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Analysis of Sweep Volume Effect on the Output Power and Velocity of a Gamma-Type Stirling Engine with Slider-Crank Mechanism Features

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ABSTRACT

The Stirling engine is an external combustion engine that can generate electricity without any pollution; in the other words, it can generate energy from renewable energy sources such as solar energy. In this research, the gamma-type Stirling engine with slider-crank mechanism with three different sweep volume ratios 1, 1.5, and 2 are manufactured and compared. It is observed that in the engine when the sweep volume ratio is 2, the result is better and more than the remaining types; Another conclusion from this comparison is that a lower temperature difference is required for a larger sweep volume ratio. So, the engine when the sweep volume ratio is 2, a lower temperature difference required for reaching a higher and better output is required.

KEYWORDS Numerical analysis, Output power, Stirling engine, Slider-crank mechanism.

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INTRODUCTION

Nowadays, the optimal use of energy resources and the reduction of environmental pollution are gaining important attention in both developed and under-developing countries. Currently, the energy sources which are used by people are highly polluting the environment and have many biodegradable effects; however, the cleanest sources of energy are renewable energy. In recent years, the movement towards clean energy has made people enthusiastic in the developing Stirling engines; also in solar energy, for promoting and bolding renewable energy awareness it can be used. Stirling engines are known to have the highest thermodynamic efficiency and ideally have efficiency as same as the efficiency of the Carnot cycle.[1]

The Stirling engine is typically suitable for applications that have a good cooling source, low velocity is considered, reducing vibration is important, slow change may be led to the desired output, and there is no problem for a time delay to start the operation.[2] According to the above-mentioned cases, Stirling engines can also be used in the aviation industry. These engines have less vibration than internal combustion engines; they are a good choice for aero applications. It should be mentioned that when using a Stirling engine in aircraft, there is always a concern about the weight of the engine; it can be solved by reducing the size of the flywheel. As it is mentioned, Stirling engines have constant power; since most aircraft work with constant power.[3] Stirling engines can also be used on a small scale. For instance, the international company, Micro-star, has developed a small cooling system to cool the computers; this system can rotate the built-in fan while using the energy of wood chips;[4] Furthermore, this engine can also be used to supply electricity to rural and urban areas.[5,6] This engine can absorb heat energy from both the sun and the combustion of materials, or in the other words using fuel/solar hybrid systems during nights when the sun is not available, in order to generate electricity.[2]. Nowadays, Stirling cycle-based systems such as heat pumps and refrigerators are used in commercial applications.[7] This engine can run on solar thermal energy mode and generate electricity without any pollution. The history of Stirling engines dates to 1807 when in England George Cayley came up with the idea of building an engine named the Caloric machine; this engine was never built, but it was the beginning of a huge number of engines that followed this idea.[4] In the beginning, these engines were called air engines, and sometimes, they were named by their manufacturers; Stirling was first chosen for these engines in 1950.[8] These engines were safer than steam engines at the time, but their performance was weak.[9] In 1950, a 200-watt model of this motor was built.

In 1972, Philips, in partnership with Ford Motor Company, developed a Stirling four-cylinder engine with 170 horsepower. Then in 1983, Kolin introduced the LTD Stirling engine; this engine could work at a temperature difference of less than 15°C.[10] In 1991, Senft developed a model of a gamma-type Stirling engine that worked at a temperature difference of less than two Celsius degrees between a hot and cold source; in 1993, he designed the LDD Ringbum engine, which used a 60-degree conical reflector to generate a temperature of about 93°C.[11] In 2005, Can Cinar and Halit Karabulut examined the type of operating fluid in a Gamma-type Stirling engine; in the comparison of two different operating fluids, Air, and Helium, they concluded that using Helium can increase the engine efficiency.[12] In 2007, Somchai Wongwises and Bancha Kongtragool compared the power of a two and four-piston gamma-type engine; it should be mentioned that the operating fluid in these engines was Air, and the temperature range of the hot source was 589-771°C and the result of this study was that the way to increase the efficiency of the gamma-type engine is increasing the number of its pistons.[10] In 2012, Noureddine Boutammachte and Juergen Knorr tested a gamma-type engine that was coupled to a water pump; the result of this study was that the output power of the engine is related to the cubic temperature difference between the hot and cold source. The heat transfer between the heat receivers or in the other words, the part of the cylinder that is in contact with the hot source, and the operating fluid should be improved.[13] Also, this year, Chin-Hsiang Cheng and Hang-Suin Yang theoretically examined the ratio of sweep volume and phase angle in the three alpha, beta, and gamma type engines. They concluded that if the optimal value of the phase angle and the sweep volume examine and use, the efficiency can be improved.[14] In 2014, Wen-Lih Chen, King-Leung Wong, and Hung-En Chen investigated the effect of recovery part on the performance of a Gamma-type Stirling engine with two pistons; the parameters studied in this study were the diameter of the constituent wires and the materials of the recovery part and according to the results of this study, all of the above-mentioned parameters have a significant impact on engine performance; the results show that the use of Copper instead of stainless steel in the recovery will increase the efficiency and the very small diameter of the wires forming the recovery will increase the pressure drop and reduce the efficiency of the recovery part.[15] At present, countries such as Germany and the United States have produced examples of Stirling engines such as Stirling refrigerators, solar Stirling engines, etc.; in Iran, several examples of Stirling engines have been made. One of the main disadvantages of Stirling engines is their low efficiency compared to internal combustion engines. In order to improve the efficiency of these engines, in this research, the effect of the sweep volume ratio of the pistons on the output work has been studied theoretically and experimentally.

