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REVIEW ARTICLE

EXPERIMENTAL STUDY ON THERMODYNAMIC CHARACTERISTICS OF STIRLING ENGINE

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ARTICLE DETAILS

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ABSTRACT

For the purpose of designing a more efficient Stirling engine, the author experimentally studied the hot cylinder surface temperature changes of micro Stirling engine with heating time, analyzed the cold cylinder surface temperature changes of the engine with heating time as well as cylinder temperature at the start of the engine. It was found that, the hot cylinder temperature of the engine changed with the heating time, which stopped temperature rise when a certain temperature was reached. The engine revolving speed increased with the increase of the hot cylinder temperature. The higher the hot cylinder temperature was, the greater the engine revolving speed was. The cold cylinder temperature of the engine changed with the heating time, which stopped temperature rise when a certain temperature was reached. This study will provide insight into the thermodynamic characteristics of Stirling engine and help us further study the thermal efficiency of the engine.

KEYWORDS

Stirling engine, temperature rise, hot cylinder, thermal characteristics, revolving speed.

1. INTRODUCTION

With low noise and wide heat source, Stirling engine is applicable in submarine, construction machinery fields requiring low noise. Electricity generation using Stirling engine can enable greater utilization rate of solar energy. Nevertheless, the low actual thermal efficiency of engine greatly hinders its further development. Hence, how to improve the thermal efficiency of engine is an important research direction of engine. Stirling engine boasts many advantages, such as heating by a variety of fuels, good atmospheric environment friendliness, sufficient fuel combustion, good dynamic operation characteristics, reliable operation and easy maintenance, good economic efficiency, etc (Perezziello et al., 2021).

In the 1980s, following the great progress in the development of Stirling engine, Stirling engine for multiple purposes such as automotive Stirling engine, underwater Stirling engine came into being. By using multi-objective optimization technique to find the optimal design parameters of the hybrid system, Karambasti B M et al. proposed a conceptual design and method of using upstream GPU-3 Stirling engine as the prime mover (Karambasti et al., 2022). Chen Pengfan et al. established the adiabatic analysis model of Stirling engine, finding that greater cylinder chamber pressure resulted in greater output power of the system (Pengfan et al., 2017). Using experimental and numerical methods, Catapano F et al. analyzed the Stirling engine performance in waste gas and heat recovery of internal combustion engine by experimental tests (Catapano et al., 2021). Chen J et al. used machine learning algorithm of gradient boosted regression tree (GBRT) to predict the power output of Stirling engine (Chen et al., 2022). By combining the thermodynamic-dynamics model with Sage model, Chen Pengfan et al. put forward the TD-Sage model of beta free piston Stirling engine (β -FPSE) (Pengfan et al., 2022). Using solar energy as the input heat energy of Stirling engine, Ahmadi M H et al. detected the parameters with the greatest influence on the output power and engine stability through analysis (Ahmadi et al., 2013).

Based on Sage GPU-3, Huang Yiqing et al. set up the third-order parameter influence research model of Stirling engine (Yiqing et al., 2018). Regalado-Rodriguez Nuria et al. identified the potential benefits of additional heat transfer area in the expansion and compression space of Stirling engine (Nuria and Carmelo, 2022). Li R et al. investigated the significance of low temperature differential Stirling engine in solar energy application (Li et al., 2021). Using analysis software MATLAB, Ng X H et al. simulated different fuel combustion schemes and made comparison with the reference models to verify the results and allow the best engine performance (Ng et al., 2023). Qiu Hao et al. recommended a one-dimensional transient Stirling cycle analysis model and analysis method (Hao et al., 2022). Kim DongJun et al. optimized the heat exchanger design of the free piston Stirling engine (FPSE) (Kim et al., 2022). Liu Meng et al. experimentally studied the heat transfer and flow characteristics of parallel plate regenerator (PPR) and identified the influence law of material parameters and geometric parameters on the regenerator effect and pressure drop (Meng et al., 2022). According to the dynamic configuration of Stirling engine, Li Jiqiang et al. studied the power and efficiency changes by modifying the proportion and thermodynamic proportion of the engine (Jiqiang and Fuping, 2022).

