An investigation of a ɣ-type MTD Stirling engine prototype

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Summary

Although thermal efficiency of moderate temperature differential (MTD) Stirling engines is higher than low temperature (LTD) engines, the complexity of design of MTD engines has led to the lack of research in this field. In this work, a prototype of ɣ-type moderate-temperature differential Stirling engine was manufactured, evaluated and structurally optimised. A mathematical evaluation was carried out based on a finite-dimension thermodynamics approach. The swept volume ratio was optimised based on the temperature difference of 450^0C. A computer program was thus written to simulate the Stirling engine performance under the assumed working conditions. Based on the mentioned temperature difference, the swept volume ratio of the engine was found to be 3. The engine dimensions were then adjusted to fulfil the computed swept volume ratio. The bore and stroke for power piston were chosen as 60 mm and 40 mm, respectively. For the displacer, they were selected as 90 mm and 60 mm, respectively based on the chosen swept volume ratio.

Key Words: Stirling engine; Gamma-type; Swept volume ratio; finite-dimension thermodynamics

1. Introduction

The Stirling engine was invented by Robert Stirling approximately two centuries ago [1, 2]. The Stirling engine is a prominent candidate for power generation which uses both renewable and natural resources. According to the considered temperature difference, the Stirling engines can be categorized as the high-temperature differential (HTD), moderate temperature differential (MTD) and the low-temperature differential (LTD) designs. The high-temperature design represents the benchmark for solar energy to electricity conversion efficiency, typically around 30%. The thermal limit for the operation of high-temperature Stirling engines depends on the material used for its construction [3]. Engine efficiency ranges between 30% to 40%, resulting in a typical temperature range of 650-800 C^0, and the normal operating speed range is from 2000 to 4000 rpm [1]. However, it comes at a cost that can be as high as 10,000 $/kW compared to 3000 $/kW for the photovoltaic systems [3]. On the other hand, the low-temperature differential Stirling engines are not as successful as their high-temperature difference counterparts. The thermal efficiency of the low-temperature differential Stirling engines also cannot achieve the efficiency of the high-temperature Stirling engines [4]. Besides the high and low-temperature Stirling engines, the moderate temperature differential engine avoids the expensive alloys and complex design required in the high-temperature design, hence brings down the cost. Nevertheless, the thermal efficiency of moderate temperature is higher than that of the low temperature.

In this experimental study, a moderate temperature Stirling engine is modelled using the finite-dimension thermodynamics approach. According to the desired temperature difference and using the mathematical model, the optimum swept volume ratio of the engine is estimated so as to maximise the objective functions (e.g. efficiency and work). Upon the obtained swept volume ratio, the prototype of the moderate temperature Stirling engine is developed and evaluated.

2. Optimization scheme

One of the first optimization goals concerning moderate temperature differential Stirling engines is to determine the optimum swept volume ratio (ξ). According to the guidelines provided in [5] and [6], the procedures of finite dimension thermodynamics were employed to calculate the efficiency of the engine η and dimensionless work W* in order to find optimum swept volume ratio.

$$|W^*| = \frac{(1-(1/\tau))m^*}{1+\xi(1+2\sigma)(1+2\sigma)[1+\xi(1+2\sigma)]} \quad (1) \qquad \eta = \frac{-\ln(Z(\xi,\sigma,\tau))}{[(\tau\ln(Z(\xi,\sigma,\tau))/(1-\tau)+G(\xi,\sigma,\tau)]} \quad (2)$$

Where: $\tau = \frac{T_h}{T_c}$, σ: dead space volumes, m*: dimensionless mass. Th: cold outer space , Tc: cold inner space

Table 1, Reference parameters

$T_H(K)$	$T_C(K)$	$P_0(Pa)$	σ	$v\ (rev\ s^{-1})$	$y_0(mm)$	γ	η_{reg}
753	303	100000	0.1	2	60	1.4	0

Where: γ: gas heat capacity ratio, υ: frequency

For the given values of parameters in Table 1, the swept volume ratio was incremented so as to find the optimum value of ξ corresponding to maximum values of η and W**. This was done by a computer program to determine the optimized swept volume ratio (Fig.1). In this work, an effort was made to design a moderate temperature differential around 450 ^0C and the sink temperature was assumed to be the ambient temperature.

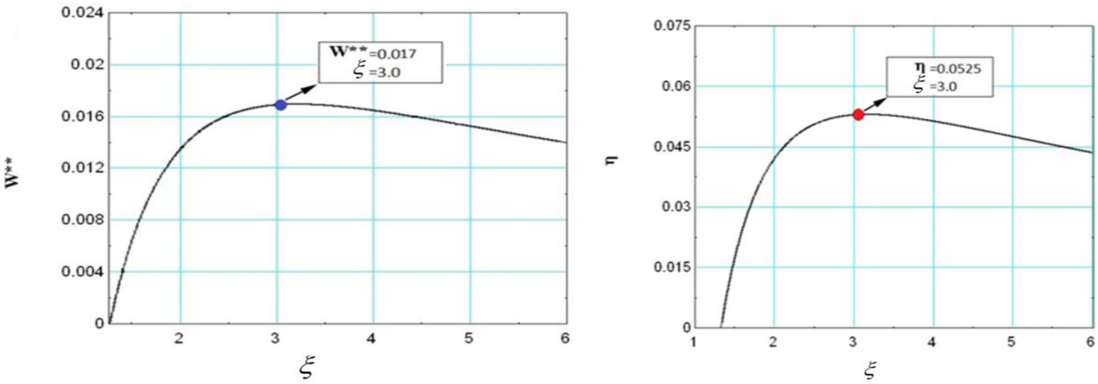


Fig. 1. (right) Efficiency and (left) dimensionless secondary work versus compression ratio

