Analysis on Performance of Leaf Spring Rotary Engine

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Abstract

This paper is a simulation study of a novel rotary engine called Leaf Spring Rotary Engine, which is a micro-small reed-flexible rotor engine. Flexible characteristics make it a unique advantage. This engine’s structure is different to others, mainly for rotor structure. Engine working principle is similar to conventional rotary engine. As a new engine, creation of numerical models and analysis of impact factor for engine performance are the focus of this work. Designed displacement of the engine is 1.77 cm³ and theoretical compression ratio is 7.3. According to the principle of the engine, the whole structure and sub-system were designed, and thermodynamic model of the engine were established.

Results show that output power of one cylinder is 81.4 W; indicative efficiency is 24.38% under ideal condition when engine operates at speeds of 3000 RPM; the energy loss under heat transfer condition is about 18.34% of the overall energy. The leakage area of 0.02 mm² is considered so that power loss induced by the leakage is about 32.4% of output power under ideal conditions. Besides, the results also show that the reasonable matching of combustion duration and ignition angle can improve output power. Moreover, high compression ratio of the engine causes high heat loss.

Keywords: leaf spring rotary engine; thermodynamic model; performance; influence factors

1. Introduction

As the development of micro-electromechanical system (MEMS) and the proposal of the concept of miniaturization of military equipments, the research on the micro-power system which is small, light, high energy has become the focus of attention. In 1996, Epstein A. H. started research on micro gas turbine in Gas Turbine laboratory, Massachusetts Institute of Technology [1]. In 2001, Fu K., Knobloch...

Previous investigations have demonstrated that the research of micro-power system becomes a trend. However, theses researches do not consider flexibility of combustion chamber. Based on this background, this paper presents a novel micro-small reed-flexible rotor engine and produces a prototype. The engine’s flexible characteristic is a unique advantage compared to others. Therefore, the research focuses on analyzing the performance characteristics under ideal condition and the factors related to the performance of the engine. The prototype is not mature, so difficulties of making successful experiments are great.

2. Structure&Principle

The Leaf spring rotary engine is similar to the Wankel rotary engine which is a 4-stroke cycle engine in the structure and the working principle. The rotor centerline aligns with the housing centerline. The end of spring is fixed to the rotor, and the other end depends on its elasticity to contact with combustion wall. The chemical energy is concerted to mechanical energy through the compression process, combustion process, exhaust process. Engine operates smoothly and impact force is small when leaf springs are added to chamber. It is illustrated in Figure 1.

3. Thermodynamic Model

3.1. Basic Equation

Assuming the combustion chamber is uniformly mixed refrigerant ideal gas, the system state parameter is a function of time regardless of the position and space. In other words, the composition of the cylinder, pressure and temperature are the same at every moment.

Energy conservation equation, mass conservation equation, the ideal gas state equation, gas constant equation, specific heat ratio and the characteristic of each stage are used to deduce thermodynamic equation. This paper uses different thermodynamic equation at four stages. The basic thermodynamic equation is (1).

\[
\frac{dp}{d\phi} = \frac{\gamma p}{m_c} \frac{dm}{d\phi} - \frac{\gamma - 1}{V} \frac{dQ_w}{d\phi} - \frac{p}{V} \frac{dV}{d\phi}
\]  

(1)
Where, $\varphi$ is the output shaft angle, $m_c$ is gas mass of the combustion chamber, $Q_w$ is the heat loss between the working fluid and chamber wall, $p, V$ are respectively for the chamber pressure, volume.

### 3.2. Heat Release Model

Since the actual engine combustion process is complex, the current law is not yet precise description for combustion. The Weber law is applied to simulate the actual combustion process to predict performance parameters of flexible rotor engine system. This paper adopts this method [7]. The fuel mass $m_{f,\text{cycle}}$, fuel calorific value and fuel mass fraction burned $x$ decide the change rate of heat release. So it follows (2). The burned fuel mass fraction can be simulated using the modified Wiebe function [8].

$$\frac{dQ_c}{d\phi} = m_{f,\text{cycle}} \times LHV \times \frac{dx}{d\phi} \quad (2)$$

Where, $\varphi$ is the output shaft angle; $\varphi_{ia}$ is combustion initiation angle; $\varphi_{ie}$ is combustion end angle; $m$ is the shape parameter.

### 3.3. Heat Transfer Model

Heat transfer in Leaf Spring Rotary Engine is composed of convective heat transfer between gas and inner wall surface, the thermal conductivity of parts, convective heat transfer between outer wall and air. Heat transfer model is computed by Hohenberg formula [9]. Heat transfer coefficient of inner wall surface heated parts uses Woschni equation.

$$\frac{dQ_c}{d\phi} = h_{\text{gas}} [s_{\text{rotor}} (T - T_{\text{rotor}}) + s_{\text{spring}} (T - T_{\text{spring}}) + s_{\text{cylinder}} (T - T_{\text{cylinder}}) + s_{\text{cover}} (T - T_{\text{cover}})] \quad (3)$$

Where, $h_{\text{gas}}$ is the convective heat transfer coefficient; $s_{\text{rotor}}$, $s_{\text{spring}}$, $s_{\text{cylinder}}$, $s_{\text{cover}}$ are respectively rotor fire area, springs fire area, cylinder fire area and cover fire area; $T_{\text{rotor}}$, $T_{\text{spring}}$, $T_{\text{cylinder}}$, $T_{\text{cover}}$ are respectively rotor average temperature, spring average temperature, cylinder average temperature, cover average temperature.

