PRELIMINARY TESTING RESULTS OF A DIAPHRAGM FPSE

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ABSTRACT

The paper presents design and preliminary testing results of a Free Piston Stirling Engine (FPSE) prototype operating at low temperature heat sources. The main focus of this work is to demonstrate the construction of the displacer using flexure bellows as a mechanical supporting spring and as a working fluid seal. The power piston, on the other hand, is made of a planar elastomer material in the shape of a disk with a suitable mechanical elasticity, rigidity, and thermal properties to support the range of operating temperatures. A small prototype of the FPSE was built and tested at operating temperature of under 200 ^{o}C. The measured operating frequency was 15 Hz, a reciprocating stroke of 8mm and operating pressure close to atmospheric pressure. The prototype was equipped with instruments to measure all the operating parameters. The power output was measured from the p-v diagram using a two-channel oscilloscope. The preliminary results demonstrated the operation concept and reliable start up, but further improvements will be needed to fine tune the reciprocating components and reduce mechanical friction.

KEYWORDS

Free piston Stirling engine, metal bellow, and diaphragm

1 INTRODUCTION

Energy is one of the key challenging issues that both industrialized and developing nations will have to face in the future to sustain the economic development and social wellbeing for their population. According to World Bank estimates, around 1.6 billion people worldwide do not have access to electricity; due to limited power grid infrastructure extension into rural areas where most of the population in developing countries lives. Rural electrification helps to improve living conditions and reduce health problems born from burning primitive fuels in inadequate appliances. In many instances, however, existing electricity grids in developing countries are either not extended to remote rural areas and/or cannot supply enough electrical power to guarantee stable operation of the grid due to high investment and maintenances costs [1]. This is most acutely demonstrated in sub-sahara africa and some parts of south asia where access to electricty is as low as 10% and 13% respectively [2]. Adoption of off-grid sustainable power generators is one of critical technologies with many applications including crops irrigation, medicine preservation through cooling, lighting, etc. to enhance people lives in isolate rural regions of the developing countries and limit migration into big cities.

The focus in this work is to develop a cheap free piston Stirling engine that can be power by solar energy and afforded by small farmers in developing countries for water irrigation applications to increase agricultural productivity to meet food needs of a growing population.

A Stirling Engine is an external combustion heat engine that can operate on virtually any source of heat to produce shaft power provided a sufficiently temperature difference exists between the he heat source and heat sink. Mechanically, the engine is simple with few moving components. The development of Stirling engines have been dampened by the success of internal combustion engines which have superior specific power output, reliability and lower in manufacturing cost.

2 MECHNAICAL DESIGN AND CONFIGUATION

A simplified mechanical layout of the Free Piston Stirling engine is shown in Figure 1. It consists particularly of an integrated displacer-bellows assembly housed in the cylinder and separates the heat sources and the heat sink. The displacer-bellows assembly is hollow and light structure that forms a suspended mass-spring oscillating components with no friction with the cylinder. The narrow passage between the displacer and cylinder allows air flow between the hot side and cold side while the bellows convolutions (extended surface area) form the regenerator.

The working space of the engine is sealed by a power piston in the form of a flexible material flat disk (diaphragm) of suitable hardness grade and which acts as the power piston. The flexible power piston forms a second resonating assembly with the shaft load. A small pressure gradient across the displacer exerts a force that sustains the displacer oscillation and hence the shuttling of the working fluid between the hot and cold end which in turn generates a pressure change in the engine and drives the diaphragm power piston.

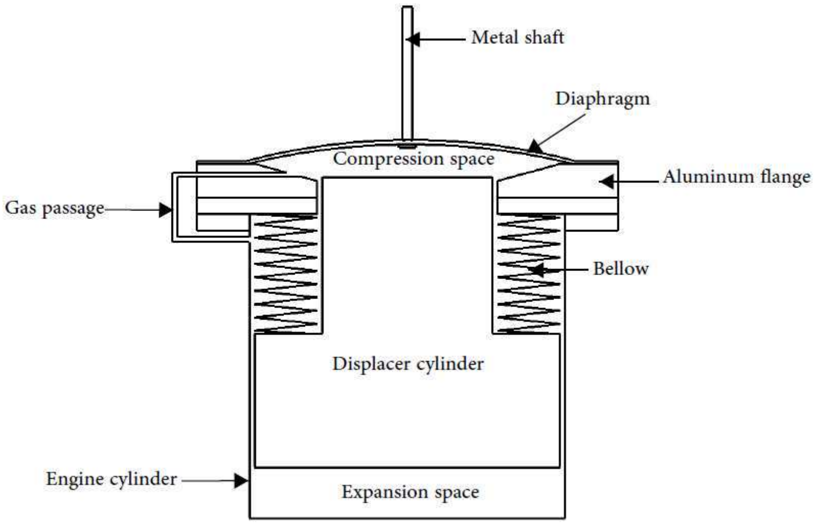

Figure 1: Mechanical arrangement of FPSE

One design issue that needs to be overcome is the life span of the oscillating components – bellows and diaphragm. There is considerable progress in materials technology that makes it possible to operate flexible structures for large number of cycles before failure.

