The Development of a Gamma-Type Stirling Engine with the Feature Acquiring Thermal Power Data

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Abstract

To explore the effect of operating parameters on the performance of Stirling engines conveniently, this research developed a Stirling engine with the feature that user can easily acquire the working fluid thermal properties (such as temperature and pressure) and engine power output. A commercially available Gamma-type Stirling engine was used as the main part and some modification were carried out to make the engine with the characteristic of high thermal resistance. A pulley was installed on a DC motor /generator and a belt was used to connect the flywheel of the engine and the pulley. When the engine is running, electricity is generated by the DC generator. Four temperature sensors were separately installed on the inner and outer walls of the engine's displacer cylinder, and a pressure sensor was installed on cold side wall of the displacer cylinder. The temperatures of the inner and outer walls of the hot and cold side of the displacer cylinder, and the working fluid pressure in the displacer cylinder can be acquired while the engine is running. Two experiments with different operation conditions were carried out, and the temperatures, pressures, rotation speeds and power outputs were acquired by using a purposed build and low-cost data acquisition system, respectively. After analyzing the rationality of the experimental data, it shows that the target engine has been successfully developed.

Keywords: Stirling engine, thermal properties, power output

可擷取熱功數據之伽瑪型史特靈引擎開發

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摘　要

為便於探究各操作參數對史特靈引擎性能之影響，本研究開發一具可容易量測熱力性質(包含溫度與壓力)、功率輸出(包含直流馬達轉速與電壓)之史特靈引擎。以市售伽瑪型史特靈引擎為主體，修改部分零件使其耐熱；連接皮帶輪以利帶動直流馬達(發電機)發電，並於引擎移氣器汽缸冷熱端開設孔口並於內外部分別裝置溫度感測器，且在移氣器汽缸冷端開設孔口並裝置壓力感測器，以利量測引擎運轉時移氣器汽缸冷熱端內外壁溫度及氣體壓力。經過進行兩種不同條件的引擎運轉，並經由一個自行開發低消費之數據擷取系統分別擷取溫度、壓力、轉速及輸出功率，再透過分析前述實驗數據的合理性後，證明本研究之目標引擎開發成功。

關鍵詞：史特靈引擎，熱力性質，輸出功率

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I. INTRODUCTION

According to Fu [1], the petrochemical energy such as coal, oil and natural gas is accounted for about 78% of global energy consumption, indicating that humans rely on non-renewable energy to a relatively high degree in 2011. However, the use of non-renewable energy sources also causes obvious greenhouse effect and environmental changes. In addition, acid gases such as sulfur dioxide are also caused by acid rain and soil pollution, so humans have to think about developing alternative energy sources. According to the World Energy Council [2], the world's oil will be exhausted within 50 years; natural gas will be exhausted within 70 years; coal mines will be exhausted within 300 years; uranium mine will be exhausted within 70 years. Therefore, how to develop a stable renewable energy application system or device has become an important issue.

In view of the rapid depletion of non-renewable energy sources and the environmental changes brought about by their use, countries are facing the replacement of non-renewable energy with renewable energy such as green energy, and Taiwan has promoted the "Green Energy Technology Industry Promotion Plan" in 2016 [3]. The four aimed points of energy harvesting, energy conservation and energy storage and system integration support the development of the industry to enhance the competitiveness of the green energy industry. Although countries are actively developing various green renewable energy technologies, there are still many limitations that have not been overcome, so they are still unable to completely replace fossil fuels. However, viewing at the modern consumption of fossil fuels, we believe that humans should continue to develop green energy renewable energy technology. Differing from internal combustion engines using petrochemical fuels, Stirling engine is an external combustion engine, possessing the characteristics of using diversified heat sources (such as solar energy, biomass energy, geothermal heat, various waste heat, etc.) Even if Stirling engine has been published for more than two hundred years, it is believed that the study of effective application of Stirling engine is in line with the worldwide trend and Taiwan's green energy technology industry promotion program [3]. For example, reference [4-14], Chang [15] compares them as shown in Table 1. According to the list of Chang [15] (see Table 1), it is not difficult to see that in different studies, the fuel efficiency or thermal efficiency of Stirling engine is quite different, and the reason for this has not been systematically explained. Improving the fuel efficiency is an important issue for the competitiveness of engine in the green energy industry. Furthermore, there is no complete discussion on the causal quantitative relationship between the actual heat absorbed by Stirling engine and the output power. Therefore, it is necessary to develop an easily replaceable engine accessory for the acquisition of thermal and power data. In this study, the temperatures of inner and outer walls of a Stirling engine are measured. In the context of such demand, we will inspire us to develop a Stirling engine that can easily extract thermal and power data as the research purpose of this paper.