In this paper, the thermal and working performance of the engine are studied experimentally, covering the changes of the hot cylinder surface temperature of the miniature Stirling engine with heating time, the changes of the cold cylinder surface temperature with heating time and the changes of hot cylinder surface temperature with heating time. This study will help us further understand Stirling engine operation characteristics and provide reference for engine optimization design.

2. STIRLING ENGINE HEATER SYSTEM

Stirling engine is a piston engine that raises the temperature inside the chamber through external heat supply. Stirling engine cycle [16] is a closed-loop system formed by heating equipment, hot chamber (expansion

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chamber), heat recovery device, cooling equipment, cold chamber (compression chamber), etc (Mingjiang et al., 2019). The chamber has a working medium inside. Stirling engine cycle involves four working processes: isothermal compression process, isothermal preheating process, isothermal expansion process and isothermal heat recovery process. The working process is essentially a process of thermal work, heat energy conversion into kinetic energy, with a heat exchange system inside. Stirling engine heat exchange system mainly consists of heater, cooler and regenerator. As an important part of the heat exchange system of Stirling engine, heater is the heat source of Stirling engine (Donghan, 2009). The heating temperature of the heater greatly affects the working power and efficiency of Stirling engine. The heater passes heat to the hot cylinder which then passes heat to the working medium gas. In general, the higher the heater temperature is, the higher the hot cylinder surface temperature is; the higher the working medium temperature is, the greater the engine power is. Thus, heater temperature plays an important role in improving the Stirling engine power. This paper aims to investigate the effect of

heating on hot cylinder temperature and operation performance of the engine.

3. WORKING PRINCIPLE OF THE ENGINE HEREIN

The working power of the engine derives from the expansion and contraction of the heated working medium. According to the thermodynamic theory of engineering physics, gas with a certain mass will expand and contract when it is heated and cooled, as shown in Figure 1. Figure 1 (a) shows the piston position before the hot cylinder heating, and Figure 1 (b) shows the piston position after the hot cylinder heating. Obvious external movement is observable. Hence, gas expands when it is heated and contracts when its temperature drops.

As can be seen from Figure 1, if the gas in the cylinder expands and contracts repeatedly, the gas can make the right piston reciprocate. If the reciprocating motion is mechanically driven, the Stirling engine as shown in Figure 2 can be designed.

