EFFECT OF INLET SECTION ON PULSE COMBUSTOR PERFORMANCE

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Abstract

Experimental investigation on a valveless pulse combustor that applies Helmholtz resonation concepts is presented. The pulse combustor is attached with a J-shape inlet. Part of the burnt gases mixes with inlet air in the J-shape inlet due to pulse action. Since the J-shape is in the same direction as the tailpipe, it also produces additional thrust. The thrust produced is from 22.07 N to 31.88 N. The J-shape inlet increases the minimum required fuel supply. It also reduces the noise that is produced by the pulse combustor. It is shown that the optimum range of fuel supply for the pulse combustor is in the lean region. The effect of the J-shape inlet to the operating frequency is the same as lengthening the tail pipe with a frequency of 125 Hz with the J-shape and 157 Hz without.

***Keyword**: Valveless pulse combustor, Helmholtz resonation, J-shape inlet, operating frequency*

1. Introduction

Pulse combustor is a periodically burning combustion device. It can be designed based on 3 acoustic principals; Rijke tube, Hemlholtz resonator and Quarter wave resonator (Zinn, 1984). As shown in Figure 1, a pulse combustor consists of 3 main sections; inlet, combustion chamber and tail pipe .

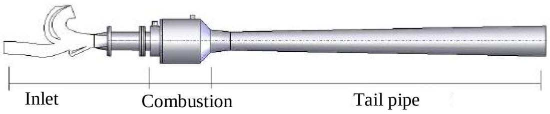


Figure 1: Pulse combustor

In a Helmholtz type pulse combustor, when combustion occurs, the increased pressure gives an impulse that makes the combustor and the gas within it to resonate. The combustion will create overpressure condition in the combustion chamber that will drive out the exhaust gas and create an expansion wave at both inlet and exhaust exit. Due to the expansion wave, the pressure in the combustion chamber drops to sub atmospheric pressure, allowing some of the hot exhaust gas to travel back into the combustion chamber and also causing fresh fuel-air mixture to be drawn into the chamber through the inlet section [Geng et.al 2006]. Illustration of the operating principle of a pulse combustor is shown in Figure 2. The combustion will be repeated at a resonant frequency of the pulse combustor and the frequency depends on the pulse combustor geometry. This acoustic resonation is referred to as Helmholtz resonation and the frequency of this resonation can be determined using equation 1 based on the diagram in Figure 3 (Litke et. al. 2005).

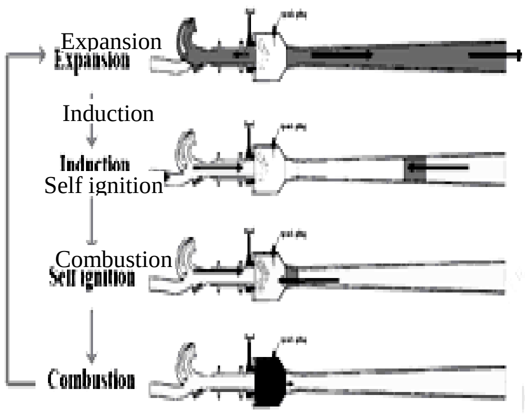


Figure 2: Pulse combustor operating cycle

$$f = \frac{a}{2\pi}\sqrt{\frac{A}{Vl}} \qquad (1)$$

a = the speed of sound in air

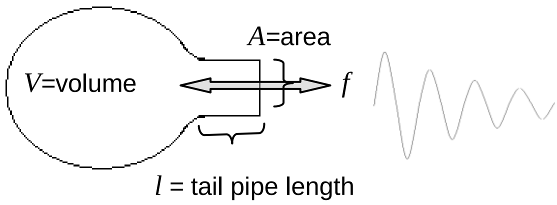


Figure 3: Helmholtz resonator

Equation 1, does not take into account the combustion process in determining the frequency. Kilicarslan (2005) took this into account giving us;

$$f = \frac{1}{2\pi}\left(\frac{R}{c_{pr}}\right)^{1/2}\left(\frac{\Delta h}{1+h}+h_t\right)^{1/2}\left(\frac{A_t}{L_t V}\right)^{1/2}$$

(2)

c_{pr} = constant pressure specific heat of gases in the tailpipe

As stated in equation 2, the speed of sound is affected by the heat released during the combustion process.

