Investigation on a Free-Piston Stirling Engine and Pneumatic Output

Kwankaomeng S[1,]* and Promvonge P[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, 10520, Thailand

*Corresponding Author: kksudara@kmitl.ac.th, Tel: (662) 3298350-1, Fax: (662) 3298352

Abstract

This paper presents numerical and experimental study of a free-piston Stirling engine (FPSE) with pneumatic output. A free-piston Stirling engine (FPSE) was designed and manufactured which works at relatively low differential temperature. The FPSE is a beta type configuration. The FPSE couples with a pneumatic cylinder. Theoretical analysis was done over a wide range of conditions to determine engine performance and characteristic with air as the working gas. In the proof-of-concept device, the displacer or the light piston was driven by pneumatic cylinder as gas spring that in turn, controls engine speed. The hot end of the displacer cylinder was heated with electric heater at 250°C maximum temperature. The other end of the displacer cylinder was cooled with a water circulation having 40°C temperature. The power piston was connected to the piston of pneumatic cylinder for lifting load. The engine was operated at the initial pressure at approximately 6 bars. The testing results showed that the work and power was obtained at 1.5 bars of pressure difference and 120 rpm engine speed of 12.5 N.m and 4 W, respectively, while the work and power, from the simulation results were 15 N.m and 5 W, respectively, at the same operating condition and engine specification. Output power from numerical simulation was slightly higher than that of experiment according to theoretical assumptions.

***Keywords**:* free-piston, Stirling engine, pneumatic, Beta type

1. Introduction

Global warming and environmental pollutions are continuing affect and become a serious problem. Emission and heat release from energy consumption is one of the major sources that produced by energy conversion system from households, transportations, and industries. 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 convert heat from multi-fuels to be useful work. Many applications were investigated and integrated with the Stirling engine such as water pump, generator, linear alternator, hydraulic pump and etc. Beale W.T. [1] purposed the design concepts of a 250 watt free cylinder

Stirling engine for use as a solar water pump. However, the engines were inefficient for pumping. Loss in power occurred because the reduced pump frequency. West C.D.[2] designed and focused on liquid piston using fluidyne technology on Stirling engine to pump water in form of pulsating pressure. NASA Glenn Research Center presented dynamic model of a linear alternator coupled with Stirling engine producing electricity [3], [4], and [5]. Moreover, NASA Glenn Research Center also performed research on Stirling engine with hydraulic output know as a 1kW (1.33 hp) free-piston Stirling engine or RE-1000. The design of a suitable hydraulic output mechanism of this engine was performed by a design team from Foster-Milller, Inc. and Sunpower, Inc [6], [7], [8] and [9]. Stirling Energy Systems (SES), Inc., has been successful on a niche market of the solar power Stirling engine coupling electric generator [10].

Xi, C. et al. [11] showed pneumatic connection of free piston and free displacer impact on overall performance of Stirling cryocooler. The motion parameters such as displacement, amplitude and phase shift of piston and displacer were investigated both theoretical and experimental works. Thombare D.G. and Verma S.K. [12] presented technological development in the Stirling cycle engines. They revealed that proper selection of drive mechanism and engine configuration is one of essential factor for a successful operation of engine system with good efficiency.

However, few research works have been conducted on pneumatic output of Stirling engine as a heat engine. In this study presents characteristic of the FPSE with pneumatic driving system and pneumatic output. The motion of the displacer and the power piston coupling with the pneumatic piston such as displacement, phase motion, velocity and pressure have been investigated respectively by means of simulation and experiment.

2. Methodology

The FPSE consists of two moving pistons which are a light weight piston called displacer and a working piston as illustrated in Fig.1. The Displacer and the working piston movements are controlled by flow of the working gas 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 FPSE. 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 restart the new cycle motion by gas spring and bounce chamber, respectively.

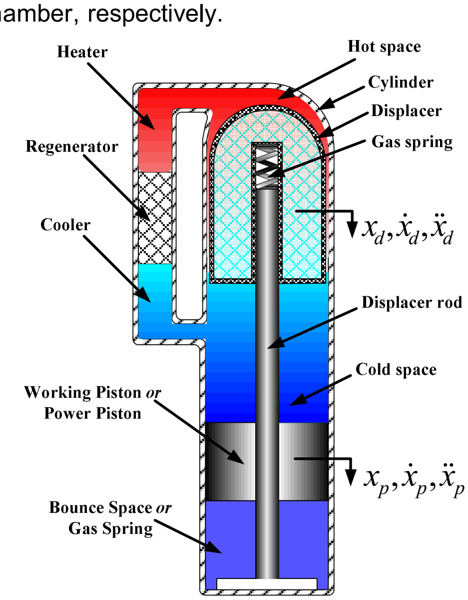

Fig. 1 Free-piston Stirling engine

2.1 Design of the FPSE Model

The simulation model of the FPSE coupling with pneumatic pump as a single-acting illustrated in Fig. 2.