Table 2

	Mechanical configuration	Displacer	Power piston	Phase angle	Swept volume ratio	Working gas	Cooling system
	Gamma	Bore × stroke (m) 0.09×0.06	Bore × stroke (m) 0.06×0.04	90°	3	Air	Air cooled

3. Engine construction

According to the results obtained in the previous section, a moderate temperature Stirling engine with Gamma configuration was developed. The main engine design parameters are shown in Table 2. The power cylinder was made of a cast iron pipe and the power piston was made of an aluminium bar. The power piston was tuned to match the power cylinder bores. The clearance between the power piston and power cylinder was 0.5 mm. The displacer was built from aluminium. The displacer cylinder was made of a steel pipe. The clearance space between the displacer and the cylinder liner was 10 mm. The rod of the displacer was made of stainless steel. The cooling fins were built from aluminium. The two middle pages were made of aluminium with dimensions 20 × 16 × 2 (cm) and were connected by 14 bolts and nuts. The flywheel was constructed from iron with 20 cm thickness and 2.3 kg weight. The prototype Stirling engine developed in this work is depicted in Fig. 2.

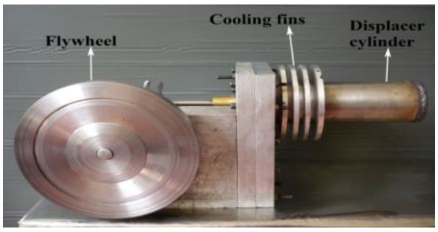


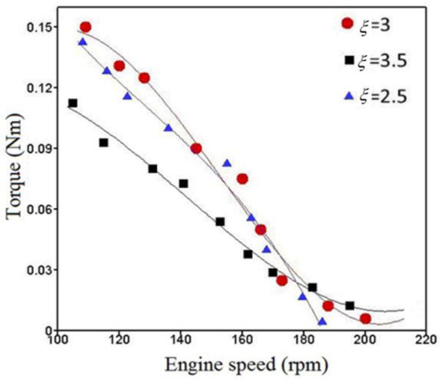
Fig. 2. Photographs of gamma-type Stirling engine

4. Indicated power and testing

The mean indicated power can be calculated approximately from equation 3:

$$P = \frac{W_{total} n_{mean}}{60} \qquad (3)$$

where W_{total} is the total work done per cycle and n_{mean} is the mean engine speed at mean hot source temperature of 450^0C and sink temperature of 30^0C. n_{mean} was measured to be about 160 rpm. The developed Stirling engine was tested at thermodynamics Laboratory in order to evaluate the validity of the obtained swept volume ratio from the optimization study. Upon the presented optimization technique (Fig 1) the optimum swept volume ratio was found to be 3. Thus, the experimental investigation was organized with three swept volume ratios 2.5, 3 and 3.5 so as to see whether or not the swept volume ratio of 3 is optimal.



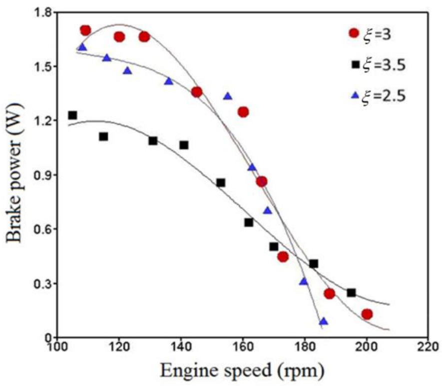


Fig. 3. (right) Brake power and (left) Engine torque versus engine speed

Fig. 3 demonstrates the variations of the engine torque and the brake power versus the engine speed for the three swept volume ratios. As can be observed, a higher engine torque and a higher brake power can be picked up at the lower engine speeds. Furthermore, around the engine speed of 120 rpm which is the considered speed in the optimization study (see Table 1), the swept volume ratio 3 showed some superiorities compared to other graphs through which the validity of the optimization scheme can be confirmed.

The brake power in Fig. 3 was calculated using the following equation [7]:

$$P_{Brake} = \frac{2\pi T n}{60} \qquad (4)$$

where n is the engine speed in rpm and T is the engine torque in Nm.

5. Conclusion

In this study, an optimization scheme which had been previously applied to the low-temperature differential Stirling engines based on the assumption of low-temperature difference [5] was used to optimize their moderate temperature counterparts. The optimized swept volume ratio was found to be 3 through the optimization study. A gamma-type moderate temperature differential Stirling engine with adjustable swept volume ratio was designed and constructed to evaluate the validity of the optimization method. The regenerator was omitted to determine the minimum possible output power and to simplify the engine structure. To validate the obtained optimum swept volume ratio, the engine was experimentally evaluated at different swept volume ratios including 2.5, 3 and 3.5. The results showed that the optimal swept volume ratio of the engine is 3 for the engine speed range of 100-160 rpm (in order to maximise the torque and brake power) and 3.5 when the engine speed is in the range of 160-200 rpm.

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