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Design and anylysis of gamma type Stirling engine

Davood Jalali Vahid and Hojjat Danandeh Oskouei*

Faculty of Mechanical Engineering, Sahand University of Technology, Tabriz, Iran

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Abstract. This article discusses how to design and manufacture a gamma type Stirling engine. The Stirling engine is an external combustion engine that does not produce any pollution. In this study, we studied the design and manufacturing of industrial Stirling engine. After designing and manufacturing all the parts, the designed Stirling engine has been launched by a 550-watt electric heater and has been tested in two uninsured and insulated modes. In non-insulated mode, the motor had a power of 68.69 watts with a yield of 12.66% and, when the motor is insulated, it had a power of 86.48 watts with a yield of 15.72%.

Keywords: External combustion engine / gamma type / power / Stirling engine

1 Introduction

The Stirling engine is an external combustion engine that has made it easy to repair and maintain the engine in addition to low engine noise and no pollution. On the other hand, the Stirling engine is very simple in terms of mechanism because it does not have any valves. However, this engine has a high sensitivity to friction and fails with the slightest friction. On the other hand, external combustion of this engine has made the engine important in recent years, because in addition to its high efficiency and lack of any pollution, it can function with all kinds of energy. Since the invention of the Stirling engine in 1816 by Robert Stirling, a lot of research has been done on the sterling engine, the first mathematically accepted scheme for analyzing the sterling engine offered by Schmidt 50 years after its invention [1].

This theory considered the ideal gas expansion and contraction process as isothermal and with some simplifications, provided equations for calculating the distribution of pressure as a function of the crank angle, as well as determining the cycle work (first order method). In 1975, Finkellstein [2] developed Schmidt's thermodynamic analysis and presented adiabatic initial analyzes and considered adiabatic condensation and expansion chambers in solving adiabatic equations. Considering this, the equations would not be linear and numerical methods must be used to solve them (second order method).

Hennis et al. [3] at late 2009 addressed the increasing the efficiency of the Stirling Alpha Engine, the SOLO 161 model, using heat exchangers in a cold and hot chamber. They considered eight modes, which the linear arrangement of exchanger tubes had the highest output of 43.66% and the highest output power. They eventually showed that, despite an increase in dead weight, the overall engine efficiency increased by an average of 13%.

Tlili [4] in 2011, using adiabatic process for expansion and contraction chambers applied the Scotch Yoke mechanism on an Alpha-type motor. The swept volume of 24.5 cc, the heating and cooling chamber temperature of 923 and 350 Kelvin, the air agent are the initial data considered for this modeling. The result of this study show the efficiency and output power of the engine in different engine and temperatures conditions, which the average engine power is 48.79 watts.

Rogdakis et al. [5] investigated the thermodynamic and experimental combination of the Stirling engine. The engine under investigation was a SOLO V161 that was investigated by a hydrogen operating fluid at a maximum pressure of 150 times. The swept volume of this engine is 160 cc at 1500 rpm. The output power obtained (numerical) is a power output of at least 1.6 KW electrical and 8.8 KW heat power. Also, the range of motor efficiency is reported from 12.6 to 20.23 and the thermal efficiency is in range of 61.01–69.31, which indicated a maximum error of 20% to experimental data.

Valenti et al. [6], in 2013, addressed numerical and empirical studies of the Stirling engine system for home use. The swept volume of the hot and cold chamber was 27.4 and 28.4 cc, respectively, and the nitrogen was used as operating fluid. The results indicated an electrical capacity of 1 KW and a heating capacity of 8 KW, indicating a difference of 4% between experimental and simulated results.

* e-mail: hdanandeh@tabrizu.ac.ir

Ferreira et al. [7] modelled and estimated the cost of the Alpha Stirling engine for the simultaneous generation of power and heat. The research took into account two fluid types of hydrogen and helium at an average pressure of 30 bar. The swept and dead volume of cylinders were 130 and 25 cc, respectively, and regenerator volume was 69.8 cc. The results showed that the motor efficiency in contrast to the output power in the hydrogen agent fluid is higher than the helium. The minimum output is 28.5% and the output power is 1.7 KW. At the end, the cost of each part of the engine is given, which engine body has the highest cost. The price per watt is estimated to be about 17 euros.

