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Design and performance of a moderate temperature difference Stirling engine

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A B S T R A C T

The present work developed a prototype Stirling engine working at the moderate temperature range. This study attempts to demonstrate the potential of the moderate temperature Stirling engine as an option for the prime movers for Concentrating Solar Power (CSP) technology. The heat source temperature is set to 350–500 °C to resemble the temperature available from the parabolic trough solar collector. This moderate temperature difference allows the use of low cost materials and simplified mechanical designs. With the consideration of local technological know how and manufacturing infrastructure, this development works with a low charged pressure of 7 bar and uses air as a working fluid. The Beta-type Stirling engine is designed and manufactured for the swept volume of 165 cc and the power output of 100 W. The performance of engine is evaluated at different values of charge pressures and wall temperatures at the heater section. At 500 °C and 7 bar, the engine produces the maximum power of 95.4 W at 360 rpm. The thermal efficiency is 9.35% at this maximum power condition. Results show that the moderate temperature operation offers a clear advantage in terms of the specific power over the low temperature operation. In terms of the West number, the present work demonstrated that the moderate temperature difference operations could offer the performance on par with the high temperature operations with more simple and less costly development.

1. Introduction

Presently, the situation of electricity production consists of central power plants and distributed generation systems. For either case, renewable energy resources is one of the solutions to reduce the dependency on petroleum import, to increase the energy efficiency and to avoid the confrontations or conflicts usually arisen from the building of new large power plants based on fossil fuel. Undeniably, for a tropical country such as Thailand, solar energy is the renewable energy resources with the largest potential [1]. There is, however, a huge gap between the technical potential and the practical utilization of solar energy. According to the Ministry of energy of Thailand, the target for solar energy use in 2011 is a mere 45 MW from the present accumulated installation of 30 MW. One of the reasons behind the stagnant growth of solar energy utilization is the limitation of technological options. Presently, the technologies to harvest solar energy are rather limited to photovoltaic systems. The recent commercial successes in Europe and Mediterranean, however, have brought attentions to another option namely the solar thermal technologies or Concentrating Solar Power (CSP) [2–4]. On a smaller scale, the choices of the prime movers currently under development for CSP installations that generate from 1 to 100 kW of electricity include the Rankine cycle [5], the organic Rankine cycle [6–10] and the Stirling engine [11,12].

The present study focuses on the Stirling engine development. There are two major directions of the Stirling engine development; the high temperature and the low temperature designs. The high temperature design represents the benchmark for the solar-to-electricity conversion efficiency at 29.4%. Nevertheless, it comes at the cost that can be as high as 10,000 $/kW compared to 3000$/kW for the photovoltaic systems [2,12]. In contrary, the low temperature designs are currently developed to harness the low-grade heat at low cost [13–17]. However, the low temperature difference makes the efficiency and the specific power very small compared to the high temperature design. These limitations make it difficult for the low temperature design to work with the solar collectors while resulting in a reasonably modular and less costly installation. This work proposes that the moderate temperature is where the balance is. The higher efficiency and the specific power compared to the low temperature design allow a reduction in the cost of the solar field. The moderate temperature avoids the expensive alloys and complex design required in the high temperature design hence brings down the cost. This is in line with Tlili [22] who indicated that, to be competitive in small scale generations, Stirling engine working with average concentration ratio is the optimum choice. With 1-axis tracking parabolic trough, the operating temperature is

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typically 300–390 °C [23] where the maximum temperature up to 550 °C is in commercial development [24].

There are few research works in the moderate temperature range. Kongtragool and Wongwises [17] demonstrated the performance of gamma-type Stirling engines with single-acting, twin power piston and four power pistons. The maximum power output reached 32.7 W for the four power piston version at 500 °C heater temperature under atmospheric pressure. Ishiki [18] studied on the atmospheric Beta-type Stirling engine using a pin-fin array heat exchanger. The engine yielded 91 W shaft output at 362 °C heater temperature. Karabulut [20,21] mentioned the limitations on the weight and volume the Rhombic drive placed on the solar dish application based on Stirling engines. They proceed to investigate the performance of the Beta-type Stirling engine based on a novel lever-controlled mechanism. The maximum power output is 183 W using helium at a moderate 4 bar charge pressure with no separate regenerator used.

The present work describes the design and construction of a Stirling engine developed for the moderate temperature range (350–500 °C). The engine prototype is experimentally evaluated such that the potential of the moderate temperature Stirling engine can be demonstrated. The performance of the engine is compared with results from related studies.