Table 1. Literature review

Discussion / Author	Work Pressure	Temperature Difference	Fuel Economy	Thermal Efficiency
Halit Karabulut[4]	v		**	15%
B. Demir[5]	v	v	**	**
Angkee Sripakagorn[6]	v	v		9.35%
Liu Chi-Hsin[7]	v		0.22%	**
Shu-Chun Su[8]		v	**	**
Cheng[9]	v	v		32.2%
Yu-Feng Chang[10]	v	v	**	
Ramla Gheith[11]	v	v	**	
Sheng-Kai Zhang[12]		v		30.5%
Hsiang-Chang Hsu[13]	v	v	9.18%*	
Can[14]	v	v	**	

Note：* Expressed by Chang [15]；** Indicates that the original document doesn't provide.

II. THE LITERATURE DISCUSSION

As mentioned in introduction, no complete study has been established on causal quantitative relationship between the actual heat absorbed by Stirling engine and the output power in many studies. The key points of relevant research literatures are summarized as follows:

In 2009, Halit Karabulut [4] build a β-type low-temperature Stirling engine and designed two different cylinder inner walls, with 2 mm by 3 mm rectangular grooves on smooth surfaces to obtain higher heat transfer area.

In 2010, Demir [5] designed a Gamma-type Stirling engine to perform performance tests under different working fluid pressures (1~3 bar) and different heat source temperatures (700~1050 ℃).

In 2011, Angkee Sripakagorn et al. [6] developed a medium-temperature difference β Stirling engine, which uses an electric heater to control the heat source temperature to 350-500 ℃. In order to effectively reduce heat loss, the heater is covered with ceramic fiber for insulation.

In 2011, Liu [7] used control valve to maintain cylinder pressure. Tests are conducted tests to measure the output power of the α-type Stirling engine speed and torque to study the effects of different average pressure (0.1~0.3 MPa) on the speed, torque and output power. The experimental results showed that when the working pressure raises, the engine speed, torque and output power increase.

In 2012, Su [8] analyzed the small β Stirling engine module, using a resistance heater (power 100 W) as the heat source, and measuring the output power. The result shows that the speed is positively correlated with the temperature difference between the hot and cold ends.

In 2013, Cheng [9] developed and tested the beta 300 W Stirling engine to measure engine torque, speed and output power under various operating conditions. Their experiments were conducted with different working fluids (air and helium), working pressure (4~8 bar), regenerator grid number (50~165) and temperature (650~850 ℃).

In 2015, Chang [10] used the Computational Fluid Mechanics (CFD) program to simulate the heat transfer mechanism of the medium-temperature γ-Sterling engine.

In 2015, Ramla Gheith et al. [11] optimized the Gamma-type Stirling engine regenerator. Experiments were first carried out with different materials (stainless steel, copper, aluminum and nickel-copper alloy) and the engine performance and the state of each material after 15 hours of use were examined.

In 2017, Zhang [12] firstly used the computational fluid dynamics to simulate the internal circulation process of the Gamma-type Stirling engine, analyzed and compared the various parameters of the engine, and sought to optimize the combined parameter design to improve the engine output power.