1.1 Inlet section

One of the important aspects needed to be considered in developing a pulse combustor is the inlet section. The inlet section design plays an important role in determining the pulse combustor type. Valved pulse combustor is relatively easy to design since it relies mainly on the movement of the inlet valve to open and close the inlet section. But in this type of pulse combustor, the durability of the valve will limit the operation time of the pulse combustor since it will experience fatigue and thermal load due the fluctuation of combustion process [Zbicinsk I., 2002]. One of the methods to overcome the problem is to use valveless type inlet section. In valveless inlet section, one needs to understand the flow fluctuation behavior. Inlet section should be designed to ensure the proper function of the pulse combustor. Based on the original purpose of pulse combustor that is to create thrust, most valveless pulse combustor designs have inlet section open area facing the same direction as the tail pipe.

Unlike steady state burning combustor, air intake in pulse combustor depends on fluctuation pressure of combustion process in the combustion chamber. In valved pulse combustor, when combustion occurs, the valve will close the inlet section therefore causing the mixture of fuel and air to be trapped in the inlet section. When the combustion occurs in a valveless pulse combustor, combustion gas will be driven out through the tailpipe and inlet section due to sudden increase in pressure. Therefore, before a new mixture intake, the inlet section must be freed from the combustion exhaust gas. This situation puts a lower limit on the minimum fuel supply required to operate the pulse combustor since the combustion pressure must be high enough to drive all the combustion exhaust in the inlet section to the atmosphere. Any slight change made to the inlet section not only affects the requirement fuel supply but also affects the performance of the pulse combustor.

1.2 Thermodynamic Cycle of Pulsejet

There are various suggestions regarding the pulsejet's thermodynamic cycle. The normal assumptions are the combustion of isentropic and uniform pressure rise process, and all changes of state are assumed to be isentropic [Lancaster, 1959]. The p-V diagrams of the pulsejet engine are shown in Figure 4.

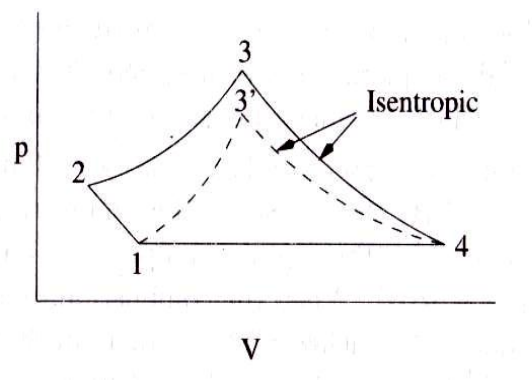


Figure 4: Pulsejet cycle on p-V diagram [Ganesan, 2005]

Stage 1-2 is induction where air, fuel and hot gas is drawn into the combustion chamber and ignition take place at point 2, Combustion process is represented by line 2-3, Expansion and acceleration of combustion gas is indicated by line 3-4 while line 4-1 is where pulsating gas column leaves the system. This cycle is nearer to the Otto cycle [Ganesan, 2005].

According to Geng et. al (2006) pulsejet cycle is said to be based on the Humphrey thermodynamic cycle, where isochoric heat addition (combustion) follows an isentropic compression and isobaric heat rejection follows an isentropic expansion. However, since the wave compression is weak, the thermodynamic efficiency is low, especially compared with the Brayton cycle where mechanical compression offers very high thermodynamic efficiency.

2. Experimental Approach

Experiments were conducted using a pulse combustor unit designed by P.A Hilton Ltd. (Figure 5) originally to create thrust. The inlet section consists of 4 parts; J-shape inlet, inlet spacer, vane and fuel manifold (Figure 6). This paper will explain the effect of J-shape inlet on the pulse combustor operation.

Figure 5: Pulse Combustor

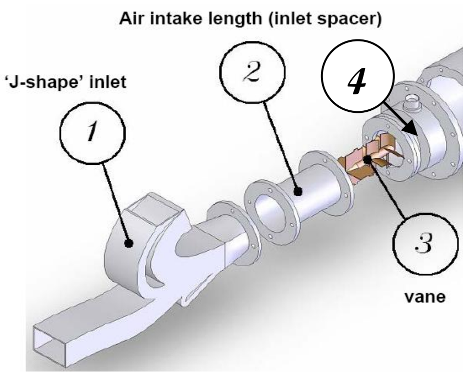
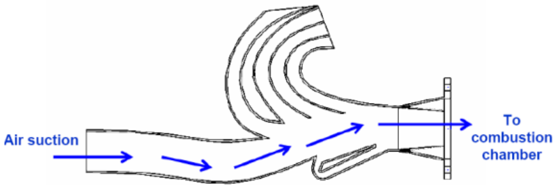