2. Design

The aim of this work directs toward the moderate temperature difference design. The hot end temperature is thus designed between 350 and 500 °C. The maximum power is set to 100 W for a compact prototype engine. This work opts for a relatively low charged pressure of 7 bar which also help limiting the size and weight of this prototype. In addition to the containment issues, the safety issue regarding the use of hydrogen is also concerned. As a result, air is selected as the working fluid. For a Stirling engine, there are three basic configurations namely alpha, beta and gamma configurations to choose from. The first consideration is the compactness of the engine package. This aspect rules out the alpha configuration. The gamma configuration yield a slight advantage over the beta configuration in terms of ease of construction due to two separate volumes in which the displacer and the power piston move. The dead volume associated with the connection between the two volumes in gamma configuration, however, compromises the effective expansion temperature and hence the efficiency of the engine [25]. The present work employs the beta configuration.

A first estimation of performance of a Stirling engine is typically obtained from the empirical West equation:

$$W_N = \frac{L_S}{P_m V_{SE} n \left(\frac{T_E - T_C}{T_E + T_C}\right)} \quad (1)$$

The West number, W_N , is 0.35 for engines rated below 5 kW and is 0.25 for engines rated between 5 and 150 kW [26,27]. The performance of developmental engines, however, rarely reached the level prescribed by the West number. However, it can be noticed that, for the design purposes, there is no formal guideline to indicate the running speed required for the use of the West formula.

Iwamoto [28] proposed a method to estimate the output power and the running speed at the same time based on a set of nondimensional parameters. From experimental data of many engines, Iwamoto arrived at two empirical relationships:

$$L^*_{S,\max} = 0.24 n^*_{opt} \quad (2)$$

$$n^*_{opt} = 6.8 \times 10^{-5} S^{*0.6} \quad (3)$$

Table 1
Engine specifications.

Engine type	Beta
Working gas	Air
Maximum charged pressure	7 bar
Displacer: swept volume	165 cc
Displacer: bore × stroke	74 mm × 37 mm
Power piston: swept volume	165 cc
Power piston: bore × stroke	74 mm × 37 mm
Heater section dead volume	20 cc
Heater: design/surface area	Slot/877.8 cm^2
Cooler section dead volume	16.5 cc
Cooler: design/surface area	Slot/708.4 cm^2
Regenerator matrix	#80 Stainless steel mesh
Regenerator porosity	75%
Regenerator section dead volume	47 cc
Compression ratio	1.61
Heating method	Electrical heaters
Cooling method	Water jacket

where n^*_{opt} is the optimum dimensionless engine speed at the condition of the maximum dimensionless output power $L^*_{S,\max}$. As a result, a designer can estimate more accurately the swept volume and the running speed at the same time from a given set of design specifications. Following the method of Iwamoto, the present work arrived at the swept volume for the expansion space at 165 cc and the engine speed of 627 rpm using the design specifications described earlier. The low speed operation translates to the low flow friction loss for the present air charged engine.

From the preliminary sizing of the engine provided by the method of Iwamoto, detailed sizing was performed via the thermodynamic and heat transfer analysis. This work employed the "simple" calculation routine from Urieli [29]. The code involved solving derivative equations describing the flow and energy coming in and out of the different volumes of the Stirling engine. The set of equations allows the simple pressure loss, heat transfer, and indicated power to be determined. As a result, the sizing of the heater, cooler and regenerator volumes can be specified. The final specifications of the engine are provided in Table 1.

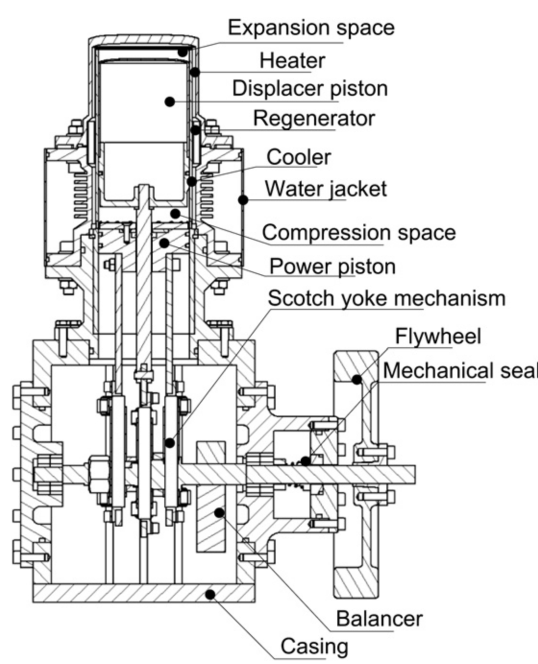

Fig. 1. Details of the Stirling engine.