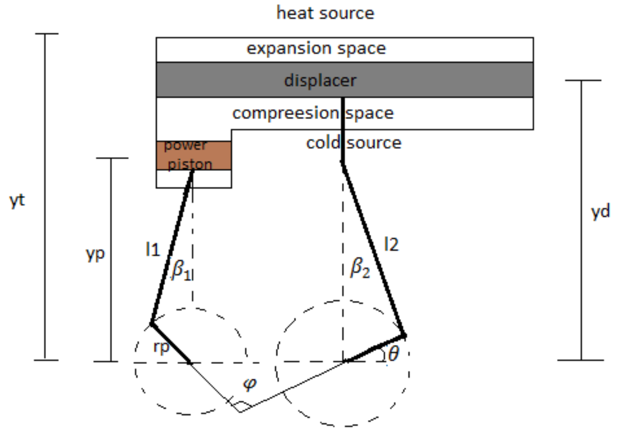

Fig. 1: Stirling engine with slider-crank mechanism.

MATERIALS & METHODS

Analyzing the Striling Engine

A schematic of a Stirling engine using slider-crank mechanism is shown in Fig. 1. Ys is the moving cylinder length, “Yt” is the total engine height, “Yp” is the displacement of the piston, “Yd” is the displacement of the displacer, “Lp” is the length of the piston, “ld” is the length of the displacer, “l1” is the length of the link connected to the piston and “l2” is the length of the link connected to the displacer; all of the links are considered as a rigid body and their center of mass is on the middle of the links and all of the engine parts can have both rotational and transverse motion while moving. By writing the piston and displacement equations and derivatives from them, the velocity and acceleration equations of piston and displacement can be obtained; in this engine, the displacement of the piston and the displacer will be defined as follows in eqs. (1) and (2).

$$Y_P = l_P + l_1 \cos\beta_1 + r_P \cos(\theta + \varphi - \pi/2) \tag{1}$$

$$Y_d = \frac{l_d}{2} + l_{dt} + l_2 \cos(\beta_2) + r_d \sin\theta \tag{2}$$

In the above-mentioned equations, “lp” is the length of the piston, “ld” is the length of the displacer, “l1” is the length of the link connected to the piston, “l2” is the length of the link connected to the displacer, “rp” and “rd” are the rotational radius for the power and displacer pistons, respectively. Also, the volume of the expansion chamber “V_e (Ø)”, compression chamber volume “V_c (Ø)”, and the total volume “V(Ø)” are defined in eqs. (4)-(6), respectively.

$$V_e(\emptyset) = V_{emin} + \frac{1}{2}V_{es}(1 + \sin(\emptyset + \alpha)) \tag{4}$$

$$V_c(\emptyset) = V_{cmin} + \frac{1}{2}V_{es}(1 + k + k\sin\emptyset - \sin(\emptyset + \alpha)) \tag{5}$$

$$V(\emptyset) = V_e(\emptyset) + V_c(\emptyset) + V_r \tag{6}$$

That “V_{emin}” is the empty space in the expansion chamber, “V_{cmin}” is the empty space in the compression chamber, “V_{es}” is the swept volume by the power piston, “Ø” is the crankshaft angle, “α” is the phase difference angle, “V” is the recovery volume and “k” is the sweep volume ratio. By placing the compression and expansion chamber volume in eqs. (1) and (7) can be obtained.