### 3.4. Leakage Model

Gas leakage during operation of the engine uses one-dimensional steady flow to simulation. It is known that the mass flow of gas is the same through the cross-section according to the continuity equation. Gap area can be viewed as tapered nozzle, so outlet flow calculation formula [10] as follows:

$$\frac{dm_s}{dt} = \begin{cases} \frac{A_s p}{\sqrt{R_m T}} \left( p_{\infty} \right)^{1/\gamma} \left( \frac{2 \gamma}{\gamma - 1} \left[ 1 - \left( \frac{p_{\infty}}{p} \right)^{\gamma - 1} \right] \right)^{1/2} \frac{p_{\infty}}{p} \left( \frac{2}{\gamma} \right)^{\gamma/\gamma - 1} & p_{\infty} > \left( \frac{2}{\gamma} \right)^{\gamma/\gamma - 1} \\ \frac{A_s p}{\sqrt{R_m T}} \left( \frac{2}{\gamma + 1} \right)^{\gamma + 1/2(\gamma - 1)} \left( \frac{2}{\gamma + 1} \right)^{\gamma/\gamma + 1} \frac{p_{\infty}}{p} \left( \frac{2}{\gamma} \right)^{\gamma/\gamma - 1} & p_{\infty} \leq \left( \frac{2}{\gamma} \right)^{\gamma/\gamma - 1} \end{cases} \quad (4)$$

Where, $m_s$ is leak mass; $A_s$ is gap area; $R_m$ is gas constant; $P_{\infty}$ is external atmospheric pressure.

### 4. Analysis of Performance Factors

#### 4.1. Heat Transfer Loss
High surface to volume ratio results in high heat loss in Leaf Spring Rotary Engine. In addition, the heat loss reduces the efficiency of the engine output power and effectiveness so that it affects the overall engine performance. Maximum temperature is 2300K and maximum pressure is 2.5Mpa under heat transfer conditions. Maximum temperature decreases by 450K and maximum pressure decreases by 0.7Mpa, which reduces engine indicated efficiency and output power. Indicated efficiency and power can be shown in Figure 3. The output power of heat transfer conditions accounts for 76.5% of ideal conditions and heat loss accounts for 18.34% of the input energy.

4.2. Leakage Loss

The cylinder residual gas mass is related to the output shaft angle for different leak area, which can be shown in Figure 4. For the same leak area of initial stage, the mass of working fluid changes slowly because of low pressure in chamber. As cylinder pressure keeps increasing during compression stroke, the gas flow mass through the leak gap increases due to pressure difference and working fluid mass ratio gradually increases. At different speeds, engine power of the same leak area is shown in Figure 5. Under the condition of 1200r/min, when the leakage area is 0.02mm\(^2\), the engine output power is 13.2W. In the same condition, when the leakage area increases to 0.1mm\(^2\), engine output is reduced to about 1W. Namely, residual gas mass is unable to achieve normal combustion. When the speed is up to 3000r/min, the engine output power is 55W when leak area meets 0.02mm\(^2\). Compared to the ideal condition of 81.4W, the power loss percentage is 32.4%. If leak area is 0.1mm\(^2\), output is 13W and power loss percentage is up to 84.03%.
4.3. Combustion duration and ignition time

The combustion duration is related to combustion chamber structure and cylinder gas flow tissue. Inversely proportional relationship between engine speed and combustion duration is low speed corresponding to the high combustion duration. Therefore, improving the engine output power should adjust to ignition time, so different operating speed corresponding to different ignition timing shown in Figure 6. When the engine speed is designed to 3000r/min, the relationship cylinder power and indicated efficiency with ignition timing are shown in Figure 7, assuming the combustion duration is a fixed value.

4.4. Throttle Opening Degree

Analysis on load characteristics for different speed can get working ability in the condition of point. Figure 8(a) and Figure 8(b) respectively show 2400r/min and 3000r/min speed characteristic curve of point conditions. The calculation results at the speed of 2400r/min suggest that when the throttle opening is 40%, the cylinder power is 11W and indicated thermal efficiency is 10.2%.

5. Conclusion

In the present work, a leaf spring rotary engine has been built to investigate the combustion properties. Initial pressure and temperature are controlled to simulate the engine operating conditions. Heat transfer loss is calculated using basic parameters and initial boundary conditions. Heat transfer loss accounts for 18.34% of the input energy. This is most likely due to high surface-volume ratio of combustion chamber to determine large energy loss. The growth rate of leakage mass starts to increase
due to the increase of leak area. The reasonable matching of combustion duration and ignition angle can improve output power. Short combustion duration should find best ignition angle after top dead center. Conversely, long combustion duration should find best ignition angle before top dead center. With the throttle opening’s increase, the cylinder power increases linearly and indicated thermal efficiency increases slowly. This is mainly because that when the throttle opening increases, the cylinder gas state changes greatly so that heat loss and leakage loss increases, thus affecting the efficiency of the engine indication.

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References