In 2017, Hsiang-Chang Hsu [13] conducted the V2 Stirling engine research and modeled and manufactured the gamma Stirling engine by numerical methods and Solidworks, for the working fluid (hydrogen and air), heater (2 kW and 6 kW) and working fluid pressure (2~3 bar).

In 2018, Can [14] test the alpha-type Stirling engine at different pressures (1 to 4 bar) and working fluids (air and helium). The heater temperature range is controlled between 800 and 1000 ℃ and is increased by 50 ℃. The cold end is cooled by water cooling (30 ℃). The experimental results show that when helium is used, the maximum output power is 30.7 W at 437 rpm, heater temperature 1000 ℃ and 3.5 bar. The engine torque increases with the increase of pressure, and begins to decrease after a certain critical point (3 bar).

From the above literature review, we found that the research focus of each researcher is different. Although we have obtained specific quantitative data, we still think that we can't sort out Stirling engine fort the causal quantitative relationship between actual absorbed heat and output power. We believe that if we can develop a Stirling engine that can easily change engine parts and extract heat and power data, it will be convenient for future series of research, and it is easier to integrate Stirling engine under various operating conditions. In order to facilitate the reader's understanding of the development engine in the following description of this article, the gas dynamic cycle of Stirling engine is briefly summarized as follows:

The general scholar divides the Stirling gas power cycle into four ideal processes, consisting of two equal volumes and two isothermal processes.

(1) Ideal isometric heat absorbing regeneration process.

(2) Ideal isothermal expansion process.

(3) Ideal isometric heat release regeneration process.

(4) Ideal isothermal compression process.

Scholars have learned through experiments that the actual Stirling gas power cycle is quite different from the above ideal cycle. For example, during the isometric heat absorbing regeneration process (1), the displacer moves upwards to the end of its stroke, with the phase advanced always leading the working piston by about 90 degrees crank angle. During the heat absorbing regeneration process, the proportion of working gas in the cylinder of the displacer that can contact the hot end face is gradually increased. After isometric heat absorbing regeneration process, the engine power cycle will enter the isothermal expansion process (2), in which the displacer moves from the cold end of the displacer cylinder to the hot end, and its travel displacement is much smaller than that of the working piston (due to the fact that the displacer and working piston have 90 degrees crank angle phase difference), so most of the working gas contact with the hot end of the displacer cylinder. After isothermal expansion process, the engine power cycle will enter isometric heat release regeneration process (3). With the same physics, the displacer moves downwards to the end of its stroke, with the phase advanced always leading the working piston by about 90 degrees crank angle. During this process, the proportion of working gas in the cylinder of the displacer that can contact the cold end face is gradually increased. After isometric heat release regeneration process, the engine power cycle will enter isothermal compression process (4). During this process, the piston goes to the bottom dead center (the working fluid has a minimum volume), the timing corresponds to the end of the isometric heat release process. And finally, the engine completes the power cycle.

To estimate the heat actually absorbed by the engine, the temperature inside and outside the engine must be measured. Experimental procedures in this study are described in the next two sections, including the selection and refurbishment of engine, evaluation of proper installation location of sensors, and the collaboration of measuring apparatus.

III. DEVELOPMENT AND EXPERIMENT

3.1 Development Process

First, it is improved with the existing Stirling engine (acrylic) in our laboratory. In order to effectively withstand the high temperature provided by the heat gun, the heating end, the cooling end and the cylinder wall of the engine are changed from acrylic material to aluminum alloy in Fig. 1. Then the operation test is carried out. The experimental results show that the operation stability is good. When the engine speed is stable, the engine output voltage and current are measured with different loads (resistance value 22~390 Ω). The results show that the engine output power can be determined by the measured voltage, current of motor/generator. Then, Stirling engine (the sensor has not been installed) manufactured by the Institute is determined as the development object, and after confirming that the engine is functioning normally, it is then modified to measure the output power and pressure of the engine under different loads. Finally, the data measurement of different operating conditions is carried out, the sensor is placed in the appropriate position of the engine and the temperature and pressure are measured, and then the engine performance is analyzed to verify the feasibility of the engine developed by the research institute. The development process is shown in Fig. 2.