$$V(\emptyset) = V_{emin} + \frac{1}{2}V_{es}(1 + \sin(\emptyset + \alpha)) + V_{cmin} + \frac{1}{2}V_{es}(1 + k + k\sin\emptyset - \sin(\emptyset + \alpha)) + V_r \tag{7}$$

The recovery volume or in the other words, the space between the expansion chamber and the compression chamber, makes up the useless volume in the engine and it can be written like eqs. (8)-(10).

$$V_{emin} + V_{cmin} + V_r = V_d \tag{8}$$

$$V(\emptyset) = V_d + \frac{1}{2}V_{es}(1 + \sin(\emptyset + \alpha)) + \frac{1}{2}V_{es}(1 + k + k\sin\emptyset - \sin(\emptyset + \alpha)) \tag{9}$$

$$V(\emptyset) = V_{es}(X + \frac{1}{2}(2 + k) + \frac{1}{2}k\sin\emptyset) \tag{10}$$

“X” is the ratio of dead and sweep volume of the power piston. Assuming that the pressure is constant throughout the engine and the pressure changes are negligible, the pressure will be obtained by eq. (11).

$$P = \frac{mR}{\frac{V_e}{T_e} + \frac{V_c}{T_c} + \frac{V_d}{T_d}} \tag{11}$$

By replacing the volumes of compression and expansion with $T_d = \frac{T_e + T_c}{2}$, the eq. (12) will be obtained.

$$p = \frac{mRT_e}{V_{es}}(\left[\frac{2X}{1 + \tau} + \frac{1 + k + \tau}{2\tau} + \frac{k\sin\emptyset}{2\tau} + \frac{(\tau - 1)\sin(\emptyset + \alpha)}{2\tau}\right]^{-1}) \tag{12}$$

$k = \frac{V_c}{V_e}, x = \frac{V_d}{V_{es}}, \tau = \frac{T_c}{T_e}$ are the used parameters in eq. (12). To calculate the output work, eq. (13) can be used.

$$W = \oint p\,dV = mRT_e \int_0^{2\pi} \varphi \frac{d\phi}{d\emptyset} d\emptyset \tag{13}$$

According to eq. (13), eq. (14) is obtained by placing the values and integrating from them.

$$W = mRT_e \frac{2\pi\tau k(1-\tau)\sin\alpha}{a^2+b^2}\left(\frac{\beta-\sqrt{\beta^2-(a^2+b^2)}}{\sqrt{\beta^2-(a^2+b^2)}}\right) \quad (14)$$

It should be noted that in order to calculate the heat input to the coupled engine with solar dishes, it must be considered that the solar energy is the same as heat input to the engine; this energy consists of direct sunlight and can be observed in eq. (15).

$$Q_T = (\tau\alpha)_b I_b C \quad (15)$$

Parameter "Q_T" is the rate of thermal energy transferred to the engine. Phrase "$(\tau\alpha)_b$" is the effective absorption coefficient of the receiver for scattered and direct radiation, Parameter "C" is the concentration rate of direct sunlight, and parameter "I_b" is the luminosity of direct sunlight; when the heat reaches the engine, the temperature of the hot source can be obtained like in eq. (16); parameter "h" is The heat loss coefficient is the collector. As a consequence, the required parameters were obtained for achieving the goal of this work.

$$Q_T = \varepsilon\sigma(T^4 - T_o^4) - h(T - T_o) \quad (16)$$

RESULTS & DISCUSSION

Effect of Sweep Volume on the Output Work

According to the equations and the geometric parameters of the engine, the output work in this engine increases by increasing the sweep volume ratio to 2; in the other words, if the displacer piston sweeps twice as much as the power piston, it will do its maximum work with these geometric parameters and the inlet temperature. The sweep volume ratio increases by more than 2 engine volumes ratio; As a result, the amount of operating fluid will increase, so it will need more inlet heat. Whit this inlet heat and larger volume of sweep volume ratio, the work will be reduced, and it is observable from Figs. 2-4.

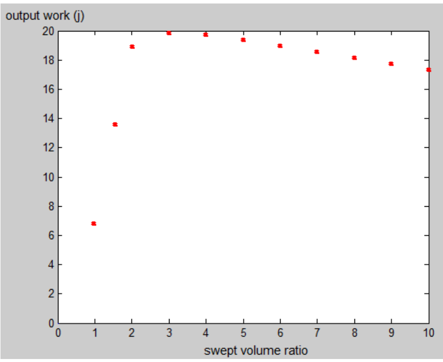

Fig. 2: Impact of dead volume on output work.