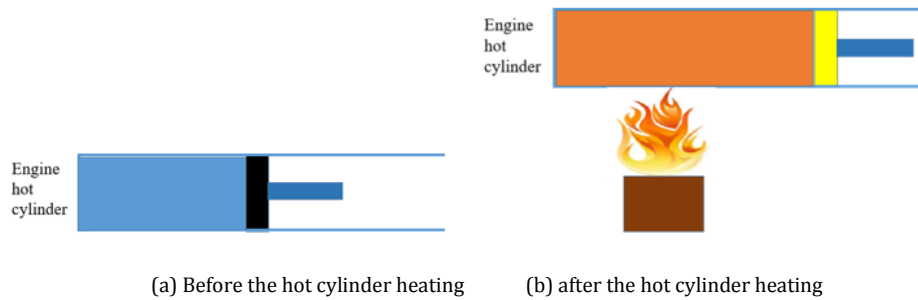


Figure 1: Thermal expansion and cold contraction of cylinder gas

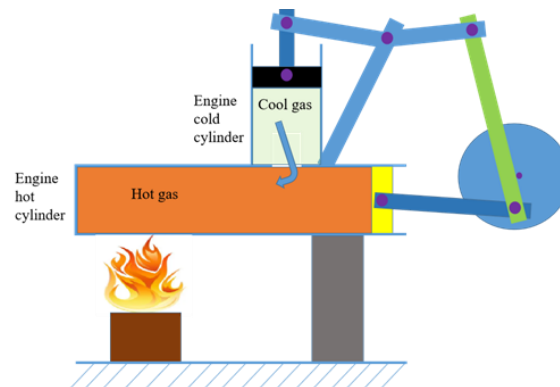


Figure 2: Stirling engine

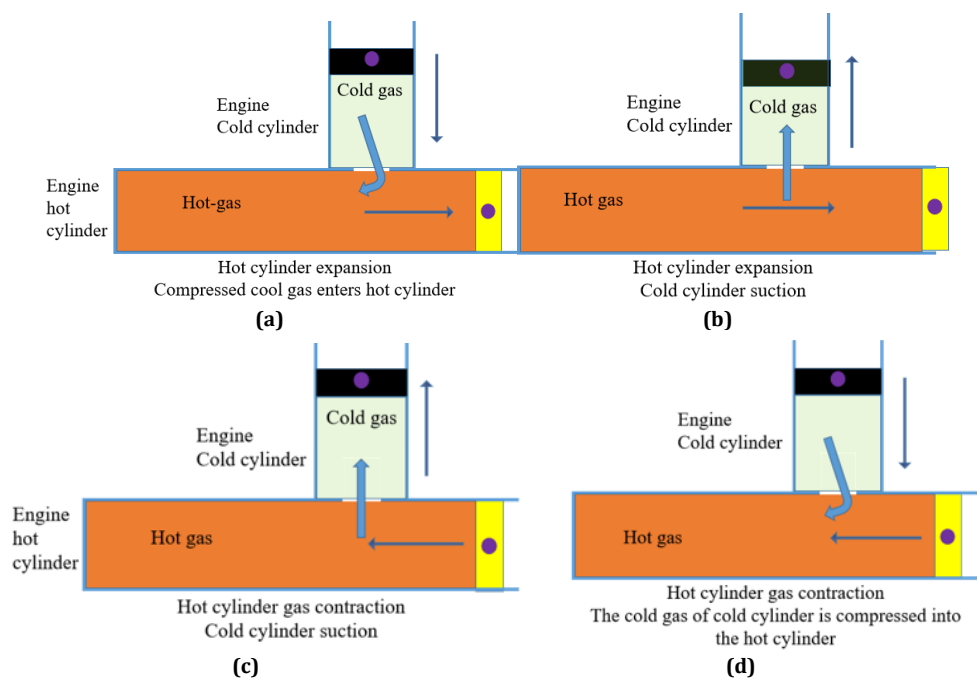


Figure 3: Cycle process of Stirling engine

As shown in Figure 2, when the gas working medium in the cold chamber enters the hot cylinder, the hot cylinder is heated, leading to gas expansion that pushes forward motion of the hot cylinder piston. When the hot gas working medium is squeezed into the cold chamber, the gas will contract with the piston retracted. The four working positions of the engine are shown in Figure 3:

At the beginning of the cycle, let the power piston (cold cylinder piston) stay in the outer dead point of motion, with the displacer piston (hot cylinder piston) situated in the inner dead point of motion, and start operation. First, the hot cylinder expands and pushes the displacer piston, the cool piston moves down and pushes the cold working medium into the hot cylinder. During the heating, external work is done under constant volume. Second, the hot cylinder absorbs heat, leading to pressure rises and gas expansion, so that the displacer piston continues external movement, while the cool piston moves up, with the hot working medium entering the cold cylinder. During the heating, the gas expands under constant pressure. Third, the displacer piston continues internal movement, the cool piston moves up, with the hot working medium entering the cold cylinder. During compression under constant volume, the mass volume remains constant while the gas temperature drops. Fourth, the displacer piston continues internal movement, the cool piston moves down, with the cold working medium entering the hot cylinder. During compression under constant volume, the pressure goes up, while the gas temperature is unchanged.

The ideal Stirling cycle consists of the following four processes (Donghan, 2009):

1. Constant volume heating: the heat of the hot chamber is transferred from the backheating hole to the cold chamber under a constant volume.
2. Isothermal expansion: under heating and constant temperature, heat is passed from the external surface of the hot chamber to the working medium.
3. Equal volume cooling: under equal volume, heat is passed from the hot chamber working medium to the cold chamber working medium.
4. Isothermal compression: under constant temperature, low temperature working medium enters the hot chamber from the cold chamber.

The four processes are represented as coordinates, as shown in Figure 4:

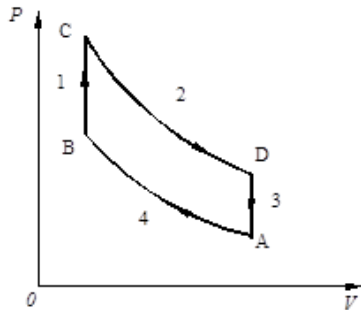


Figure 4: Stirling cycle P-V diagram

Theoretically, the Carnot cycle features the highest thermal efficiency. If the Stirling cycle and the Carnot cycle share the same upper and lower temperature limits, the Stirling cycle and the Carnot cycle have equal thermal efficiency. Therefore, in theory, the Stirling cycle is a cycle with the highest thermal efficiency.