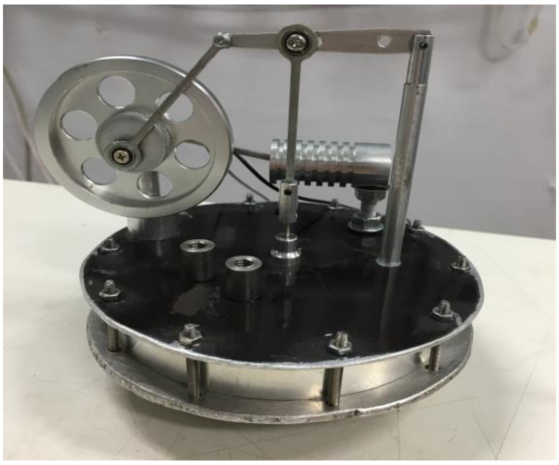

Fig.1. Aluminum alloy Gamma-Type Stirling engine [15]

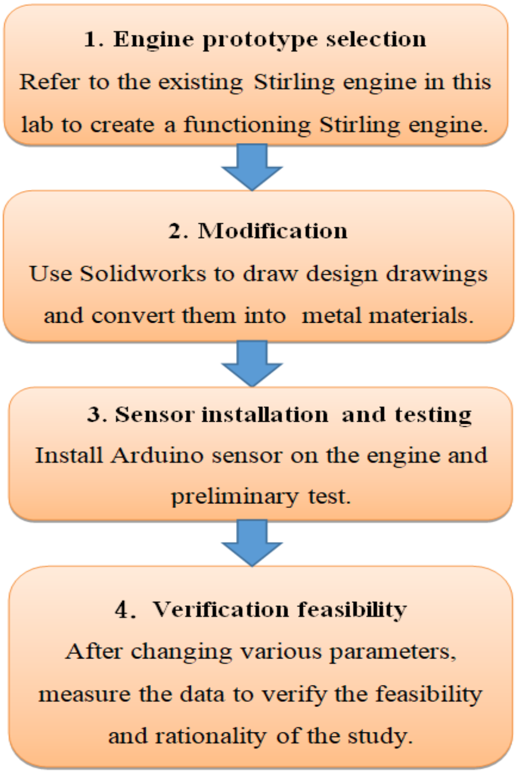

Fig.2. Development process

3.2 Experimental Apparatus

The heat gun is used as a heating system by Gamma-type Stirling engine modified by the Institute. The heat gun can be divided into two gear positions, wherein the high temperature is 1000 ℉ (727 ℃) and the low gear temperature is 600℉ (327 ℃). The air cooling method is used as the cooling system, and the fan is used to maintain the cold end temperature of the engine (2400~2440 rpm rotation speed, 50/60 Hz frequency). The engine output shaft drives a motor/generator via a pulley to generate electricity. The output voltage and current of motor/generator are measured to determine the power of the engine. A temperature sensor is also installed inside and outside the hot and cold end of the engine to measure the internal and external temperature. In addition, the pressure sensor is placed on the cold end of the engine to measure the pressure in the cylinder. Finally, the Arduino data acquisition system developed by Wang [16] is used to measure the experimental data. The experimental device is shown in Fig. 3and Fig. 4. The engine specifications and performance are as detailed in Table 2.