Ahmadi et al. [8] addressed the optimization of the GPU3 beta engine model based on power output and engine efficiency at various engine speeds. The temperature of the hot and cold chamber was 288 K and 977 K, respectively, average pressure was 41 times, and operating fluid was helium. The results showed that increasing the length of the course reduces engine power and efficiency. Other result of this research was the significant impact of internal irreversibility.

Li et al. [9], in 2015, investigated the loss of the gamma sterling engine and the impact of these losses on the engine efficiency using Schmidt method. They considered the temperature of 317.9 K for a hot chamber, a temperature of 299.1 for cold chamber, operating fluid of air, and 1 bar initial pressure as the initial parameters for simulation. The results showed that the losses due to motor leakage was about 2%.

Fransson et al. [10] addressed the numerical simulation of gamma-type stirling engine power. They include the initial pressure of 12.5 bar and the phase difference of 80 and 90 degrees. They studied the power on different cylinder diameters with different lengths, which reduction in the power consumption by increasing the diameter of the cylinder can be noted as the result.

Ni et al. [11] in 2016 had numerical and experimental analysis on the Stirling engine of the beta model based on 100 watts power. The operating fluids used in this study was helium and nitrogen, which better efficacy and efficiency was observed in the helium. They showed that reducing the initial pressure of the engine reduces the cycle efficiency.

Review of related literature indicates the importance of use of the Stirling engine, because in addition to high efficiency and lack of pollution, it has high flexibility in term of the type of fuel consumed. For example, this engine can be launched by solar energy using a parabolic collector.

2 Design and construction of Stirling engine

2.1 Construction the main components

The Stirling cycle involves two constant temperature processes and two fixed volume processes, which works as shown in Figure 1, that shows the temperature-pressure diagram of the Stirling cycle in a closed thermodynamic cycle. The efficiency of this cycle is in based on equation (1), which is ideally equal to the efficiency of the Carnot cycle, which has the highest efficiency between two temperature sources [12].

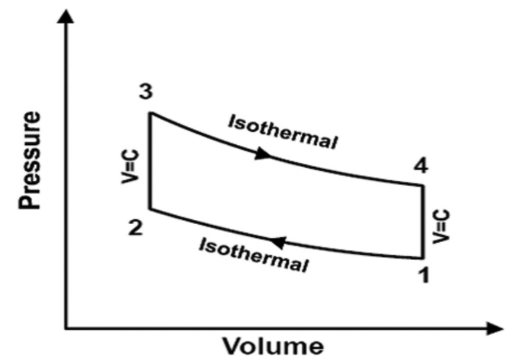

Fig. 1. Diagram of temperature-pressure Stirling cycle [7].

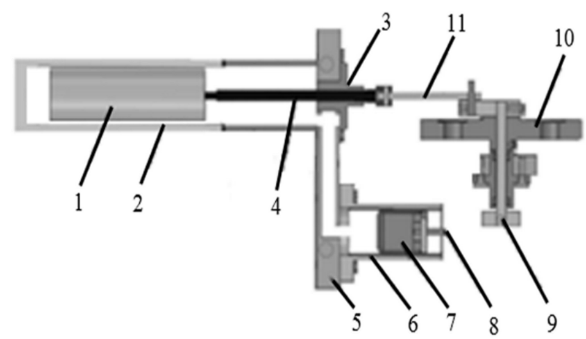

Fig. 2. Scheme Stirling engine of gamma type.

$$\eta_c = \frac{W_{\text{out}}}{Q_h} = \left(1 - \frac{T_c}{T_h}\right). \quad (1)$$

Conventional Stirling engines are divided into 3 types of alpha, beta and gamma, which phase difference of 90 degrees in the motion of the pistons is a common point between them. In this study, the gamma type is considered for the design and construction of the Stirling engine, the general design of which is in accordance with Figure 2.

Designing and manufacturing of Stirling engine parts the output power base for the research is considered to be 80 watts. Based on this, the West's (2) and Beale's (3) ratios were used to obtain the swept volume that was the starting point for design. In order to use the mentioned relations, the temperature of the hot and cold chamber was 250 and 50 °C, respectively, Beale coefficient was 0.11, the coefficient of West was 0.4, revolution was about 700 rpm and the maximum pressure was 6 bar.

Thus, the displacement cylinder volume is obtained using the West's and Beale's coefficients which was 103 and 121 cc, respectively. On this basis, the optional cylinder volume is considered to be 103 cc. Due to this volume, the internal diameter of the displacement cylinder is 75 mm and the swept length is 23 mm.

