A Typical Simulation of a 3-KW Stirling Engine

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Abstract

Stirling engine is being received more and more attention with the development of renewable energy utility. The paper described the design and simulation of a 3-KW Stirling engine based on a testing V-type machine while in the process of manufactured at the Huazhong University of Science and Technology. The engine was driven by solar energy. Based on the testing machine, the heater model of variable heat source, regenerator model and complete appliance model were built, and the thermal performance was simulated and shown under a typical sunlight in the area of Wuhan. The results suggested that the output power curve of Stirling engine appeared as the shape of a saddle in consideration that the radiant energy density of solar energy was non-constant, and electrical heating was employed to serve as the auxiliary heat source. There was about 1.83 KW output work of the manufactured engine during the simulation, and the effective efficiency was about 25.4%.

Keywords: Stirling engine, simulation, solar energy

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1. Introduction

Stirling engines could utilize solar energy as the external heat source, and the theoretical thermodynamic analysis of Stirling cycle engines indicates a thermal efficiency equals to that of the Carnot cycle. Therefore, Stirling engines are again coming to the scene.

In the current background of environmental pollution and energy situation, the development of solar energy and other renewable energy has become a wondrously urgent need. And Dish-Stirling solar power generation system has broad prospect. Development of Stirling engine technology could improve sustainable management of energy supply while relieve our country's tight energy tension. Simply, energy supply in the rural and remote mountainous areas could be guaranteed and energy consumption structure could be improved [1].

In theory, the thermal efficiency of Stirling cycle is equal to that of the Carnot cycle. However, the practical cycle of Stirling engines extremely differs from the theoretical one while the former has relatively high thermodynamic efficiency but is lower than that of the Carnot cycle. The ideal cycle of the Stirling engine is given in Figure 1.

In Stirling cycle, the working fluid is compressed along process 1-2 isothermally, and the heat generated by compression process is absorbed by cooling medium when the working fluid flows through the cooler. The process 2-3 is an isochoric warming in which the working
fluid obtains heating up while it passes through the regenerator. And then during process 3-4, the working fluid is heated by heater and expands isothermally afterwards along with the useful work is outputted. Finally, process 4-1 represents isochoric cooling in which heat is given to regenerator when the working fluid gets through it and the cycle is completed by now.

As for the study of Stirling engines technology, it has received more and more attention as a viable and potentially competitive option to solve the energy crisis.

Refer to the design of Stirling engines, L. Berrin Erbay [2] analyzed the Stirling heat engine operating in a closed regenerative thermodynamic cycle. Polytropic processes have been used for the power and displacement pistons. Following regeneration, the maximum power density and efficiency for design have been found and the compression ratio at maximum power density has been determined. Shahrir Abdullah et al. [3] presented some design considerations to be taken in designing of a low temperature differential double-acting Stirling engine for solar application. And the third order analysis was used during the design optimization stage in order to establish a complete analytical model for the engine. Upon optimization, the optimal engine speed was 120 rpm with the swept volume rate of 2.31 while the volume rates of heater, cooler and regenerator was 1.31, 1.31 and 2.01 respectively. R. Impero Abenavoli et al. [4] described the design configuration of a new, rotary Stirling engine. The variable function of the expansion and compression volumes changing with time was thoroughly deduced as the instantaneous variation was caused by the rotating elements, then the expressions of the engine power and efficiency were obtained. And a simple plan of the Stirling engine was also shown. Zhaolin Gu [5] used a supercritical heat-recovery and heat process to demonstrate that a composite working fluid could be effectively utilized in Stirling engines compared to common gaseous ones, especially retaining the intrinsic high thermal efficiency of the cycle. Ihsan Batmaz [6] manufactured a V-type Stirling engine with two heaters. The prototype engine was tested in laboratory condition using an electrical heating system. Tests were conducted within the temperature range of 650-1000°C with 50°C increments. The pressure ranged from the ambient value to 2 bar with 0.5 bar increments at each stage of temperature. The maximum power was obtained at 950°C and 1.0 bar charge pressure as 118 W.

On the other hand, most research results correlating with the simulation of Stirling engines have been found. S.C. Kaushik [8] has presented an investigation on finite time thermodynamic evaluation of Ericsson and Stirling heat engine. It is found that both engines with an ideal regenerator ($\varepsilon_R=1.00$) would be as efficient as an irreversible Carnot heat engine operating at the same conditions, but this is impractical as an ideal regenerator requires either infinite regenerator area or infinite regeneration time. It is also verified that the regenerative heat losses, regenerator effectiveness and the direct heat leak losses do not affect the maximum power output of either heat engine. Stig Kildegard Andersen et al. [9] have developed a new regenerator matrix design that improves the efficiency of a Stirling engine in a numerical study of the existing SM5 Stirling engine. A new, detailed, one-dimensional Stirling engine model that delivers results in good agreement with experimental data was used. The regenerator matrix temperatures were found to oscillate in two modes. The first mode was oscillation of a nearly linear axial matrix temperature profile while the second mode bended the ends of the axial matrix temperature profile when gas flowed into the regenerator with a temperature significantly different from the matrix temperature. The first mode of oscillation improved the efficiency of the engine but the second mode reduced both the work output and efficiency of the engine. Youssef Timoumi [10] has developed and used a second-order Stirling model, which includes thermal losses, to increase the performance of Stirling engines and analyze their operations. This model has been tested using the experimental data obtained from the General Motor GPU-3 Stirling engine prototype, and could be used to investigate the effect of the geometrical and physical parameters on Stirling engine performance and to determine the optimal parameters for acceptable operational gas pressure. P. Novotný [11] holds that a successful realization of Stirling engines is conditioned by its correct conceptual design and optimal constructional and technological mode of all parts. He presents calculation models of engine parts, dynamics and thermodynamic cycles of the external heat supply engines.
model has been used for a virtual prototype of Stirling engine and then the feasibility of the use of 3D virtual design is verified.