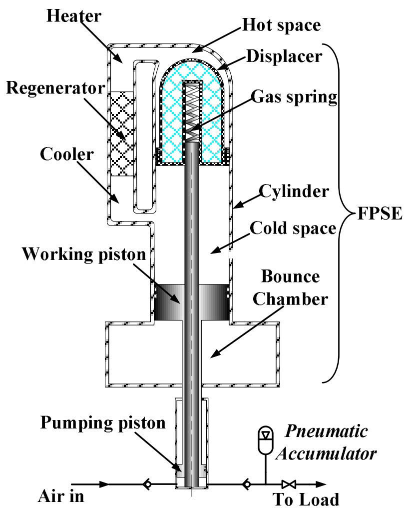

Fig. 2 FPSE with single-acting pneumatic pump

In theory assumption, the working piston connects rigidly with the pump piston called piston assembly. The bounce chamber treated as constant pressure tank. The displacer is controlled by gas spring. When the working gas pressure (P_w) is higher than the bounce chamber pressure (P_b), the working piston moves and produces work from this power stroke. The pump piston also pressurizes air in the pneumatic cylinder generating pressure high enough to open the check valve, letting the pressurized air flow from the pump cylinder to the load or pneumatic accumulator.

2.2. Design of a FPSE Prototype

The Schematic of the prototype with pneumatic connection is presented in Fig. 3. The initial design focus is on a low temperature difference of engine configuration [13]. An electric heater was selected to heat the engine. The design utilized a pneumatic cylinder to drive the displacer that, in turn, controls engine speed and motion. The prototype consists of two major dynamic components, the displacer assembly and the piston assembly. The displacer assembly consists of the displacer and the pneumatic piston attached to the displacer. The piston assembly includes the working piston and the pump piston. The working piston and the pneumatic piston was connected in-line attachment with spherical rod end and yoke in order to decrease alignment problem and eccentric allowance.

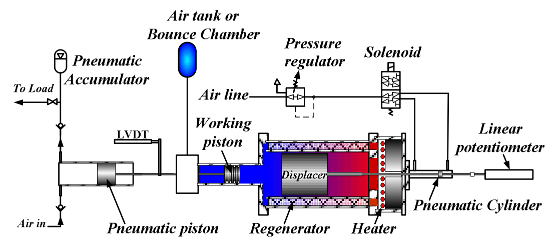

Fig. 3 The schematic of a free-piston Stirling engine with pneumatic output

2.3. FPSE Specification

The specifications of the FPSE are given in Table 1.

Table 1 Design specifications of free-piston Stirling Engine prototype

Working piston cylinder diameter	38.1 *mm*
Displacer cylinder diameter	82.6 *mm*
Working Piston diameter/stroke	38.1 / 40 *mm*
Displacer diameter/stroke	82/100 *mm*
Displacer rod/Piston rod diameter	6.4 *mm*
Pneumatic piston diameter	38.1*mm*
Hot / Cold space temperature	$250^{\circ}C$ / $40^{\circ}C$
Working fluid/Cooling fluid	Air/Water
Power to heater	585 *W*

3. FPSEP Analysis and Numerical Results

3.1 Dynamic analysis of the FPSE

The parameters and reference positions of FPSE prototype are illustrated Fig. 4.

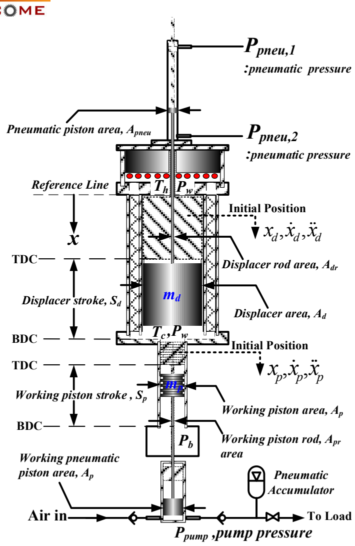

Fig. 4 Reference positions and variables of *a* free-piston Stirling engine with pneumatic output

The free body diagrams showing the pressures acting on the displacer and piston assemblies are shown in Figs. 5-6, respectively.