The Carlquist's relation (4) using the data above predicts the engine efficiency about 17.21–22.18%. Further, according to the design of Figure 2, other parts were

Table 1. Component specifications of Stirling engine.

N	Piece details	Piece material	D_i (mm)	D_o (mm)	Length (mm)	Weight (gr)
1	Displacement piston	aluminum	63	73	46	230
2	Displacement cylinder	aluminum	75	118	88	795
3	Displacement cylinder bushing	Brass	5	30	30	71
4	Displacement piston connecting rod	Steel	–	5	110	14
5	Power cylinder head	Steel	–	–	20	2907
6	Power cylinder	Steel	50	68.2	69.5	920
7	Power piston	Steel	44.4	49.95	50	308
8	Power connecting rod	Steel	–	–	106	40
9	Crankshaft	Steel	–	10	110	68
10	Flywheel	Steel	–	184	12.2	900
11	Displacement cylinder connecting rod	Brass	–	–	5	66

Table 2. General specifications of Stirling engine.

Dead volume of displacement cylinder	66 cc	Displacement cylinder swept volume	103 cc
The dead volume of the power cylinder	18 cc	swept volume of the power cylinder	86 cc
Total weight	9.5 kg	cylinders volume ratio	1.2
Operating fluid	air		

designed and built. low weight of parts, appropriate thermophysical properties, reasonable price for selected material, and temperature range of the piece were considered in designing all the pieces; the specifications of the main pieces are given in Table 1. The overall engine profile is also shown in Table 2.

$$W_{\text{out}} = F{\cdot}P{\cdot}\omega{\cdot}V_{\text{swd}}{\cdot}\frac{T_h - T_C}{T_h + T_C} \tag{2}$$

$$W_{\text{out}} = Be{\cdot}P{\cdot}\omega{\cdot}V_{\text{swd}} \tag{3}$$

$$\eta_e = \left(1 - \frac{T_C}{T_h}\right){\cdot}C{\cdot}\eta_H{\cdot}\eta_M{\cdot}Z \tag{4}$$

2.2 Engine balance

In this engine displacement crank and power crankshaft are two nonbalance masses, each with a 90-degree angle. Thus, according to Figure 3, the engine is balanced by adding two masses along the lines of the nonbalance masses.

To do this, if center of mass of the nonbalance objects is obtained the mass and the distance of the unknown masses, can be obtained from equation (5) for the x axis as well as equation (6) for the y axis.

$$X: \quad m_2{\cdot}r_2 = m_4{\cdot}x, \quad m_4{\cdot}x = 61 \tag{5}$$

$$Y: \quad m_1{\cdot}r_1 = m_3{\cdot}y, \quad m_3{\cdot}x = 60. \tag{6}$$

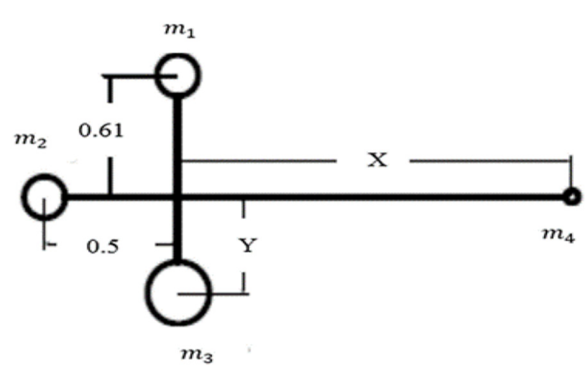

Fig. 3. Unbalance and balancing objects.

Thus, taking into account x and y, the balancing masses m_3 and m_4 are obtained.

$$y = 0.39 \text{ mm}, \quad m_3 = 190 \text{ gr}$$

$$y = 13.65 \text{ mm}, \quad m_4 = 44 \text{ gr}$$

2.3 Electrical heater

The engine was first launched by an electric heater placed inside the displacement cylinder. In fact, the dead volume of the displacement cylinder mentioned in Table 2 is due to the presence of this heater. The maximum heater heating power is about 550 watts. It is also possible to reduce the input power using the electric dimmer. The final form of the