In this study, the engine backheating hole had incomplete backheating, and the actual four cycle processes of the Stirling engine should be implemented within a limited time. As a result, there is a certain gap between the actual thermal cycle and the ideal cycle of Stirling engine, but the ideal Stirling cycle means great significance for the design and research of Stirling engine.

4. EXPERIMENTAL MEASUREMENT OF ENGINE OPERATION CHARACTERISTICS

4.1 Efficiency of Stirling Engine (Donghan, 2009)

Engine thermal efficiency η_t can be represented as the quotient of engine power and external heat:

$$\eta_t = \frac{N_s}{N_t} \quad (1)$$

Where, N_s is engine power; N_t is the external heat flow.

Let the fuel combustion efficiency be:

$$\eta_r = \frac{Q_s}{Q_l} \quad (2)$$

Where, Q_s is the actually released heat during fuel combustion; Q_l is the theoretical heat during complete fuel combustion.

The heat absorption efficiency of the hot cylinder is:

$$\eta_{rx} = \frac{Q_{rx}}{Q_s} \quad (3)$$

Where, Q_s is the actually released heat during fuel combustion; Q_{rx} is the heat absorbed by the hot cylinder.

The efficiency of engine heat conversion into mechanical energy is:

$$\eta_{xj} = \frac{Q_{xz}}{Q_{rx}} \quad (4)$$

Where, Q_{xz} is the work done by the engine; Q_{rx} is the heat absorbed by the hot cylinder.

Accordingly, the total engine power can also be expressed as:

$$\eta_t = \eta_r \eta_{rx} \eta_{xj} = \frac{Q_{xz}}{Q_l} \quad (5)$$

4.2 Measurement of Thermal Temperature Characteristics of Stirling Engine

In this experiment, the experimental measurement parameters of the engine mainly include revolving speed, hot cylinder temperature, cold cylinder temperature. The measurement system design herein focuses on revolving speed - time - temperature measurement of the engine, and arrangement of temperature measurement points is also discussed.

In this experiment, non-contact infrared thermometer (as shown in Figure 5) was used to measure the surface temperature of hot cylinder and cold cylinder to investigate the variation rule of cylinder surface temperature with heating time, as well as the impact of different cylinder heating temperatures on engine output power and revolving speed. The non-contact infrared thermometer is of model DTM1. The object surface temperature was determined by measuring infrared energy of the surface radiation. The temperature measurement range was $-50^{\circ}\text{C} \sim 1350^{\circ}\text{C}$. With short response time, the thermometer can be used to measure the hot and cold cylinder surface temperature.



Figure 5: Non-contact infrared thermometer



Figure 6: Digital tachometer

A digital tachometer (Figure 6) (model: TM600) was used to measure the engine revolving speed. With a measuring range up to 99999rpm, it has high precision.

In this experiment, an alcohol lamp was used for heat source supply to the engine, and the flame directly heated the hot cylinder of the engine. The temperature at point A at the end of the hot cylinder was taken as the measurement temperature (as shown in Figure 7) to detect the temperature change of the hot cylinder with the heating time of the alcohol lamp.