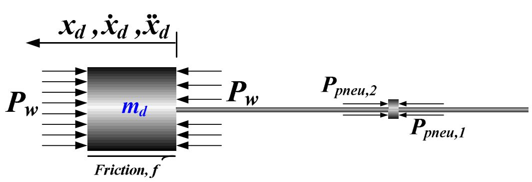

Fig. 5 Free body diagram of displacer assembly with pressure acting

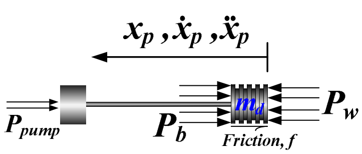

Fig. 6 Free body diagram of the piston assembly with pressure acting

The displacer and the working piston acceleration can be derived from the equation of motion as shown respectively in Eqs. (1)-(2). Where f is friction and subscript *d, p, i, c,* and *h* represents displacer, working piston, initial condition, cold and hot respectively.

$$\ddot{x}_d = \left(1/m_d\right)\begin{bmatrix}(P_{pneu,1} - P_{pneu,2})(A_{pneu} - A_{dr}) \\ -P_w A_{dr} - f\end{bmatrix} \quad (1)$$

$$\ddot{x}_p = \left(1/m_p\right)\begin{bmatrix}(P_w - P_b)A_p + P_b A_{pr} \\ -P_{pump} A_{pump} - f\end{bmatrix} \quad (2)$$

Equations (1) and (2) are functions of the working gas pressure (P_w). The working gas pressure equation as a function of the temperature (T) and volume (V) ratio derived from the ideal gas law with assumed equality of pressure in the hot and cold spaces and a fixed mass of the working gas mass [14] is:

$$\frac{P_w}{P_{w,i}} = \frac{\left(\frac{V_{c,i}}{V_{h,i}}\frac{T_{h,i}}{T_{c,i}} + 1\right)}{\left(\frac{V_c}{V_{c,i}}\frac{V_{c,i}}{V_{h,i}}\frac{T_{h,i}}{T_c} + \frac{V_h}{V_{h,i}}\frac{T_{h,i}}{T_h}\right)} \quad (3)$$

Hence, the dynamic action of the displacer and working piston is obtained by solving the Eqs. (1) - (3) simultaneously. The power of the FPSE can then be readily determined from the relationship between flow rate (Q) and pumping pressure (P_{pump} or P_p):

$$Power = QP_{pump} \quad (4)$$

3.2 Simulation results

The simulation was done with air as the working gas at 6 bar working gas pressure and with an engine displacement of 45 cm^3 (1.75 in^3) running at 120 rpm can produce 5 W. The performance of this operation condition and the results are shown in Figs. 5 - 8.

3.2.1 Displacement and velocity

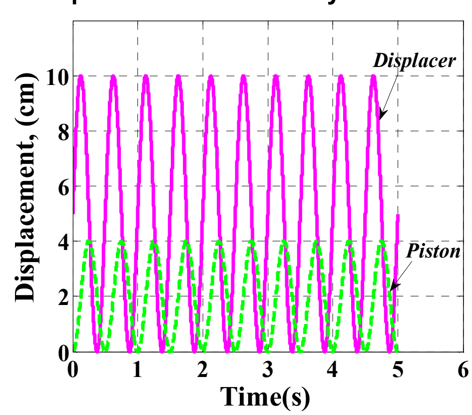

Fig. 7 Piston and displacer displacement

The working piston and displacer displacement, phase motion (relationship between piston and displacer displacement) and velocity are shown in Figs. 7-9, respectively. The motion of the displacer leads the working piston with phase angle of 90 degree.

