Design and Manufacture of a Rhombic-Drive Stirling Engine

Sutapat Kwankaomeng [*1], Bancha Kongtrakool[2] and Banterng Silpsakoolsook [3]

[1] Department of Mechanical Engineering, Faculty of Engineering, Kingmongkut's Institute of Technology Ladkrabang,
Ladkrabang, Bangkok, Thailand 10520
[2] Department of Mechanical Engineering, Faculty of Engineering, Srinakharinwirot University,
Ongkarak, Nakhonnayok, Thailand 26120
[3] Department of Chemistry, Faculty of Science, Siam University, Phasichareon, Bangkok, Thailand, 10160
* Corresponding Author: E-mail: kksudara@kmitl.ac.th, Tel: 02 329 8350-1, Fax: 02 329 8352

Abstract

This paper presents design, manufacture and test of a rhombic-drive Stirling engine. The engine is a Beta-type configuration. The two dynamic pistons called displacer and power piston reciprocate in the in-line concentric cylinder arrangement. Rhombic drive mechanism is designed for engine balance of a single acting engine. The displacer rod is assembled concentrically inside the power piston rod. The sliding of both piston rods is controlled by a matched pair of gearwheels. The prototype has swept volume of 110 cm^3. In the proof-of-concept device, the hot end of the displacer cylinder was heated by a LPG burner and the power piston cylinder was cooled by water. Air is used as the working gas at atmospheric pressure for initial charging of the engine. The experiments were set up and conducted to investigate the engine performance at variation of the heater temperature of the heat source. The testing results showed that the unpressurized engine started operation in only about 100 seconds at the heater temperature of 460 °C with 312 rpm. At the heater temperature of 540 °C, the engine speed was 680 rpm. At the engine speed of 280 rpm, the maximum torque was 0.245 Nm while the maximum power was 7.85 watts at 360 rpm. Engine speed increases with the flame temperature inclement. The prototype with initial atmospheric air filling gave the promising power.

Keywords: Stirling engine, Beta type, Rhombic drive, unpressurized, flame temperature

1. Introduction

Searching renewable or sustainable energy and alternative engines is necessary to obtain efficient engine and compete conventional engine. Stirling engine, first patented by Robert Stirling in 1816, is one of mechanical device that converts heat from multi-fuel choices to be useful work. Stirling cycle engine, a hot gas engine or an external combustion engine, offers potential advantages over conventional engines in fuel flexibility, noise, and emissions. Multi-fuel choices, such as agricultural by-product, biomass, biodiesel, solar energy and etc., can be employed as the heat source for Stirling engine. Since Stirling engines are external heat source engines, consistent burning of fuel can be controlled and possibly achieve complete combustion resulting in low pollution produce compared to that of the internal combustion engine. Many applications were investigated and integrated with the Stirling engine such as water pump [1,2], generator [3,4], linear alternator [5], hydraulic and pneumatic output [6-8] and etc.

In 1953, the rhombic drive mechanism was invented by Meijer [9] in Philips Company, Holland in 1959. Extensive research works, designs, and improvements in numerical simulations and experimental investigations were performed on rhombic drive mechanism of Stirling engine.

Shendage, D.J. et al. [10] presented an analysis of beta type Stirling engine with rhombic drive mechanism. The present work is mainly about the design methodology for beta type Stirling engine and the optimization of phase angle, considering the effect of overlapping volume between compression and expansion spaces.

The beta-type Stirling engine operating at atmospheric pressure was performed by Cinar, C. et al [11]. They manufactured and tested of a beta-type Stirling engine with a 192 cc total swept-volume. Experiments were conducted at atmospheric pressure and with an electrical heater at 800, 900 and 1000 °C temperatures. Torque and output-power variations were obtained for different engine speeds. The test engine reached a maximum of 5.98 W at 208 rpm, at the hot-source temperature of 1000 °C.

The improvements of the engine performance were extensively investigated such as regenerator and regenerative gap, center distance of two gears, offset of the crank and the center of the gear. Eid E. [12] numerically analyzed the of a beta-typed engine performance having a regenerative displacer based on Schmidt theory. The regenerative displacer with successive homogeneous stainless steel wire meshes filled the space of the displacer of engine. The porous displacer performs as a displacer and as a regenerator simultaneously. His proposed engine with a regenerative displacer delivers 20% more power with 10% more efficiency than the GPU-3 engine.