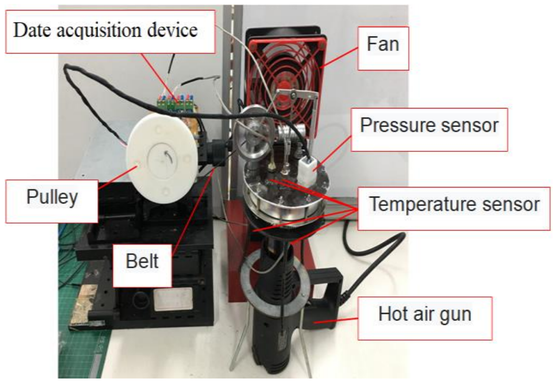

Fig.3. Experimental device

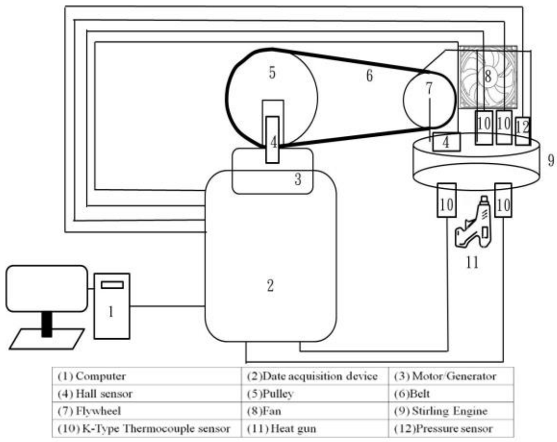

Fig.4. Schematic diagram of the experimental system [16]

Table 2. Stirling Engine Specification & Performance Sheet

Specification	Performance
Displacer cylinder: Diameter:97mm, Height:18mm	Hot end temperature: 200 ℃~400 ℃

Piston cylinder: Diameter:12mm, Length:38mm	Cold junction temperature: 25 ℃~60 ℃
Piston: Diameter:12mm, Length:17mm, Stroke:6mm	Rotating speed: 0 rpm~700 rpm
Displacer: Diameter:92mm, Thick:6mm	Cylinder pressure: 100 kPa~114 kPa

3.3 Experimental methods

In this study, a heat gun was used as the heat source of the metal Gamma-type Stirling engine under two different experimental conditions. 390 ~ 22 Ω electrical resistance are used under different loads. The output voltage and current of motor/generator are measured to verify the reasonableness of the measured data.

3.4 Evaluation of Sensor Installation Location

Evaluation on proper mounting location of temperature and pressure sensors is described separately below.

3.4.1 Temperature sensor installation position

In order to calculate the actual heat absorption of the engine, it is necessary to know the temperature difference between the inner and outer walls of the hot and cold end of the engine, so this study needs to measure the internal and external temperature of the hot and cold end of the engine.

3.4.2 Pressure sensor installation position

To prevent from being damaged under high temperature, the pressure sensor is placed at the cold end of the engine mover. To measure the internal pressure and the high and low pressure difference of the cylinder during engine operation, a hole is drilled to mount the pressure sensor at the cold end as transmitter. The pressure sensor is aligned with the inner wall of the cold end of the engine. To fix the pressure sensor to the engine, a module is designed and sealed with a hot melt adhesive to maintain air tightness of cylinder, as shown in Fig. 5. The timing of measuring the pressure is set when the piston is at the bottom dead center.

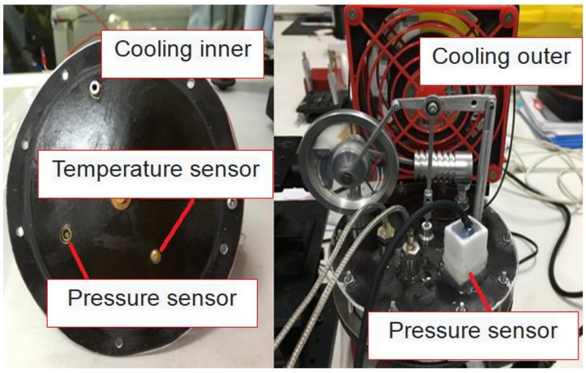

Fig.5. Temperature and pressure sensors are placed on the cold end of the engine [15]

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The engine output power (load is 115 Ω) for two different operating conditions is discussed below. The experimental results are summarized in Table 3.