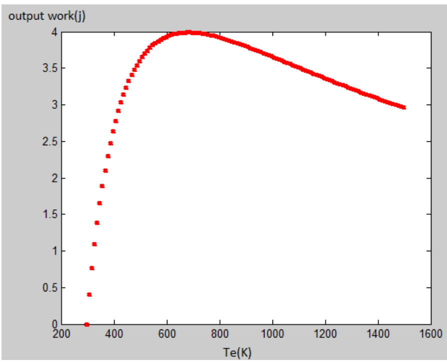

Fig. 3: The effect of hot source temperature on the output of the engine when the sweep volume ratio is 1.

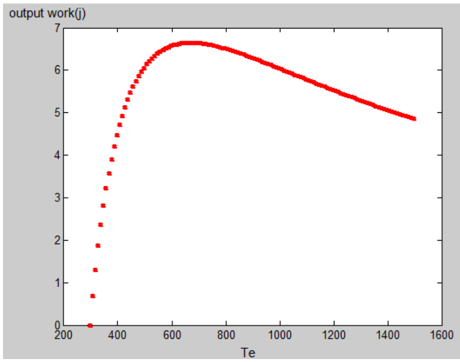

Fig. 4: The effect of hot source temperature on the output of the engine when the sweep volume ratio is 1.5.

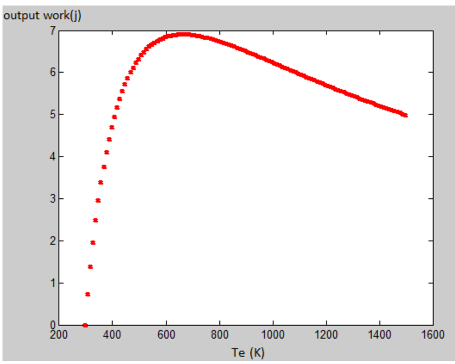

Fig. 5: The effect of hot source temperature on the output of the engine when the sweep volume ratio is 2.

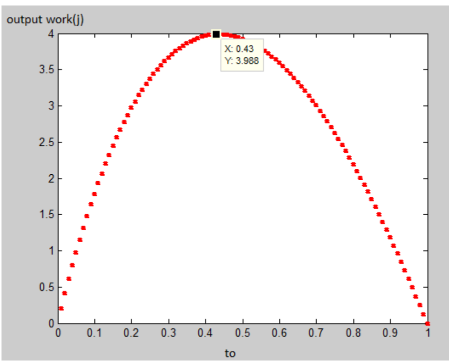

Fig. 6: The effect of temperature ratio on output work in engine when the sweep volume ratio is 1.

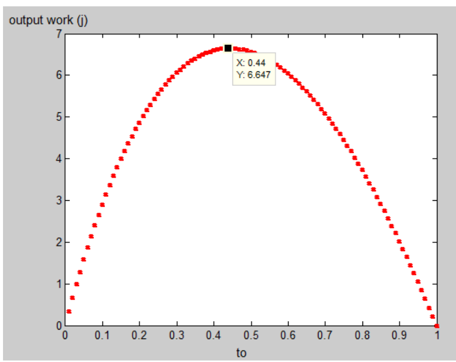

Fig. 7: The effect of temperature ratio on output work in the engine when the sweep volume ratio is 1.5.

Effect of Hot Source Temperature on the Output Work

Fig. 5-7 show the effect of hot source temperature on the output work. According to the above-mentioned figures, with increasing the temperature of the hot source from ambient temperature to 700 K, the output work increases, but with increasing this amount, the output work will decrease. As mentioned earlier, Stirling engines operate between hot and cold sources, but the temperature difference between the two sources is significant. If the temperature difference becomes too large, the cold source will not be able to cool the operating fluid and may cool part of the operating fluid; the same small volume of operating fluid will participate in the cycle and as a result, the output work will be reduced.

Effect of Sweep Volume Ratio on Temperature Ratio

Figs. 8 and 9 show the effect of temperature ratio on output work in three engines using different sweep volume ratios. At high-temperature differences, the operating velocity of the Stirling engine increases; this increase in velocity, increases the heat transfer between the cold source and the hot source and causes the engine to shut down quickly.
On the other hand, the temperature difference is required for the engine to work. This temperature difference should be such that the engine has an acceptable velocity and produces good output. According to figure 8, the temperature ratio of 0.43 is the ratio that the engine temperature difference is optimal and have an acceptable rotational F instance, in an engine with a sweep volume ratio of 1 and a temperature ratio of 0.1, if the hot source temperature is 800, the cold source temperature is 80, and it is very clear that the cold source can hardly cool the fluid temperature to 800 degrees. Or at a temperature ratio of 0.9, the temperature of the hot and cold source is very low and the expansion and contraction of the operating fluid is difficult.

