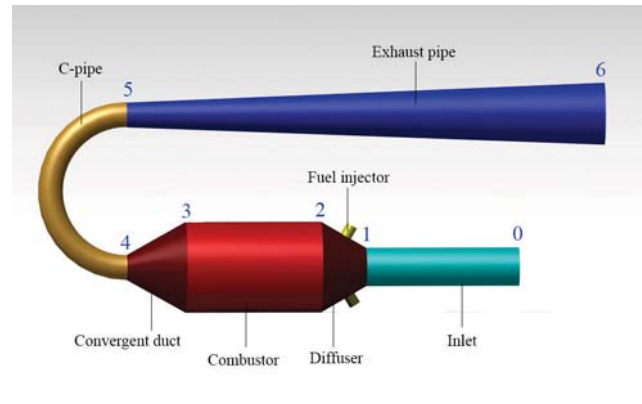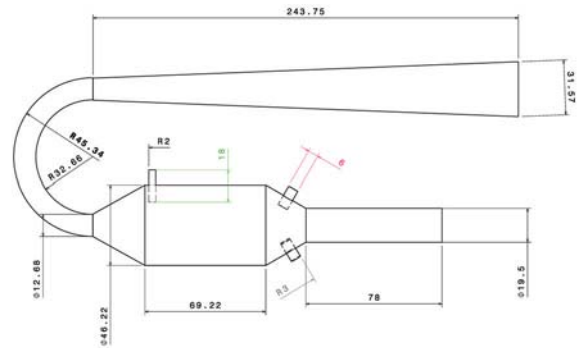

Fig. 1. CAD design of combustor

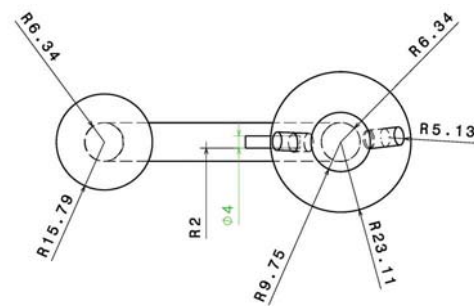Fig. 2. Drafting of CAD design from view 1

Fig. 3. Drafting of CAD design from view 2

The parameters have been calculated from the inlet section to the exhaust section is shown in table II. It has been observed that, in the combustor, there will be a rise in pressure and temperature while velocity decreased due to deflagration. The exit velocity of the valveless pulse jet engine is 215 m/s, and the pressure and temperature is 110200 Pa and 656.45 K respectively at $M_a = 0.69$

Parameters	Station						
	0	1	2	3	4	5	6
Pressure (pa)	101325	95190	101420	110050	95670	95670	110200
Temperature (K)	288.16	283.06	288.24	656.46	630.73	630.73	656.45
Velocity (m/s)	102.08	102.08	101.98	213.87	227.30	227.30	215.94
Mach Number	0.3	0.3	0.299	0.62	0.65	0.65	0.629
Density (kg/m^3)	1.225	1.225	1.225	0.5841	0.5285	0.5285	0.5849
Mass flow rate (kg/s)	33.46	33.46	187.75	187.75	13.57	13.57	88.60

Run	Exit temperature (K)
1	655.80
2	656.55
3	657.20
4	656.31
5	655.76
6	656.25
7	654.43
8	654.20
9	654.66
10	656.80

IV. EXPERIMENTAL SETUP

Fabricated model of valveless pulse jet engine is shown in Fig.4.Stainless Steel 304 with thickness 3mm were used for the entire model to withstand high temperature. Intake, diffuser, combustor, convergent section, C-shape pipe and exhaust were separately fabricated and joined with welding. Two fuel injectors and NKG spark plug were used. DC transformer were used to power the igniter, which needs input of 3-6 V and deliver output up to 400kV. LPG were used as fuel and an air blower was used to initiate the engine.

Fig. 4. Valveless Pulse jet engine at test bed

V. RESULT AND CONCLUSION

This research work is primarily intended to develop the Valveless Pulse jet engine to operate with Liquefied Petroleum Gas. The significant effort on using the experimental method to attain the whole configuration of the valveless pulse jet engine was focused, and exit temperature of pulse jet was measured and results were presented in table III. Exit temperature is matching with the value from the design calculation. This valveless pulse jet engine was the initial design and development and it is planned to operate with different fuel by changing the appropriate fuel injector in future. Also, it will be tested with different fuel pressure and measurement of exit velocity and thrust will be done, with appropriate instrumentation and setup. It was observed that, the pulsating form of exhaust was stable and it was self sustaining as long as the fuel was supplied.

Design and Development of Valveless Pulse jet Engines is very simple as large number of complex equations are removed. Development of Valveless Pulsejet engine requires the careful design of an inlet, combustor, and exhaust pipe.

VI. CONFLICT OF INTEREST

The author(s) declared no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

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