Table 3. Experimental result data

Measurement data \ Operating condition	Without cover	With cover
Hot end outer temperature(K)	532.4	553.4
Hot end inner temperature(K)	498.3	528.1
Hot end inner and outer walltemperature difference(K)	34.1	25.3
Cold end outer temperature(K)	312.5	316.1
Cold end inner temperature(K)	323.6	326.3
Cold end inner and outer wall temperature difference(K)	11.1	10.2
Hot and cold end inner temperature difference(K)	174.7	201.8
DC motor speed(rpm)	35.7	37.2
Average pressure(kPa)	8.97	10.8
power(mW)	0.1	0.12
Thermal efficiency(%)	0.41	0.69
Fuel economy(%)	0.16	0.2

Note：The average cylinder pressure value is relative to the value of atmospheric pressure.

4.1 Without heat insulation shield (cover)

As shown in Table 3, under the experimental conditions without the built-in thermal heat insulation shield of the engine, the external temperature of the hot end of the engine is 259.4 ℃ (532.4 K), the internal temperature is 225.3 ℃ (498.3 K), and the temperature difference is 34.1 K. The fluid pressure is 8.97 kPa. The output power corresponding to the load curve is shown in Fig. 6. It can be seen from the figure that the maximum output power is 0.1 mW at load 115 Ω. The thermal efficiency (defined as the ratio of output power to the rate of input heat) is 0.41 % corresponding to the conversion. The fuel efficiency (defined as the ratio of output power to the rate of heat input to heat gun) is 0.16 %.

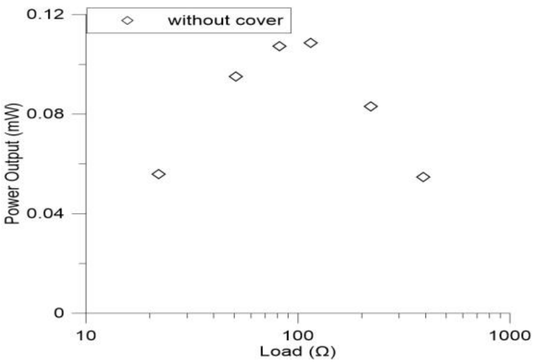

Fig.6. Output power without cover

4.2 With heat insulation shield (cover)

In order to retain the heat generated by the heat gun at the hot end of the engine, the open area was 70.7 cm^2 after coating with aluminum foil; the original open area was 330.1 cm^2 (the open area was reduced by about 4.7 times). As shown in Table 3, under the experimental conditions that the engine is equipped with a heat shield, the external temperature of the hot end of the engine is 280.4 ℃ (553.4 K), the internal temperature is 255.1 ℃ (528.1 K), and the working fluid pressure is 10.8 kPa. The output power corresponding to the load curve is shown in Fig. 7. It can be seen from the figure that the converted maximum output power is 0.12 mW at load 115 Ω.

When the engine is equipped with a heat shield, the thermal efficiency is 0.69% and the fuel efficiency is 0.2%.

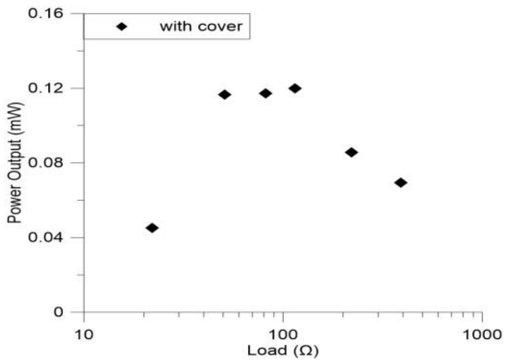

Fig. 7 Output power with cover.