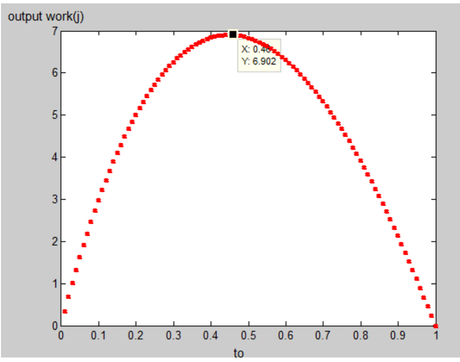

Fig. 8: The effect of temperature ratio on output work in the engine when the sweep volume is 2.

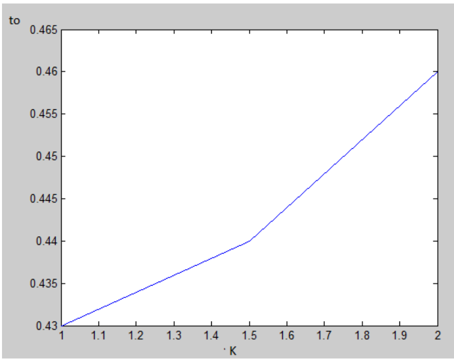

Fig. 9: The effect of sweep volume ratio on temperature ratio.

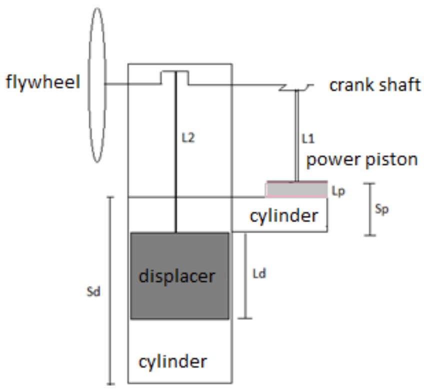

Fig. 10: Schematic of the manufactured engine.

Manufacturing and Testing Stirling Engine

The overall schematic of sterling gamma-type engines is shown in Fig. 10. This study aims to investigate the effect of the sweep volume ratio on engine output work. For this purpose, three engines with different sweep volume ratios were constructed. These engines are in Figs. 2-4. These engines have two power pistons and transporter and two power cylinders. As piston operating fluid warms, the power piston moves upwards and due to the phase difference between the power piston and the displacer, the moving piston moves downwards. As the displacer moves downwards, the heated operating fluid moves downwards and cools in the cold source. As a result, the power piston moves downwards and will be at its original position. This movement will repeat. The displacement of the power piston and the displacer causes rotation to the flywheel.

Table 1: Engine Specifications.

Part Names and Symbols		Size (motor with sweep volume ratio 1) - cm	Size (Motor with broom volume ratio 1.5) - cm	Size (Motor with broom volume ratio 2) - cm
S_d	Length of moving cylinder	10	10	10
l_d	Length of shifter piston	5	5	5
l_2	Piston shifter interface rod and crankshaft	14	14	14
r_d	Shifter Piston Course	1	1.5	1
r_p	Power Piston Course	1	1	0.5
l_1	Tyton power and crankshaft interface rod	10	10	10
S_p	Length of the power cylinder	4	4	4
l_p	Length of the power piston	1	1	1

Engine specifications are observable in Table 1. The difference between the engines is in two parameters, r_d. and, r_p. in the first engine, the ratio is 1 and in the second engine the ratio is 1.5 and in the third engine it is 2.

Experimental Results

To investigate the effect of sweep volume ratio on output work, three types of gamma-type engines with different sweep-volumes ratio are tested. According to the tests conducted by increasing the sweep-volume ratio in the engines, the velocity of flywheel rotation will increase. In the engine with a sweep-volume ratio of 1, electric power output is 0.45W, and flywheel rotational velocity is 90 rpm. In the engine with a sweep-volume ratio of 1.5 flywheels rotates at a speed of 99 rpm and the mechanical output power is 0.9W; and in the engine with a sweep-volume ratio of 2, the output power is equal to 1.3W and the flywheel will rotate at 120 rpm; The diagram of these value are observable in Fig. 11. According to the amount of power obtained for each engine and with the help of the relationship between work and output power in all three engines can also be calculated. For the engine with a sweep-volume ratio of 1 the output work is 4.5 J, the sweep-volume ratio of 0.6 output work is to 9J and the engine with a sweep-volume ratio of 0.75 output work is equal to 13 J. In Figs. 12 and 13, the working values and experimental output power are obtained.