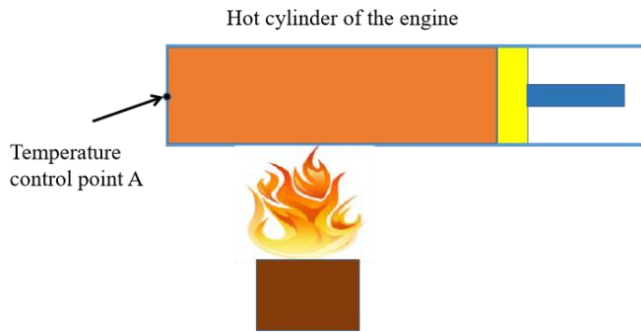


Figure 7: Temperature measurement point of hot cylinder

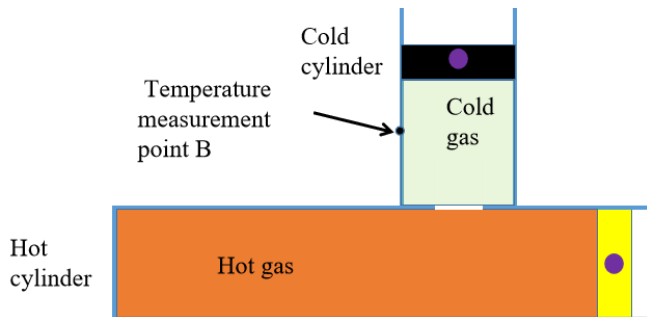


Figure 8: Temperature measurement point of cold cylinder

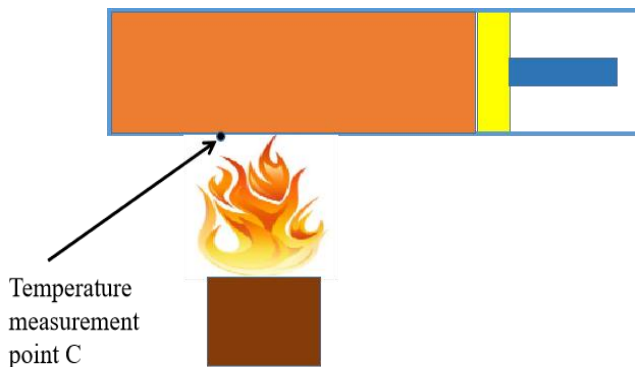


Figure 9: Temperature measurement point at the bottom of the hot cylinder

The variation rule of cold cylinder temperature with heating time was measured. Point B in the middle of the cold cylinder was taken as the measurement point for temperature measurement (as shown in Figure 8).

The variation rule of engine revolving speed with heating time was measured using stopwatch for timing. The heating diagram is shown in Figure 9. The temperature measurement point is point C. In initial heating, the engine could not start due to the low temperature of the hot cylinder. After heated for 43 seconds, the engine could start, with revolving speed up to 890 RPM. The engine revolving speed could reach 1350 RPM, 1800 RPM, 1860 RPM after heated for 60, 75 and 90 seconds, respectively, as detailed in Figure 10.

In order to investigate the impact of hot cylinder heating temperature on engine start-up, C point as shown in Figure 9 was taken as the detection point to measure the temperature at which the engine started operation. The engine was started amid temperature measurement. It was detected that when the engine point C reached 220°C, the engine started operation. Afterwards, with the increase of heating time and temperature, the engine revolving speed kept accelerating, as shown in Figure 11.

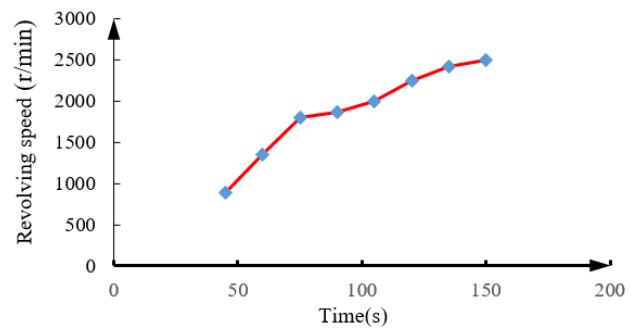


Figure 10: Variation rule of engine revolving speed with heating time

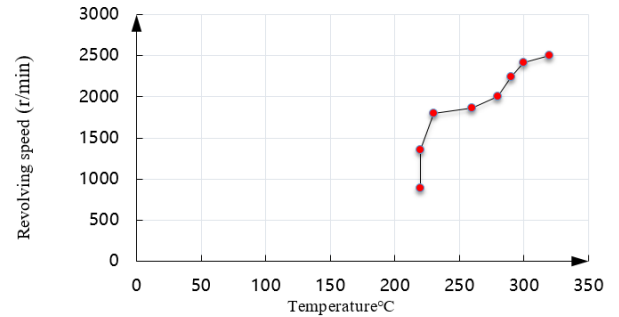


Figure 11: Variation rule of engine revolving speed with heating temperature

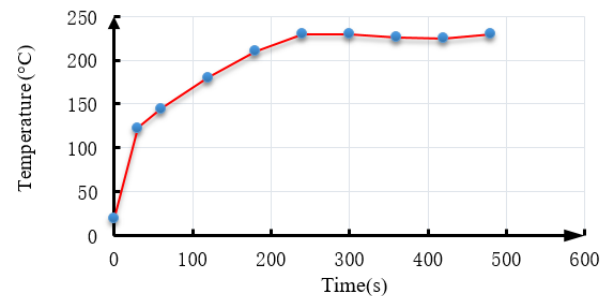


Figure 12: Variation rule of temperature at point A of hot cylinder with heating time