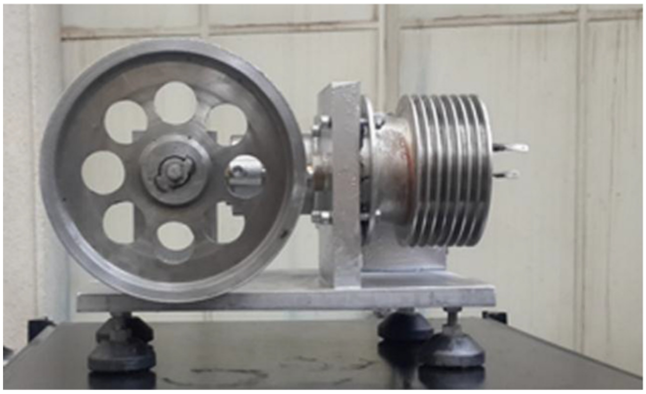

Fig. 4. The Stirling engine built.

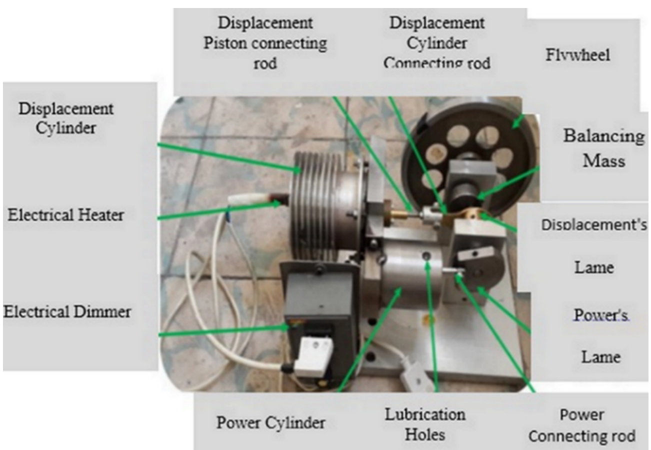

Fig. 5. Details of the Stirling engine.

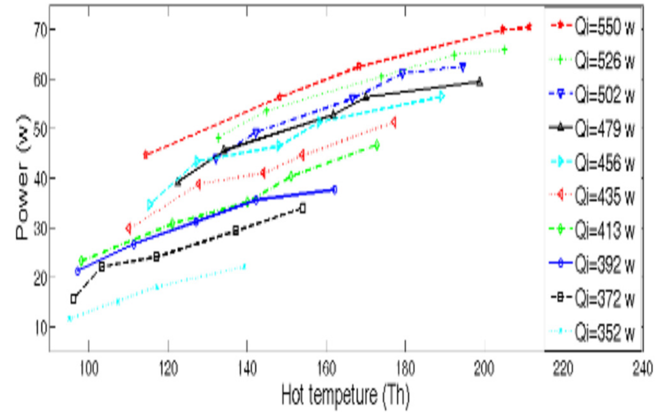

Fig. 6. Diagram of temperature-power Stirling engine without insulation.

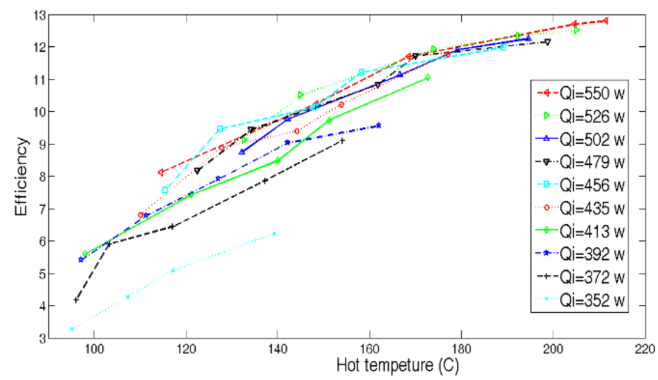

Fig. 7. Diagram of Temperature-efficiency Stirling engine without insulation.

engine is shown in Figure 4. The engine details are also shown in Figure 5.

3 Results

The experiments were carried out in two insulated and non-insulated hot cylinder displacement cases. In each test, the power output of the motor is obtained by reducing the input voltage (V) by the dimmer. In each test, the temperature of the cold and hot chambers, rotation, and torque of the engine is measured. The maximum output torque of the motor in this mode is 23.1 N.m. at 541 rpm. In fact, the maximum output power of an engine in a non-insulated state is 69.68 watts. Figures 6 and 7, respectively, show the output power and motor efficiency in terms of the temperature of the hot chamber in non-insulated conditions.