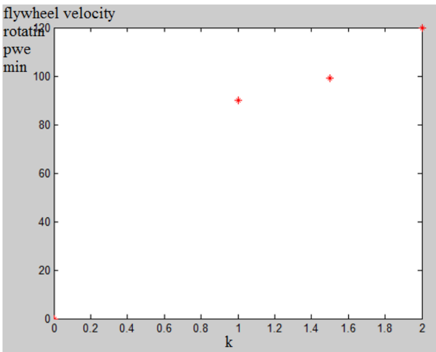

Fig. 11: The flywheel rotational velocity diagram due to the sweep-volume ratio.

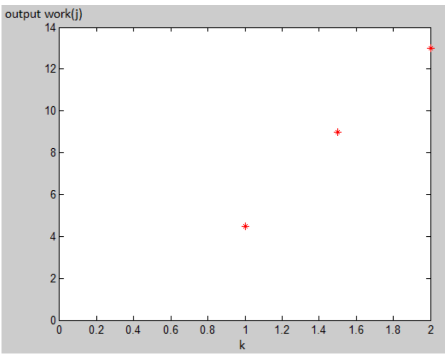

Fig. 12: The output work diagram relative to the sweep-volume ratio.

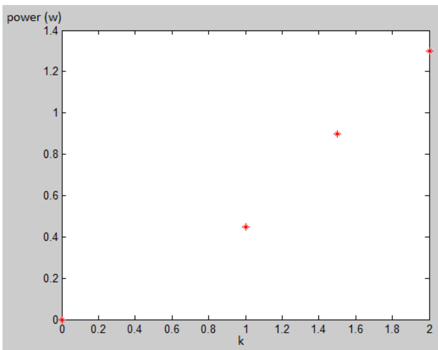

Fig. 13: The output power relative to the broom volume.

Comparison of Results

The values of experimental and theoretical output work are compared in Fig. 14. Factors such as the effect of drops in theoretical values, pressure drop, the internal resistance of the rotor, and error of measurement are not considered. The theoretical works of the engines were 6.5 J, 13 J, and 18 J, respectively. The percentage of error can be calculated by eq. (17). Accordingly, the results for engines with sweep-volume ratios of 1, 1.5, and 2 are 40%.

$$\alpha = \frac{Experimetnal\ Error - Theoretical\ Error}{Experimetnal\ Error} * 100 \qquad (17)$$

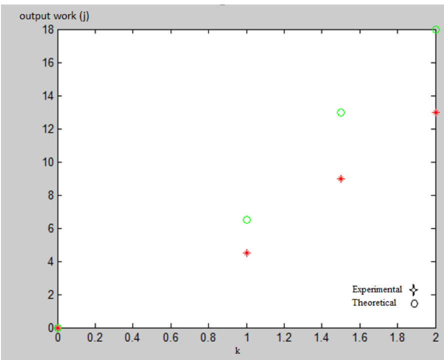

Fig. 14: Comparison of theoretical and experimental output work diagram.

CONCLUSION

According to the manufactured engines and the test results, it was observed that with increasing the temperature of the hot source, the output work does not always increase, but the temperature increase must be as high as the cold source to have the cooling ability. This temperature difference is excessive, the cold source will not be able to cool the entire operating fluid and only the operating fluid will be cool and participated in the cycle; so, the output work will be reduced. This optimal temperature difference varies in three engines. In engine when the ratio is 1, this optimum temperature difference is 0.43 and in the engine with a sweep-volume ratio of 1.5, it is 0.44; and in the engine with a ratio of 2, it is equal to 0.46. The less thermal resistance of cylinders can lead to a faster heat transfer to the operating fluid and less time is needed to run the engine. Also, the operating fluid with high volume expansion coefficient can be used to change the volume for less heat. By reducing the dead volume, the engine output will increase. In order to reduce the volume of dead, in Stirling engines, the displacing piston can be designed to play both the role of the regain part and the transporter; this will reduce the amount of fluid needed. To calculate the power of this engine in the steady state, a mass can be used as a damper.

DISCLOSURE STATEMENT

The author(s) did not report any potential conflict of interest.

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