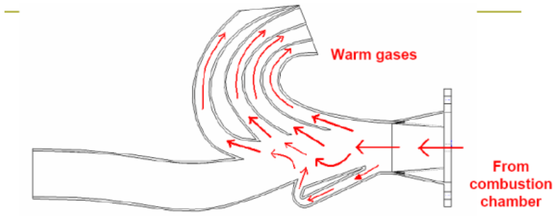
Figure 6: Inlet section

2.1 J-Shape inlet

J-shape inlet is attached to the pulse combustor in order to guide the combustion gases that rush out from it to the same direction as the combustion gas that rush out from the tail pipe (Figure 7). The existing J-Shape inlet helps the pulse combustor to operate hence creates positive thrust.



a) Intake air flow



b) Exhaust flow

Figure 7: Flow of exhaust gas in the J-shape inlet

2.2 Experimental rig.

Figure 8 shows the experimental setup for this study.

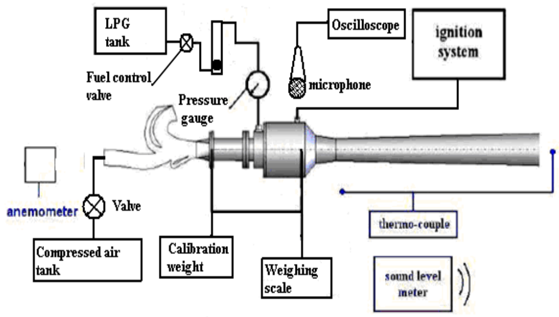


Figure 8: Experimental diagram

Experiments were conducted using liquefied petroleum gases (LPG) as fuel and the fuel flowrate was measured using a flowmeter. A pressure gauge was attached to the fuel line between fuel flowmeter and the fuel manifold to measure the operating pressure required to supply the fuel. An automotive ignition system (Figure 9) is used as the ignition system and ignition is only required to start the combustion process (not pulsating yet). Compressed air is purged through the inlet opening at high flowrate while the fuel flowrate is increased until pulsating occurs. Once the pulsating combustion occurs, the purged air is shut down. Most pulse combustors is operated this way since to start the pulse combustor at high fuel flowrate is dangerous because the fuel may exit through the tailpipe or the inlet section before combustion occurs.

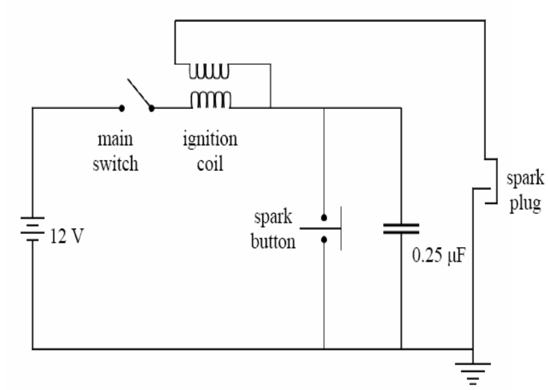


Figure 9: Ignition circuit

The thrust created by the pulse combustor is measured using spring weighing scale. The railing for thrust measurement setup is attached with calibration weight to erase the effect of free movement of the pulse combustor. The reading from the weighing scale during the operation pulse combustor is subtracted with initial reading to give net reading of the thrust.

A microphone that is connected to an oscilloscope is used to measure the frequency of the pulse combustor. When combustion occurs, the oscilloscope gave high value of the measured sound. The frequency can be calculated using the time between two peak oscillation values. The noise that is produced by the pulse combustor is measured using a sound level meter (Solo 01db).

As mentioned before, air is drawn into the pulse combustor due to the pressure fluctuation. A vane type anemometer (Kestrel 1000 pocket) is used to measure the air velocity of drawn air. The air flowrate is calculated using equation 2.

$$\dot{m} = \rho v A \qquad (2)$$

$\dot{m}$ = air flowrate
ρ = air density
A = inlet cross section area
ν = air velocity