Cheng, C. H. et al. [13] presented the numerical model for predicting thermodynamic cycle and thermal efficiency of a beta-type Stirling engine with rhombic-drive mechanism. Results show that by adjusting the influential parameters including regenerative gap, distance between two gears, offset distance from the crank to the center of gear, and the heat source temperature, the performance of the base-line case can be improved. The power output of the base-line case reaches a peak value of 16.75 W at regenerative channel gap, G = 0.0005m, accompanied by a thermal efficiency of only 13.1%. If the thermal efficiency is of major concern, the thermal efficiency can be elevated to a peak value of 16.5% at G = 0.0003m. It is also observed that the power output of the base-line case can be increased as heat source temperature is elevated. The center distance of the gears opposes on the performance of engine while the increase of the offset distance from the crank to the center of gear enhances the power output and the thermal efficiency.

Some aspects of the other driving mechanisms of beta typed-Stirling engines were compared to the rhombic-drive engines.

Karabulut H., et al. [14, 15] showed both simulation and experiment of a novel configuration of a beta-type Stirling engine. A lever drive is used instead of a rhombic drive and compared. The prototype was built and tested with no pressurized ambient air. It was found that the shaft power of 14.72 W when applying 260 °C temperature to the hot end and 20 °C temperature to the cold end of displacer cylinder. Comparison of novel engine with crank driven and rhombic drive engines indicates that the compression ratio of novel engine is lowest among the three engines. Comparison of novel engine with crank driven and rhombic-drive engines with respect to equal amount of working fluid mass indicates that the Rhombic-drive engine has advantage. If comparison is made with respect to the same amount of charge pressure, novel engine becomes advantageous.

This study aims to design, build and test of the rhombic-drive Stirling engine with beta configuration using air as working gas at atmospheric pressure in order to employ with biomass fuels in Thailand.

2. Engine Design

The engine design focus is on operating at atmospheric pressure using air as the working gas. Stirling engine consists of two moving pistons which are a light weight piston called displacer and a working piston. The rhombic-drive arrangement of components and linkages used to provide reciprocating motion without side force of both pistons. Rhombic drive mechanism, therefore, is designed for engine balance of a single acting engine as depicted in Fig. 1.

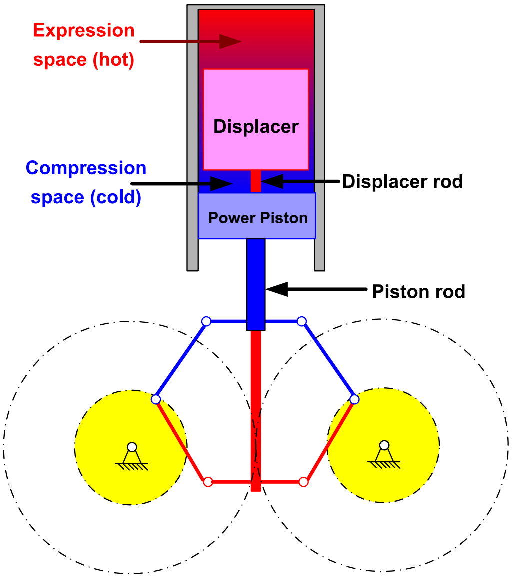

Fig. 1 Rhombic drived- Stirling engine

Beta type engine is extensively used for the rhombic-drive Stirling engine [16]. The Beta configuration, hence, is selected for engine type that the displacer and power piston reciprocating in the concentric in-line cylinder arrangement. In the rhombic drive, the whole assembly is symmetric with respect to centerline of the piston as well as the displacer. The displacer rod, therefore, is assembled concentrically inside the power piston rod. The sliding of the displacer and piston rods is controlled by the meshing and rotating gearwheels as illustrated in Fig.1. The working gas is circulated between hot and cold spaces or gas expansion and compression zones, respectively. As the working gas expands at the hot space, the displacer moves and compresses the working gas at the cold space pushing the working piston to give power stroke from the engine. The working piston, hence, can be extracted to be useful work or power. After the working piston gives the power stroke, the displacer and the working piston are returned to repeat cycle motion by the rotating gear and flywheel. The proposed engine consists of single cylinder with hot head at its top, displacer, power piston, a pair of spur gears as illustrated in Fig. 2. This preliminary design has no regenerator in the proposed engine however the piston cylinder is enhanced heat transfer by annular fins.