In non-insulated mode, some of the power input to the engine is lost through the transfer from the hot chamber of displacement cylinder. Therefore, the engine was tested once again when the hot chamber of displacement cylinder (two third of cylinder displacement) was insulated. The maximum torque in this mode is 1.34 N m. In this case, the engine speed is 616 rpm, so the maximum output power of the engine in the uninsulated state is 86.44 watts. The engine power and efficiency in terms of the temperature of the hot chamber in the case where engine is insulated are shown in Figures 8 and 9.

4 Conclusion

A more accurate comparison of the results indicated a quantitative difference between the values obtained for power and efficiency with calculated values of Beale, West and Carlquist's methods.

Due to the fact that the sterling engine fails with the slightest friction, therefore, in addition to increasing the diameter of the displacement cylinder, which reduces the length of the displacement course, the lubrication operation should be carried out regularly on the cylinder because the maximum friction of the motor at the contact point of the power cylinder. Also, increasing the power of the electric heater, and thereby increasing the temperature of the hot chamber, will increase the pressure, resulting in increased power and engine efficiency. On the other hand, the engine's balance has significantly reduced the vibration of the engine so that the engine had the least vibration in operating condition, because a small amount of unbalance prevents the engine from operating.

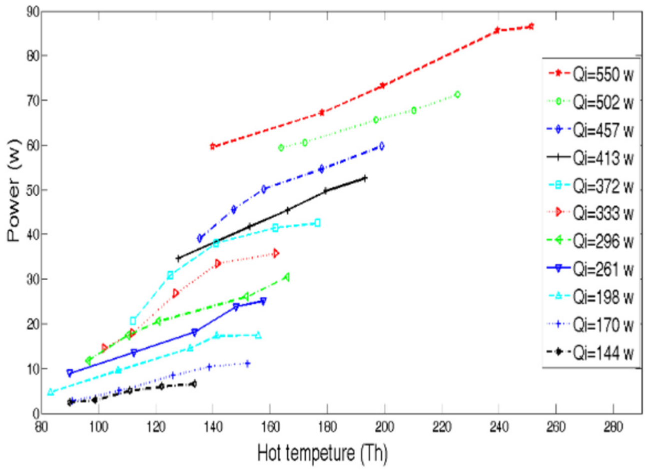

Fig. 8. Diagram of temperature-power Stirling engine with insulation.

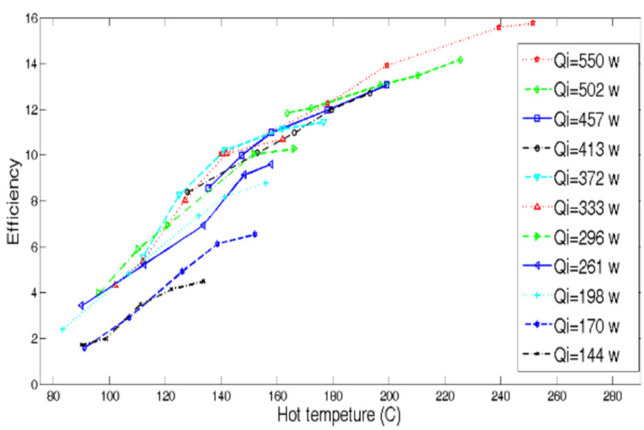

Fig. 9. Diagram of temperature-efficiency Stirling engine with insulation.

By inserting an electric heater into the cylinder, the heat loss is reduced greatly, because output of the heater directly is transferred to the operating fluid in hot chamber of displacement cylinder, which increases the engine efficiency in different conditions.

Nomenclature

W Output power, watt
Q Transfer rate heat, watt
T Temperature, K
F West's coefficient
P Pressure, bar
V Volume, m^3
ω Rotational speed, Hz
B_e Beale's coefficient
C Coefficient ratio to Carnot returns (0.65–0.75)
Z Correction factor (0.95)
m Mass (gr)
r Massage center distance to crankshaft axis, m
D Diameter, m
η_C Cycle efficiency
η_H Heating efficiency (0.85–0.9)
η_M Engine mechanical efficiency (0.85–0.9)
η_e Engine efficiency

Subscripts

out Output
o Outer side
i Inner side
h Hot
c Cold
swd Sswept of displacement cylinder

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