This paper shows the thermal performance of Stirling engine works under a typical sunlight in the area of Wuhan. And the findings suggest that: as the solar radiation intensity increases in the early morning, the output power of Stirling engine also rapidly increases; subsequently the engine speed raises as the increase of the solar radiation intensity, while the proportion of the flow resistance and various thermal losses enhances increasingly in the whole expansion work, as a result, the output power allays slightly. And it is in contradiction to that in the afternoon. Therefore, the output power curve of Stirling engine appears as the shape of a saddle. Because the solar energy is unsteady, electrical heating is employed to serve as the auxiliary heat source when the solar radiation intensity is zero or insufficient to ensure that the output power is stable. Because of this auxiliary, the performance of Stirling engine could be reflected truly.

2. Thermodynamic Calculation and Simulation

2.1. Calculation Method

At present, there are a wide variety of methods to actualize analysis and calculation of Stirling engines, but the practical isothermal calculation method is both simple and accurate. This method is seen as the most appropriate one for preliminary estimate of power and efficiency of Stirling engines. And the other practicability for this method lies in applying to all kinds of transmission organ. Naturally, this method has been accompanied by the following assumptions:

1. The whole cycle process undergoes isothermally.
2. The working fluid is considered as ideal gas and absolute no leakage.

In addition, what follows is the corresponding restrictive conditions for the use of this method:

1. The average circulation pressure is no more than 100bar.
2. The dead volume ratio is no less than 1.3 while the corresponding ratio of regenerator is almost 35 percent of that.
3. The range of speeds is 3000-4000rpm, 1500-2000rpm and no more than 1000rpm for hydrogen, helium and air respectively.

2.2. Calculation Results

In this study, a V-type Stirling engine testing machine is designed and being manufactured for solar energy applications. To make our manufacture simplify, we directly convert a V-type air compressor with most of its mechanical parts are reserved. Obviously, it is planned to improve its leak-proofness and other performances. Main design parameters are given in Table 1.

Based on the shown data, some calculated values are obtained as shown in Table 2 by using software and related formulas.

Besides, we could get more other values except the above, such as the basic power and so on. And the following Eq. (1) could be used to get the shaft output power.

\[
P = \frac{1}{60} B p_m V_E n
\]

(1)

where \( P \) (W) is the shaft output power, \( B \) is the Beale number and it is calculated by use of the formula [12]:

\[
B = 0.034 - 0.052 \frac{T_K}{T_H}, \quad p_m \text{ (bar)}
\]

\( p_m \) is the mean pressure of the cycle, \( V_E \text{ (cm}^3\text{)} \) is the piston swept volume and \( n \text{ (rpm)} \) is the engine speed.

As a result, we could get that the shaft output power is

\[
P = \frac{1}{60} \times 0.019 \times 50 \times 76.45 \times 1500 = 1.83KW
\]

The indicating diagrams are exposed in Figure 2-4.


Table 1. Main design parameters of the testing machine

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical configuration</td>
<td>Alpha</td>
</tr>
<tr>
<td>Working fluid</td>
<td>Helium</td>
</tr>
<tr>
<td>Design power</td>
<td>3KW</td>
</tr>
<tr>
<td>Cylinder diameter ($D_c$)</td>
<td>52mm</td>
</tr>
<tr>
<td>Piston stroke ($S_p$)</td>
<td>36mm</td>
</tr>
<tr>
<td>Connecting rod length ($L$)</td>
<td>90mm</td>
</tr>
<tr>
<td>Shaft speed ($n$)</td>
<td>1500rpm</td>
</tr>
<tr>
<td>Mean pressure ($p_{mean}$)</td>
<td>50bar</td>
</tr>
<tr>
<td>Phase angle ($\alpha$)</td>
<td>60°</td>
</tr>
<tr>
<td>Heat source temperature ($T_H$)</td>
<td>1058K</td>
</tr>
<tr>
<td>Cold source temperature ($T_K$)</td>
<td>303K</td>
</tr>
<tr>
<td>Dead volume ratio</td>
<td>1.5</td>
</tr>
<tr>
<td>Swept volume ratio</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Calculated Engines Values