3. Result And Discussion

3.1 Fuel flowrate

By using the J-shape inlet section, the minimum required fuel flowrate was ~50 L/m. This is an approximate value since the fluctuation pressure affected the floating ball in the fuel flowmeter. Decreasing the fuel flowrate will eliminate the pulsating process. This minimum value was also needed during the start up of the pulsating process. When the fuel flowrate was set at below 50 L/m and the air was purged, the pulse combustor was pulsating but not at the air cavity frequency and the flame was extinguished after sometime. The pulse combustor is said to be operating successfully only when the pulsating occurs without the use of high velocity purging air. The J-shape inlet section allows the pulse combustor to operate between 50 L/m to 80 L/m fuel flowrate. The combustion occurs in constant mode when the fuel flowrate was supplied below 50 L/m. This is due to the required combustion energy to push all the exhaust gas from the inlet section. The fuel couldn’t be supplied above 80L/m because the fuel pressure wasn’t high enough to support rapid fluctuation pressure in he combustion chamber.

Without the use of J-shape inlet section, the required fuel flowrate was 25L/m and but the maximum fuel flowrate that can be supplied was at the same value when J-shape was attached to the pulsejet. The minimum required fuel flowrate for this type of configuration was less then when the use of J-shape inlet because the combustion requires less energy to push exhaust gas from the inlet section.

3.2 Operating Frequency and Noise level

J-shape inlet help the pulse combustor reduce the noise level. When it was attached to the pulse combustor, the noise value was around 111.4 to 118.9 dB but the increment of noise level was not much when the J-shape was detached from the pulse combustor which the value was around 122.1 to 126.7 dB. Both configurations were not helping the pulse combustor to be operated at the allowable noise level for an operating device which is below 80 dB [Zbicinsk, 2002].

The operating frequency when J-sape was attached to the pulse combustor configurations was 125 Hz. By increasing the fuel flowrate, the pulse combustor produces high amplitude of noise but maintaining almost the same value of frequency. Figure 10 shows the captured image of measured frequency using the oscilloscope.

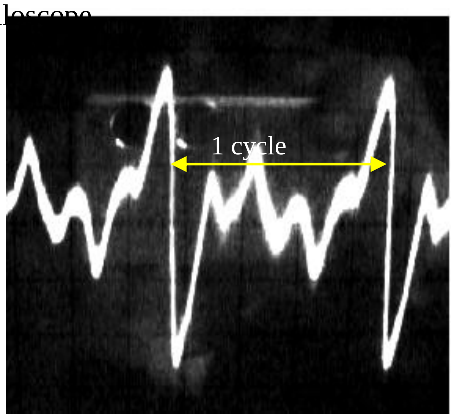


Figure 10: J-shape operating frequency, Fuel flowrate; 50 L/m, 3ms/div.

The operating frequency was lower when the J-shape inlet was detached at value of 157 Hz. Figure 11 shows the captured image of osciloscope trace for this kind of configuration.

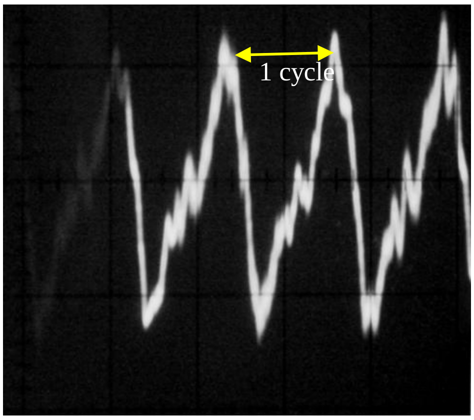


Figure 11: Without J-shape operating frequency, Fuel flowrate ; 50 L/m, 5ms/div

Comparing between operating frequency between J-shape with no J-shape configuration, it is clear that inlet length also give effect on the operating frequency of the valveless pulse combustor. Geng et. al (2006) reported that the shorter the inlet length, yield higher operating frequency for a valveless pulse combustor.

3.3 Power Output and Efficiency

As mentioned before, the pulse combustor is developed in order to demonstrate thrust. As illustrated in Figure 5, the exhaust gas that flow through the inlet section was guided to expel to atmosphere at the same the direction of the exhaust gas that flow through the tailpipe. This is used to give positive force to the pulse combustor. Figure 12 shows the graph of thrust versus fuel flowrate and efficiency of the pulse combustor.

