The Pulsejet Engine A Review of its development potential

References

O'Brian, J. (June 1974). The Pulsejet Engine - A review of its developmental potential. Monterey, California: Naval Postgraduate School. AD0787439. Retrieved from The Pulsejet Engine - A Review of Its Development Potential (dtic.mil)

This article is related to our project on the refurbishment and testing of a pulsejet engine because it offers a review of several thermodynamic analyses covering the operation of the pulsejet engine and descriptions of the wave processes, performance characteristics, and recent developments. The main reason why this master's thesis is vital to this project is that it highlights serval equations found in the analyses that can assist in the testing process of a pulsejet. More specifically, this article can assist in testing the pulsejet by giving pressure relations during the pulsejets operation that can be used to extrapolate more information from test data.

Constant volume combustion can be more efficient than continual pressure combustion. The Lenoir cycle is the thermodynamic cycle that most closely represents the pulsejet engine. The Lenoir engine consists of a piston engine without the use of precompression.

The pulsejet and Lenoir engines both take in an air-fuel mixture at low pressure and discharge combustion products at a higher pressure. This article assumes a constant volume process for the Lenoir engine with instantaneous combustion. If the pressure at the bottom of the power stroke equals backpressure and no mechanical work is produced, then the Lenoir process will further represent a pulse jet engine.

These two cycles have similar processes where --.-.-.--.

(1 –> 2) Intake

(2–> 3) Constant volume combustion

(3 –> 4) Isentropic expansion of combustion products

(4 –> 1’) Exhaust at constant pressure

(1 –> 1') Valves open, and the new cycle starts

Going into further detail

(1 –> 2) Intake

(2–> 3) Constant volume combustion

Implementing the first law of thermodynamics

$$X = U_3 - U_2 = c_V\left[T_3 - T_2\right]$$

$$X\left(E_f + U_f\right) = U_3(1 + X) - U_2 = C_V\left[T_3(1 + X) - T_2\right]$$

X = stoichiometric ratio

U_X = Internal energy

E_X = Chemical energy

$Q_X = \left(E_X + U_X\right)$ = heat energy

For constant volume process

$$\frac{P_3}{P_2} = \frac{T_3}{T_2} = \Pi$$

$$\frac{XQ_x}{C_V} + T_2 = T_3(1 + x)$$

$$\frac{\frac{XQ_x}{C_V T_2}+1}{1+x} = \Pi$$

(3 –> 4) Isentropic expansion of combustion products

Since there is no work output

$$W = \int_3^4 Pdv - \left(P_4 - P_2\right)V_3 - P_2\left(V_4 - V_2\right) = 0$$

$$\int_3^4 Pdv = \frac{P_3V_3 - P_4V_4}{\gamma - 1}$$

$$\frac{P_3V_3 - P_4V_4}{\gamma - 1} - \left(P_4 - P_2\right)V_3 - P_2\left(V_4 - V_2\right) = 0$$

$$\frac{P_4V_4}{P_2V_2} = \frac{T_4}{T_2}$$

$$\frac{P_3}{P_2} = \Pi$$

$$\Pi - \frac{T_4}{T_2} - \frac{T_4}{T_2}(\gamma - 1) + (\gamma - 1) = 0$$

$$\frac{T_4}{T_2} = \frac{\Pi + (\gamma + 1)}{\gamma}$$

Therefore

$$\frac{T_4}{T_2} = \frac{1}{(1+X)\gamma}\left(\frac{XQ_X}{C_V T_2} - X\right) + 1$$

$$\frac{P_4}{P_2} = \frac{\left(\frac{T_4}{T_2}\right)^{\frac{\gamma}{\gamma-1}}}{\Pi^{\frac{1}{\gamma-1}}}$$

$$\frac{V_4}{V_2} = \frac{T_4}{T_2}\frac{P_2}{P_4}$$

(4 –> 1’) Exhaust at constant pressure

(1 –> 1’) Valves open, and the new cycle starts

This set of relations states that this cycle's thermodynamic state equations are very dependent on the inlet temperature. The pressure and volume and ratios are at least above 2 for any given pressure and volume.