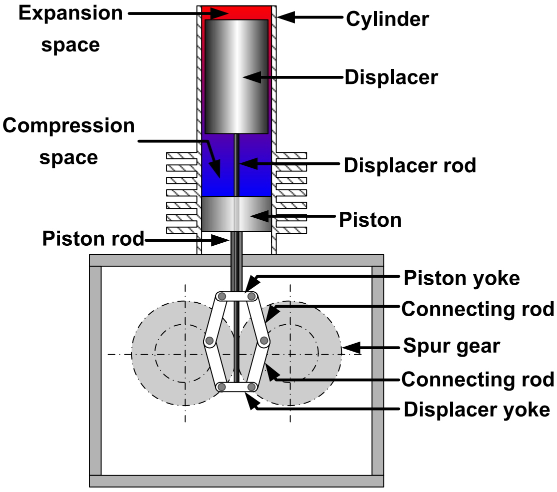

Fig. 2 Schematic of the proposed beta rhombic-drive Stirling engine

3. Prototype

The prototype is presented in Fig. 3. The displacer and the piston arrangements are illustrated in Fig.4. Rhombic mechanism, as in Fig. 5, is used to drive the displacer and the power piston that, in turn, controls engine speed and motion.

The phase angle of motion between the displacer and the power piston is controlled by the meshing of two spur gears. The displacer rod is connected to the displacer yoke and connecting rod. The power piston rod, sliding outside the displacer rod, is attached to the piston yoke and connecting arm. The two spur gears mesh together and rotate in opposite direction. The specifications of the FPSE are given in Table 1.

Fig. 3 The rhombic- drive Stirling engine prototype

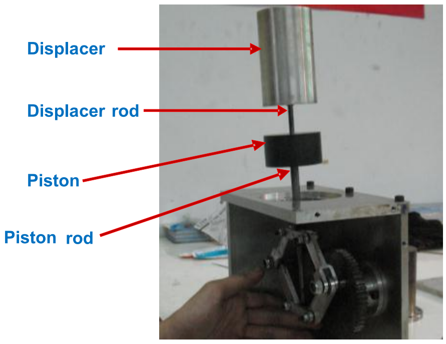

Fig. 4 The displacer and the piston assembly

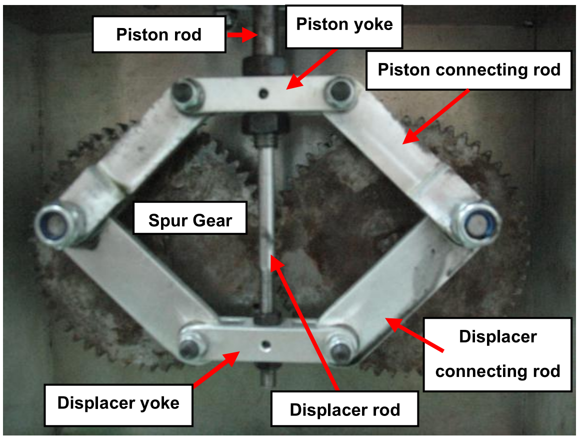

Fig. 5 Rhombic drive mechanism of prototype

Table 1 Design specifications of Rhombic Drive Stirling Engine prototype

Engine type	Beta
Swept volume	110 cc
Working piston cylinder diameter	55.8 *mm*
Displacer cylinder diameter	55.0 *mm*
Working Piston diameter/stroke	55.8 / 46 *mm*
Displacer diameter/stroke	53.1 / 46 *mm*
Displacer rod/Piston rod diameter	6.4 *mm*
Gear diameter	87 *mm*
Phase angle	60°
Hot / Cold space temperature	500 °C / 40 °C
Working fluid/Cooling fluid	Air/Water
Fuel	LPG
Torque at 280 rpm	0.25 N.m
Power at 360 rpm	7.85 *W*

4. Experimental Set Up and Results

4.1 Experimental set up

The schematic of prototype with experimental set up is presented in Fig. 6.