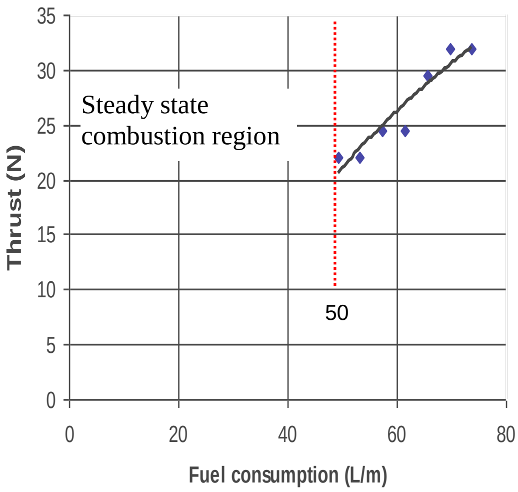


Figure 12: Thrust versus fuel consumption (J-shape attached)

The power output of the pulse combustor is calculated using equation 3 and its result is shown in Figure 13. The minimum power generated is 260,455 Watt at 50 L/m fuel supply and maximum is 892.71 Watt at 73.73 L/m.

$$P_{out} = F \text{ x } v_{in} \qquad (3)$$

Where F = thrust (N)

v_{in} = intake air velocity

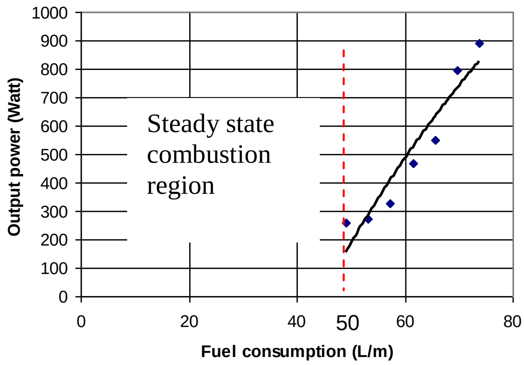


Figure 13: Output power versus fuel consumption

By adjusting the fuel flowrate, the fresh air that is drawn during induction phase is naturally varies. The air velocity values allow us to determine the equivalence ratio between air and fuel during the combustion phase in a cycle of the operation. It is shown in Figure 14 that the pulse combustor gives the highest thrust at the lowest operating equivalence ratio. The thrust is shown to decrease as the equivalence ratio increases. The experiments show that the pulse combustor was most likely to operate in lean air-fuel mixture.

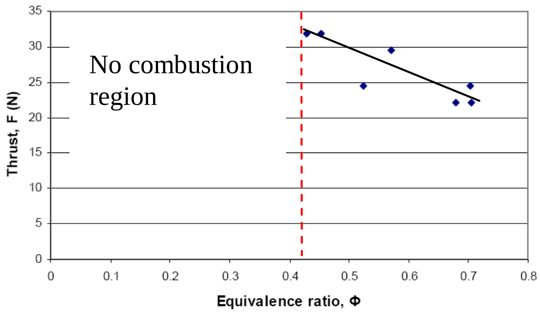


Figure 14: Thrust versus equivalence ratio

By detaching the J-shape inlet section, the pulse combustor does not produced any thrust during operation. This is due to forward thrust produced by inlet section canceling the backward thrust produced by tail pipe. It is reported by Geng et. al (2006) that the thrust produced by a pulse combustor is fluctuating at a double frequency of the operating frequency of the pulse combustor.

4. Conclusion

The attachment of J-shape inlet section gives significant effect on the thrust and the frequency produced by the pulse combustor. The thrust produced is shown to increase as the fuel supply increases. The design of inlet section will affect the operating range of the pulse combustor. It is shown that the straight type inlet enhanced air-fuel mixing and therefore allows the pulse combustor to operate in a wider range of fuel supply.

References

[1] Zinn, B.T., " *State of the Art and Research Needs of Pulsating Combustion*," American Society of Mechanical Engineers, 84-WA/NAC-19, 1984.

[2] Geng, T., Zhang, F., Kiker, A.P, Kuznetsov, A. V., Roberts, W. L., Experimental Thermal and Fluid Science, 2006.

[3] Zbicinsk, I., "*Equipment, technology, perspectives and modeling of pulse combustion drying*," Chemical Engineering Journal, 86, 2002.

[4] Lancaster, O. E., *Jet Propulsion Engines*. Princeton, New Jersey: Princeton University Press, 1959.

[5] Ganesan, V., Gas *Turbine*. 2nd Edition. New Delhi: Tata McGraw-Hill Publishing Company Limited, 2005.

6] Kilicarslan, A., "*Frequency Evaluation of a gas-fired pulse combustion*", International Journal of Energy Research, 29, 439 – 454, 2005.