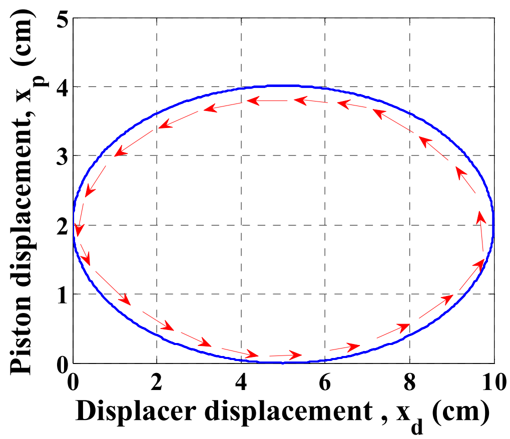

Fig. 8 Relative motion of piston and displacer displacement

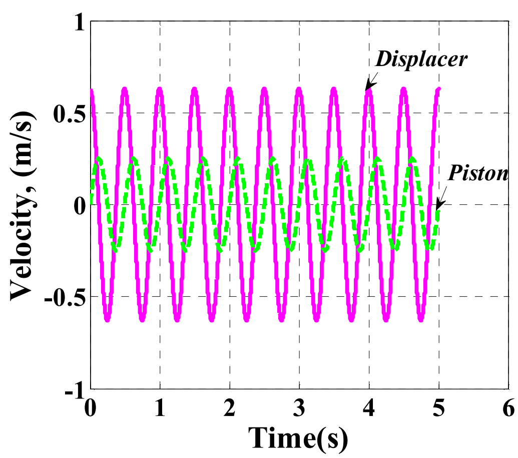

Fig. 9 Piston and displacer velocity

3.2.2 Pressure and work

In Fig. 10, the working gas pressure starts at 0.6 MPa (87 psi) then increases to 1.20 MPa (174 psi) because the gas temperature rises due to heat addition. The pressure then drops because of gas expansion at the power stroke of the engine and heat loss. The bounce chamber pressure is treated as an air spring forcing the working piston to push the working gas flow to the hot space which causes the working pressure to increase again. The pneumatic pressure can be set up depending on load or check valve. The check valve was preliminary set up at 0.69 MPa (100 psi) in the simulation. When the engine provides power as represented by the increasing of the working gas pressure, the air in pneumatic cylinder was also pressurized simultaneously with the power stroke of the Stirling cycle engine.

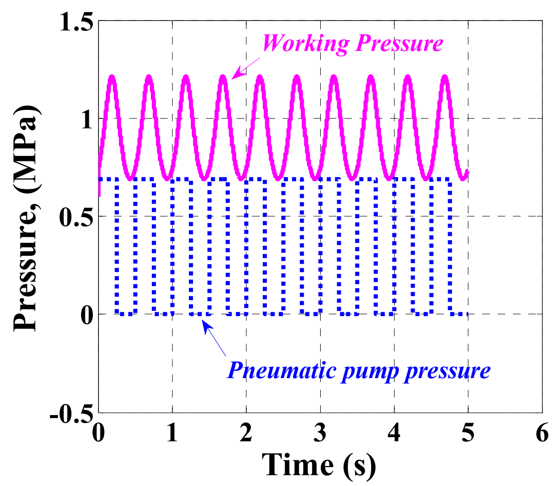

Fig. 10 Pressure in the engine

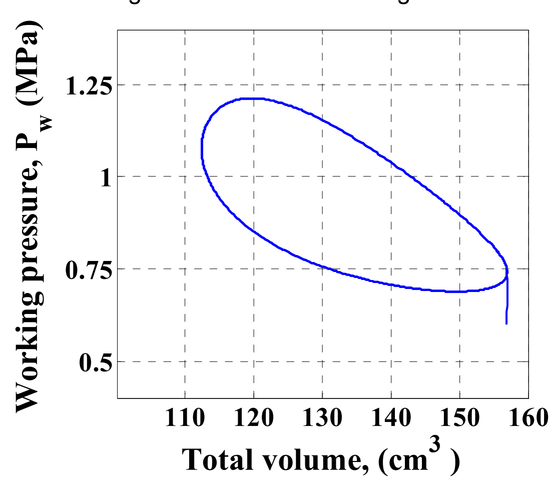

Fig. 11 Pressure-volume diagram

Fig. 11 shows pressure and volume diagram. The engine model produces work and power of 15 N.m and 5 W., respectively.

4. Experimental set up and Results

4.1 Experimental Set Up

The schematic and FPSE prototype with experimental set up is presented in Fig. 3 and 12, respectively. In the proof of concept device, a pneumatic cylinder used to actuate the displacer. The displacer controlling system includes a function generator, solenoid valve, relay, pressure regulator, battery and pneumatic cylinder. The solenoid valve operates at 12 volts DC provided by a battery. This valve controls the pneumatic cylinder that actuates the displacer. Air pressure to the valve is set by a pressure regulator. A linear potentiometer and a linear variable differential transformer (LVDT) are used to measure the displacer and working piston displacements, respectively. A yoke and spherical rod end connect the pneumatic cylinder rod to the linear potentiometer rod. The LVDT, linear potentiometer and pressure transducers are connected to a data acquisition computer to convert analog signals to digital which are displayed on a computer monitor or written to a file.