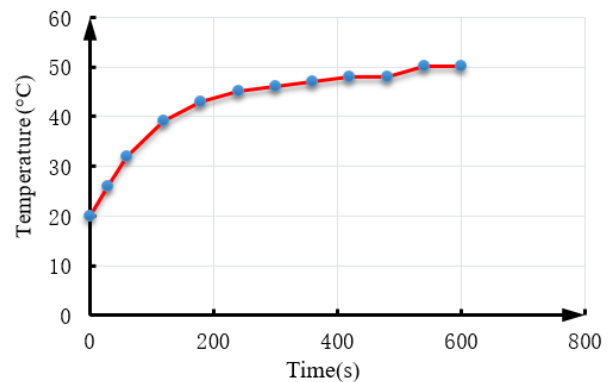


Figure 13: Variation rule of temperature at point B of cold cylinder with heating time

Measurement result analysis: According to the measurement scheme shown in Figure 7, the measurement results are shown in figure 12. In Figure 12, in the early stage, the hot cylinder temperature at point A presents nonlinear increase with the increase of heating time, which basically reaches the peak of 230°C after heated for 240 seconds. Afterwards, with the increase of heating time, the temperature does not increase, but fluctuates slightly around 230°C. According to the measurement scheme shown in Figure 8, the measurement results are shown in Figure 13. In Figure 13, in the early stage, the cold cylinder temperature at point B presents nonlinear increase with the increase of heating time, which basically reaches the peak of 50°C after heated for 540 seconds. Afterwards, with the increase of heating time, the temperature does not increase, but fluctuates slightly around 50°C. In accordance with

the measurement scheme shown in Figure. 9, the change of engine speed with heating time was measured by stopwatch timing method, and the measurement results are shown in Figure. 10.

In Figure 10, the engine cannot start at the beginning of heating because the piston thrust generated by the temperature difference between the hot cylinder and the cold cylinder cannot start the engine. With the increase of heating time, the hot cylinder temperature gradually increases, resulting in bigger and bigger piston thrust under the temperature difference between the hot cylinder and the cold cylinder. After heated for 45 seconds, the engine starts, with the revolving speed reaching 890 RPM instantly. With the prolongation of heating, the engine has higher and higher revolving speed. After heated for 150 seconds, the engine revolving speed basically reaches the maximum of 2500 RPM. Afterwards, the engine revolving speed is basically maintained at 2500 RPM. At this point, the engine output power also reaches its maximum.

In order to study the effect of hot cylinder heating temperature on engine start-up, the temperature and speed of engine start-up were measured by using the c-point as the temperature detection point shown in Figure 9, and the results were shown in Figure 11. In Figure 11, when the heating temperature is low, the engine cannot start. As the heating temperature increases, there is bigger and bigger piston thrust generated by the temperature difference between the hot cylinder and the cold cylinder. When the heating temperature at point C reaches 220°C, the engine starts, with the revolving speed reaching 890 RPM instantly. With the prolongation of heating, the engine has higher and higher revolving speed. After heated to 320°C, the engine revolving speed basically reaches the maximum of 2500 RPM and basically stabilizes at 2500 RPM afterwards because the hot cylinder temperature at point C also reaches the maximum.

5. CONCLUSION

The thermodynamic characteristics and operation performance of engine are studied experimentally in this paper. The experimental results show that: (1) At the beginning stage, the hot cylinder temperature of the engine changed with the heating time, which did not increase after a certain temperature was reached; (2) The engine revolving speed increased with the increase of the hot cylinder temperature. The higher the hot cylinder temperature was, the greater the engine revolving speed was. In this experiment, the engine could reach a maximum revolving speed of 2500 RPM; (3) At the beginning stage, the cold cylinder temperature of the engine changed with the heating time, which did not increase after a certain temperature was reached; (4) The hot cylinder had a much higher final temperature than the cold cylinder. Despite the experimental research herein, the theoretical research is insufficient, which will be one of the tasks in the next step. Through the experimental research, we understood the thermodynamic characteristics of Stirling engine, which will help us further study the engine's thermal efficiency.

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