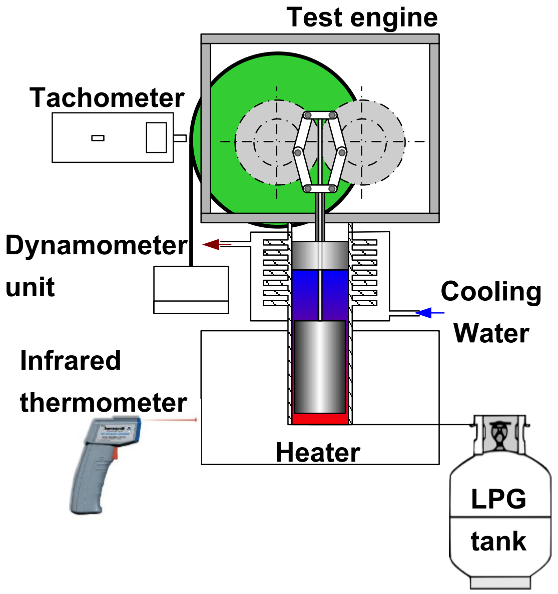

Fig. 6 Schematic view of the prototype and experimental set up

In the proof of concept device, LPG was used as fuel to heat the engine. The hot end of the engine cylinder was inserted into the heater. A rope type dynamometer was used to measure the torque. The speed of the engine was detected by a digital tachometer. Ambient air was used as the working gas. The power piston cylinder was cooled by the cooling water. Temperatures were measured by a non-contact infrared thermometer.

4.2 Experimental Results

The test engine was operated with air as the working gas at ambient pressure and heated with a LPG burner. The engine characteristics are shown in Figs. 7-10.

4.2.1 Engine speed

The experiments were set up and conducted to investigate the engine performance at variation of the flame temperature of the heat source. The testing results showed that the unpressurized engine started operation in only about 100 seconds as shown in Fig. 7.

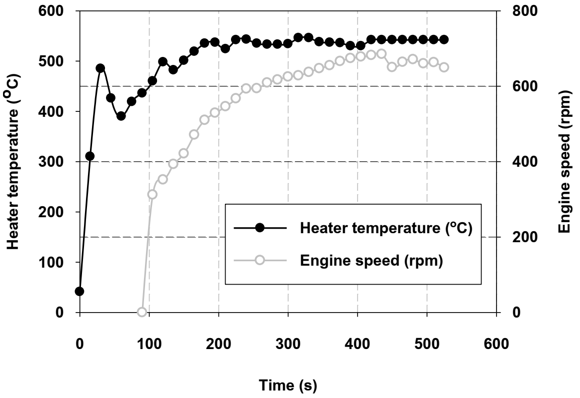

Fig. 7 Timewise variation of engine speed and heater temperature

Fig. 7 shows that after 100 seconds of applying heat to the hot head of the prototype, the engine started running with engine speed of 312 rpm and the heater temperature of 460°C. After the heater temperature reached to the steady temperature, the engine, then, run with almost steady speed. The steady temperature of heater was about 540 °C and the engine speed was remaining about 680 rpm. Engine speed increases with the flame temperature inclement.

4.2.2 Engine torque

Fig. 5 is a plot of engine torque with the variation of engine speed at 460°C heater temperature. The engine torque is decreased by the increasing of engine speed. At the engine speed of 280 rpm, the maximum torque was 0.245 N.m.