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swept volume ($V_{E}$)</td>
<td>76.45cm³</td>
</tr>
<tr>
<td>Hot area dead volume ($V_{HD}$)</td>
<td>30.58cm³</td>
</tr>
<tr>
<td>Cold area dead volume ($V_{KD}$)</td>
<td>7.65cm³</td>
</tr>
<tr>
<td>Regenerator dead volume ($V_{RD}$)</td>
<td>38.23cm³</td>
</tr>
<tr>
<td>Maximum volume ($V_{max}$)</td>
<td>207.06cm³</td>
</tr>
<tr>
<td>Minimum volume ($V_{min}$)</td>
<td>98.76cm³</td>
</tr>
<tr>
<td>Maximum pressure ($P_{max}$)</td>
<td>78.1bar</td>
</tr>
<tr>
<td>Minimum pressure ($P_{min}$)</td>
<td>30.4bar</td>
</tr>
<tr>
<td>Indicated power</td>
<td>1.572KW</td>
</tr>
<tr>
<td>Effective power</td>
<td>1.352KW</td>
</tr>
<tr>
<td>Effective efficiency</td>
<td>0.254</td>
</tr>
</tbody>
</table>

Figure 2. Expansion volume indicating diagram

Figure 3. Compression volume indicating diagram

Figure 4. Total indicating diagram

On the other hand, we also could conduct thermodynamic calculation through the basic formulas:
where the first term \( x \) (cm) is the piston displacement corresponding with crank angle, \( r \) (cm) is the crank radius, \( \alpha \) (°) is the crank angle, \( \lambda \) is the ratio of crank radius to connecting rod length.

From Eq. (2), we could get the piston running speed \( v \) and the piston running acceleration \( a \) through Eq. (3) and Eq. (4).

\[
\begin{align*}
    v &= \frac{dx}{dt} = \frac{dx}{d\alpha} \cdot \frac{d\alpha}{dt} \\
    a &= \frac{dv}{dt} = \frac{dv}{d\alpha} \cdot \frac{d\alpha}{dt}
\end{align*}
\]

Combine these interrelated formulas, we might accomplish the thermodynamic analysis, and the total tangential force diagram is produced as displayed in Figure 5 and finally the amplitude area vector gram is drawn.

![Figure 5. The amplitude area vector gram](image)

Ultimately, the flywheel moment could be calculated with the help of an empirical formula as follows:

\[
GD^2 = 3600 \times \frac{m_l m_l F}{\pi^2 n^2 \delta}
\]

where \( G \) (kg) is the flywheel mass, \( D \) (m) is the diameter of the flywheel circle, \( m_l \) (m/cm) is the scale of length, \( m_f \) (kg/cm) is the scale of force, \( F \) (cm²) is the amplitude area, \( n \) (rpm) is the engine speed, \( \delta \) is the rotary inhomogeneity. Finally its value is about 3.4kg/m². So far, some preliminary calculation is completed.

2.3. Simulation

The thermal performance of Stirling engine works under a typical sunlight in the area of Wuhan is simulated. And the corresponding solar radiation intensity is measured as shown in Figure 6.

The solar energy is variational along with variation if time, so the figure is parabolic shaped. And the irregular fluctuation is caused by some natural uncertainties such as clouds. Figure 7, corresponding with the solar radiation intensity, present the variation curve of output power.
The solar radiation intensity is nearly constant as the solar radiation intensity increases, but the engine speed continues to rise. Now the expansion work caused by piston motion in cylinder is certain while the proportion of flow resistance and thermal losses of elements becomes bigger and bigger in the whole circulating power. The result is that the output power increases tardily even drops slightly during 10:00 to 13:00 (as shown in Figure 6). The solar radiation weakens gradually in the afternoon, but the hot area temperature remains the same while the engine speed drops gradually and the proportion of flow resistance and thermal losses greatly diminishes in the whole circulating power. The output power grows slightly along with the reduction of the engine speed during 13:00 to 15:00. At about 15:00, the solar radiation intensity is low-lying that the proportion of flow resistance and thermal losses is quite small in the whole circulating power, and the output power is also reduce rapidly as the engine speed declines. It can be seen in the Fig. 6 and Figure 7 that the solar radiation intensity change curve is approximate symmetry and so is the output power curve.

3. Construction and Outlook

As shown above, when the heat source is constant, the manufactured Stirling engine is designed for 3KW output while about 1.83KW is obtained based on theoretical calculation. One of the reasons for low output is that the amount of the shuttle loss and regeneration loss is immense. However, the preliminary results testify that our design meets the needs of its working principle, and the previous work has clearly showed the improvement opportunities in the proposed design, so that we could test it with the testing machine in the hope of getting a better design and manufacture.

Besides, the output power curve of Stirling engine appears as the shape of a saddle. When the engine speed is low, the output power increases as the solar radiation intensity raises; when the speed is exorbitant, the output power reduces as the solar radiation intensity raises.

In the future work, it is tremendously necessary to minimize the shuttle loss and regeneration loss as well as the total dead volume. On the other hand, it is foreseen to improve and redesign some parts of the testing machine. If those existing problems are resolved, Stirling engines could be commercially available and become the incumbent prime-mover technology for transportation and stationary power generation applications.

References
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