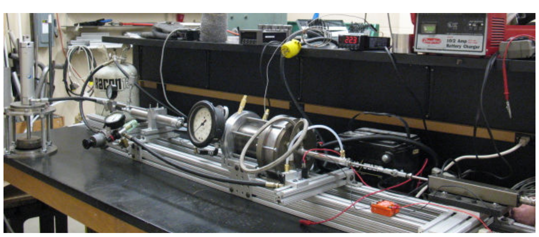

Fig. 12 The FPSE with pneumatic connection and experimental set up

4.2 Experimental Results

The experiment was done with air as the working gas at a pressure of 0.62 MPa (90 psi). The testing results showed that the work and power was obtained at 1.5 bars of pressure difference and 120 rpm engine speed as 17 N.m and 4 W, respectively. The engine characteristics are shown in Figs. 13-15.

4.2.1 Displacement

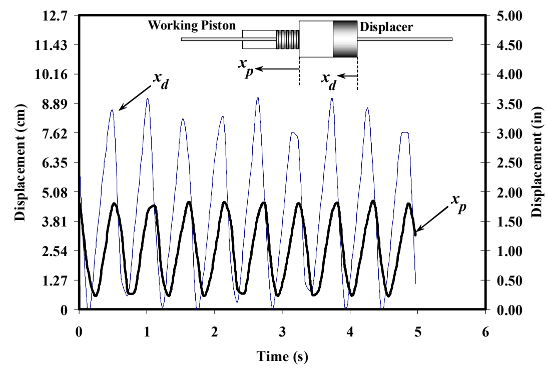

Fig. 13 Displacement of the displacer and working piston

Fig. 13 shows the measured displacements of the displacer and working piston during 5 seconds of operation. The motion of the displacer was slightly ahead of the motion of the working piston as controlled by the function generator. The working piston follows the displacer and responds to the change in pressure of the working gas.

4.2.2 Working gas pressure and pneumatic pump pressure

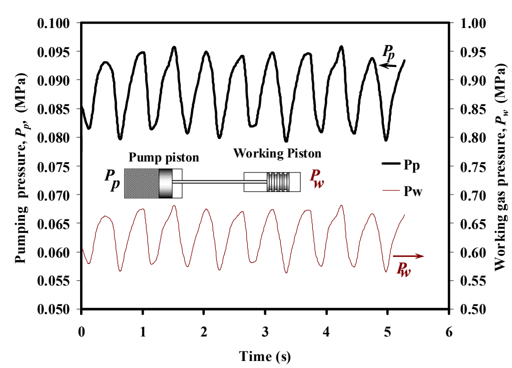

Fig. 14 Pneumatic pump pressure and working gas pressure vs. time.

Fig. 14 is a plot of pneumatic pump pressure and working gas pressure. The working gas pressure was higher than the pump pressure of the pneumatic cylinder. The pneumatic cylinder, however, can be varied in size in order to obtain suitable pressure load.

4.2.3 Pump Power

Fig. 15 shows the instantaneous power along with average power (4W) varied with time.

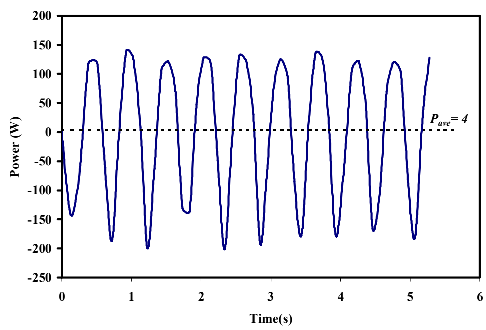

Fig. 15 Power vs. time

5. Summary and Discussion

A free-piston Stirling engine prototype has been simulated, built and tested. The engine was operated at the initial pressure at approximately 6 bars. The power piston was connected to the piston of pneumatic cylinder for lifting load. The testing results showed that the work and power were obtained at 1.5 bars of pressure difference and 120 rpm engine speed of 12.5 N.m and 4 W, respectively, while the work and power, from the simulation results were 15 N.m and 5 W, respectively. Output power from numerical simulation was higher than that of experiment according to theoretical assumptions.

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