4.3 Analysis of the rationality of the data

In order to analyze the rationality of the data, we first examine the working fluid pressure values in Table 3, which are 109.97 kPa and 111.8 kPa, respectively. After measuring the overall volume change of the engine, the working fluid has a maximum volume of 90441.4mm^3 at the top dead center; the working fluid has a minimum volume of 89763.2 mm^3 at the bottom dead center (compression ratio is 1.008); the working fluid has a volume of 90102.3 mm^3 at the intermediate point. The pressure in the cylinder of the corresponding engine is about 101.325 kPa (1 atm).
According to the ideal gas equation:

$$PV = nRT, \tag{1}$$

In equation (1), P is the working fluid pressure (atm); V is the volume (L); n is the mole number; R is the ideal gas constant (0.082 atm-L/mole-K); T is the temperature (K), from equation (1), the volume of the gas is inversely proportional to the pressure at room temperature. According to this, the piston has a minimum pressure of 100.9 kPa at the top dead center; the piston has a maximum pressure of 101.7 kPa at the bottom dead center. If the temperature after heating is considered, the internal temperature of the hot end is about 498K, the internal temperature of the cold end is about 323 K, and the estimated gas temperature is about 410 K. Then, according to equation (1), it can be estimated. The working fluid pressure should be approximately 40 kPa, while the actual value is

8.97 kPa, indicating that the working cylinder is deflated. The corresponding output power in the inspection Table 3 is only 0.1 mW, and its value is much lower than the data of the researchers in Table 1. It is judged that the engine power cylinder used in this study cannot maintain the air tightness during high pressure operation. Although the cylinder is deflated, the data in Table 3 is further examined. From Table 3, it is found that the addition of the heat shield reduces the open area by 4.7 times and the maximum output power by 1.2 times.

The rationale for a 1.2 times increase in maximum output power is discussed below:

Looking closely at the experimental data, the working fluid pressure is increased from 8.97 kPa to 10.8 kPa, which 1.2 times happens to be the same as the output power increase of 1.2 times, but the rigorous analysis should be analyzed by the engine gas power cycle. As described in Section 2, Stirling engine aerodynamic cycle can be divided into four processes, and the working fluid pressure measured in this experiment is the data taken by the piston at the top dead center (the smallest volume of the working fluid). The timing of the data acquisition corresponds to the end of the isometric heat absorbing regeneration process (at this time the displacer moves upwards to the end of its stroke, that is to say the phase of the displacer always leads the working piston by about 90 degrees crank angle, during the heat absorbing regeneration process, the proportion of working gas in the cylinder of the displacer that can contact the hot end face is gradually increased). The gas temperature in the cylinder of displacer should be slightly lower than the hot end inner temperature (498K). After measuring the working fluid pressure, the engine power cycle will enter the isothermal expansion process, in which the displacer moves from the cold end of the displacer cylinder to the hot end, and its travel displacement is much smaller than that of the working piston (since the displacer and working piston have 90 degrees crank angle phase difference), so most of the working gas contact with the hot end of the displacer cylinder. Similarly, when the piston goes to the bottom dead center (the working fluid has a minimum volume), the timing corresponds to the end of the isometric heat release process. The gas temperature in the displacer cylinder should be slightly higher than the cold end inner temperature (323K).

Finally, the engine power cycle enters the contraction process and completes a cycle. Equation of gas power cycle power according to Stirling engine

$$\dot{W} = \left(\oint P\,dV\right) \cdot rps \tag{2}$$

Where *W/s* is the power (J/s), *P* is the working fluid pressure (N/m^2), *V* is the working fluid volume (m^3), and *rps* is the speed per second. The engine output power can be estimated, but only the amount in this experiment. The working fluid pressure at the bottom dead center of the piston is measured, so the cycle integral calculation cannot be completed, but we still try to explain the rationality that the output power of the heat-insulation cover is 1.2 times the output power without the heat-insulation cover is as follows:

As mentioned above, the power cycle in which only the expansion process system works externally. The compression process is the external work on the system, although we have not obtained the pressure value of the whole process, we have measured the internal temperatures at hot and cold ends of the engine. Without heat shield, the internal temperatures of the hot and cold ends are about 498 K and 323 K, respectively (about 175 K temperature difference). The internal temperatures of the cold and hot ends of the heat insulation shield are about 528 K and 326 K respectively (about 202 K temperature difference). Therefore, according to the ideal gas equation (1) and the gas power cycle power equation (2), the cylinder high and low pressure difference is proportional to the temperature difference, so the cylinder high and low pressure difference should also be 1.16 times. In addition, the rotation speed without heat shield is 3.6 rps, and the rotation speed with heat shield is 3.72 rps (the latter is 1.03 times of the former). From equation (2), the output powers are proportional to the product of cylinder high and low pressure difference and the speed. The ratio of output powers with and without heat shield is then proportional to the product of the ratio of cylinder pressure difference and the ratio of speed. This is calculated as 1.16*1.03, 1.19 times of output power), which is consistent with the output power magnification (1.2 times) of the experimental measurements.

The rationality analysis of the low thermal efficiency data in Table 3 is as follows:

Without the information on the hot end material of the research engine, an experiment is conducted to determine the heat transfer coefficient of the metal sheet. The experimental method was to heat the hot end metal piece of the engine (thickness: 2 mm) with a heat gun and load the glass triangle beaker. 100 ml of water is placed on the metal sheet (contact area is 0.00739 m^2), and after heating for 120 seconds with a heat gun, the temperature of the upper and lower parts of the metal sheet (temperature difference 110 ℃) and the temperature change of water (11.2 ℃) are measured. The heat transfer coefficient of the hot plate of the hot end material of the research engine was obtained. The heat transfer coefficient of the hot end of the research engine is determined as 0.185 W/mK, according to the following heat transfer rate equation (3).

$$q = -kA\frac{\partial T}{\partial x} \tag{3}$$

Where q is the heat transfer rate (W), k is the heat transfer coefficient (W/mK), A is the heat transfer area (m^2), ∂T is the temperature difference (K), ∂x is the thickness (m) of metal sheet, not including the insulation. The heat transfer rate (q) of the cover is 24 W, and the heat transfer rate (q) of the heat shield is 17.3 W. The experimental results show that the thermal conductivity of the heat shield is lower than that of the heat shield and the reason is that the inner and outer walls of the hot end after the heat shield is added. The temperature difference is smaller than that of the non-insulation cover, but the cooling method of the cold end of this experiment is not enhanced at the same time, so the addition of the heat shield will not increase the heat transfer rate. Furthermore, the output power only increases by 1.2 times, which is far less than the reduction of the open area by 4.7 times. This result conforms to Su [8] who claimed that cold-end heat dissipation is better than the hot end temperature of the engine. After discussing the thermal efficiency data is reasonable, and the rationality of the analysis of the output power is as follows:

In the same way, according to the ideal gas equation (1) and the gas power cycle power equation (2). The pressure ratio of the expansion and compression process is estimated by the internal temperature ratio of the cold and hot end without the heat shield (498/323=1.5) (8.97/1.5= 6), and find the pressure difference is 8.97-6 = 2.97 kPa, and V is 678.2 * 10^{-9} m^3, the speed is 3.6 *rps* and substituted into equation (2). The output power can be calculated to be about 7.2 mW. If mechanical wear, belt drive and generator efficiency are taken into account, the measured output power of 0.1 mW should be reasonably small.

V. CONCLUSION

This research has successfully developed a modified engine. With this engine, researchers can measure the cylinder temperature, working fluid pressure, DC motor speed and power output of Stirling engine. The engine is operated under two different conditions. A DC motor/generator is driven by the engine to generate electric power. The following parameters are measured in this study, including cylinder temperature, working fluid pressure, motor speed, and power output for two operating conditions. The impact of the heat insulation shield on engine is explored, and the rationality of measured data is analyzed. Two results through experimental analysis are obtained as follows: 1, the maximum output power is increased by 1.2 times; 2, the output power value is as small as the mW level that is very reasonable. So it proves that our diagnosable Gamma-type engine has been successfully developed. In the future, researchers can use the modified engine with a diagnosable feature to conduct a series of related research.

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