However, combustion does not occur instantaneously. The next set of relations will cover the work done of pulsejet over a finite amount of time.

$$XQ_X - W_C = \overline{C_V}\left[T_3(1 + X) - T_2\right]$$

$W_C = The\ amount\ of\ work\ done\ during\ combustion$

$$\frac{T_3}{T_2} = \frac{1}{1+X}\left[\frac{XQ_X}{\overline{C_V}T_2} - \frac{R}{\overline{C_V}}\frac{W_C}{R\,T_2} + 1\right]$$

Work balance

$$W = P_2V_2 - P_4V_4 + \int_2^3 Pdv + \int_3^4 Pdv = 0$$

$$\int_3^4 Pdv = \frac{P_3V_3 - P_4V_4}{\gamma - 1} = \frac{R\left(T_3 - T_2\right)}{\gamma - 1}$$

During isentropic expansion

$$\int_2^3 Pdv = W_c$$

$$P_2V_2 - P_4V_4 + W_c + \frac{R\left(T_3 - T_2\right)}{\gamma - 1} = 0$$

This, along with the ideal gas law, leads to

$$\frac{T_4}{T_2} = \frac{1}{\gamma}\left((\gamma - 1)\left(\frac{1+W_C}{RT_2}\right) + \frac{T_3}{T_2}\right)$$

Assuming a linear variation of pressure with a specific volume will lead to

$$W_c = \frac{1}{2}\left(P_2 + P_3\right)\left(V_3 - V_2\right)$$

Including ideal gas law

$$W_c = \left(\frac{P_2+P_3}{2}\right)\left(\frac{RT_3}{P_3} - \frac{RT_2}{P_2}\right)$$

$$W_c = \frac{R\,T_2}{2}\left(\frac{T_3}{T_2}\frac{P_2}{P_3} + \frac{T_3}{T_2} - \frac{P_3}{P_2} - 1\right)$$

Non-dimensionalizing

$$\frac{W_c}{RT_2} = \frac{1}{2}\left(\frac{T_3}{T_2}\frac{P_2}{P_3} + \frac{T_3}{T_2} - \frac{P_3}{P_2} - 1\right)$$

The work done from a pulsejet cannot be determined from the temperature and pressure ratios from the initial and peak values of the constant volume combustion process.

Utilizing isentropic relations can find the pressure and volume ratios

$$\frac{P_4}{P_2} = \frac{P_3}{P_2}\frac{P_4}{P_2} = \frac{P_3}{P_2}\left(\frac{T_4}{T_2}\frac{T_2}{T_3}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{V_4}{V_2} = \frac{T_4}{T_2}\frac{P_2}{P_4}$$

The minor variations coefficient for constant volume does not affect the Lenoir cycle as compared to moderation variations.

The relevant question is, How does the constant volume process of the pulsejet engine compare to the continuous pressure process of a gas turbine?

The constant volume process has a higher thermal efficiency compared to a constant pressure with the same heat input. The theoretical efficiency of compressor – constant pressure combustion – turbine engine is 32% compared to the compressor – pulsating combustion (constant volume combustion) – turbine engine of 42%.

This was found through *Thermodynamic analysis of a pulsating gas turbine combustor* by Reynst and *Theoretical analysis of a pulse combustor for a gas turbine* by Muller.

The performance efficiency of the simplified Lenoir cycle for instantaneous combustion is

$$\eta = 1 - \gamma\left(\frac{(\Pi)^{\frac{1}{\gamma}}-1}{\Pi-1}\right)$$

The main losses in the pulsejet engine are incomplete combustion, heat loss due to surroundings, friction losses in the medium and the boundary wall, and losses from non-uniform velocity distribution.

The equation for thrust can be found when assuming the heat energy of the fuel is equal to the increase in the kinetic energy of combustion products exiting the engine.

$$Q\,\eta = \frac{mW_c^2}{2}$$

m = the combustion products + air entering the exit

It is said that the ratio of air to the mass of combustion products is around 0.25 to 0.5

Adding another efficiency term can be added to include the losses. η_a

$$Q\,\eta\,\eta_a = \frac{mW_c^2}{2}$$

W_C can be considered to be the flow velocity at the exit

$$W_C = \frac{2Q\eta\eta_a}{m}$$

Static thrust can be found with

$$T = \dot{m}W_C$$

The pulsejet engine can be characterized with the following parameters

$$C_T = \frac{T}{PS}$$

C_T = Coefficient of thrust

P = Ambient pressure

S = The Nozzle's cross-sectional area

The thrust coefficient for pulsejet can be around 0.2 – 0.5

The length is found to be 8 – 10 times the nozzle diameter.

The pulsejet engine operating frequency is similar to an organ pipe that is open pipe at one end

$$f = \frac{a}{4L}$$

f = frequency

a =speed of sound

$$a = \sqrt{g_c \gamma R T}$$

L = length of pulse jet

In summary, this thesis covers several thermodynamic analyses pertaining to our project on the refurbishment and testing of a pulsejet engine that can be used to extrapolate more information from test results.