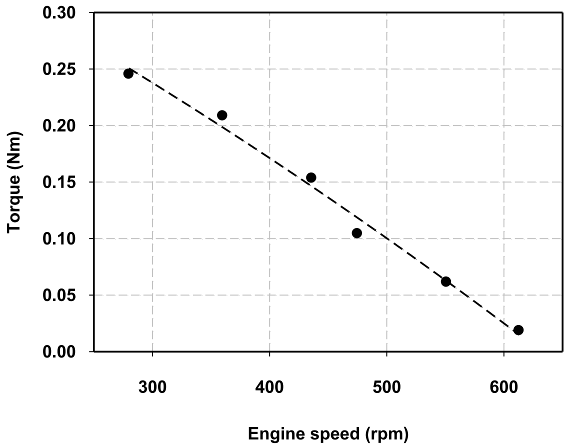

Fig. 8 Variation of engine torque with speed at 460°C heater temperature

4.2.3 Engine power

Fig. 6 shows the engine power varied with speed. The maximum engine-power was 7.85 W at 360 rpm.

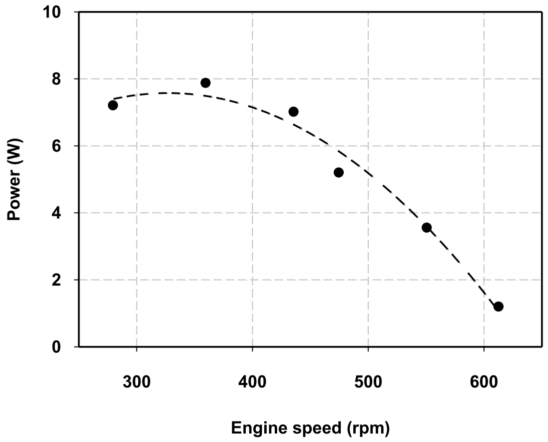

Fig. 9 Variation of brake power with speed at 460°C heater temperature

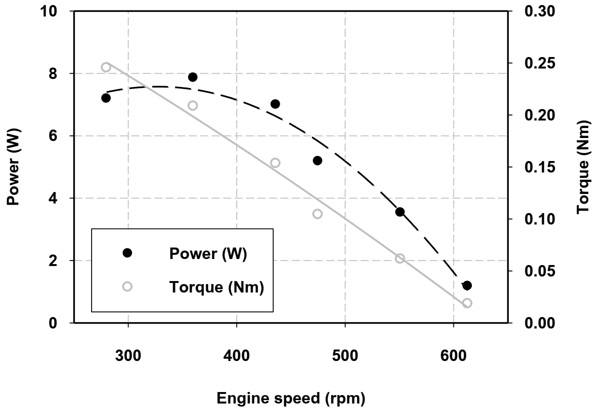

Fig. 10 Variation of brake power and torque with speed at 460°C heater temperature

As in Fig.7, the engine power is a function of speed and torque. The decrease of engine power was at the speed lower than 360 rpm. As the decline of engine torque after engine speed of 280 rpm, the power was also decrease. For unpressurized Stirling engine with air and rhombic drive operating at atmospheric pressure, the proposed prototype with 110 cc swept volume provided a maximum power output of 7.85 W at 360 rpm, at the hot-source temperature of 460°C while one of Cinar, C. et al. [11] with a 192 cc total swept volume reached a maximum power of 5.98 W at 208 rpm, at the hot-source temperature of 1000°C.

5. Summary and Discussion

A rhombic-drive Stirling engine prototype was designed, built and tested. The prototype has swept volume of 110 cc. In the proof-of-concept device, the hot end of the displacer cylinder was heated by a LPG burner and the power piston cylinder was cooled by water. Air is used as the working gas at atmospheric pressure for initial charging of the engine. The experiments were set up and conducted to investigate the engine performance. The testing results showed that the unpressurized engine started operation in only about 100 seconds at the flame temperature of 460 °C with 312 rpm. At the flame temperature of 540 °C, the engine speed was 680 rpm Engine speed increases with the flame temperature inclement. In a comparison of between the proposed engine with rhombic drive and a 110 cc swept volume and the tested engine of [11] with crankshaft which has a 192 cc total swept volume power; it was found that; the proposed one delivered more power than [11]'s prototype. The rhombic-drive prototype with initial atmospheric air filling gave the promising power although working without regenerator. The engine performance can be increased by using a regenerator, a working fluid with a higher thermal conductivity, such as helium or hydrogen and a high pressurized in hermetic engine.

6. References

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