In a Stirling engine heat is supplied externally and transferred to the working fluid in the enclosed space through the heater head wall. Using a solar concentrator to focus direct solar rays onto the heater head would supply heat at required operating temperature. Heat rejection is through a natural conviction radiator on the cold end.

2.1 Design of the oscillating components

The displacer and diaphragm form the main oscillating mechanical parts of the engine without physical linkage between the two. For the engine to operate successfully, the displacer and power piston have to be tuned to operate at the design frequency. This requires considering carefully the effect of friction, working fluid damping and the stiffness of the flexure mountings on each component.

2.1.1 Displacer

The displacer is assembled form two components, a rigid cylinder and a supporting flexible bellows. The rigid part is composed of two rigid lightweight cylinders with different cross sectional areas. The different in cross sectional areas between the top and bottom part of the displacer allows creating a force imbalance and oscillation at low-pressure variation levels. The displacer-bellows assembly is mounted on a flange which in turn is bolted to the main outer cylinder of the engine. Figure 2 shows a general outline of the displacer.

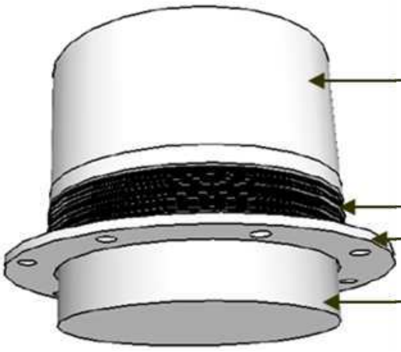

Figure 2: The displacer assembly

In sizing the displacer parts, it was important to use off the shelve bellows and stainless steel cylinders and of standard dimensions. However, the selection of the bellows needs to satisfy the required stroke, oscillation frequency and dynamic stability to avoid wobbling and swerving under dynamic forces. Among the parameters to be selected include the bellows inner and outer diameter, the number of convolution (height), stiffness of the material and deflection [3].

The natural frequency of oscillation of the displacer-bellows assembly depends on the assembly mass and the bellows overall stiffness. This expressed as:

$$\omega_d = \left(\frac{k}{m}\right)^{0.5} \qquad [1]$$

Where the bellows stiffness, k, is proportional to the stiffness of one convolution and inversely proportional to the total number of convolutions (i.e., $\mathbf{k} = \frac{\mathbf{k_n}}{\mathbf{n_w}}$) with k_n: is the convolution spring rate (N/m), n_w: is the number of the convolutions.
The displacer assembly main dimensions are given in Table 1.

Table 1: The displacer data

Bellow type/material	Edge-welded stainless steel bellows
Operating frequency	~15 Hz
Operating pressure	atmospheric
OD/ID	95 / 76 mm
Number of convolutions	15
Nominal free length	24 mm
Axial stroke	±5 mm
Nominal stiffness rate	10 N/mm
Life cycle	100,000 (axial movement)

2.1.2 Power piston

The power piston was formed from a flat flexure diaphragm clamped at its circumference. thin diaphragm are widely used in microelectromechanical systems (MEMS) and transducers [4]. A diaphragm power piston offers simplicity; complete sealing of the working fluid in the engine, no friction, and long life. Figure 3 illustrates the structure of the diaphragm where it is clamped around its circumference and free at the centre. A rigid mass is added to the centre of the diaphragm to increase the volume swept and fine tune the natural oscillation frequency.

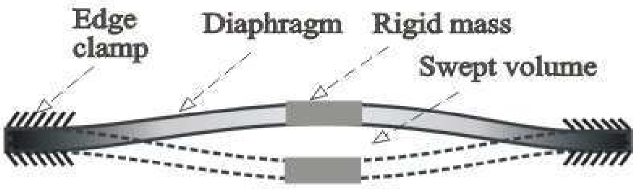

Figure 3: Flexure diaphragm

The diaphragm was made of a 6 mm thick and 100 mm diameter flat rubber diaphragm. The maximum deflection of the diaphragm occurs at its centre and is approximately proportional to the magnitude of pressure gradient in the engine sealed space. This can be expressed as follows [5]:

$$w_o = \frac{3r^4(1-\mu^2)}{16Et^3}\Delta p \qquad [2]$$

Where, r and t are the diaphragm radius and thickness, E and μ are diaphragm material Young's modulus and Poisson's ratio, and p is applied pressure over the surface of the diaphragm.

The operating service of the diaphragm is measured by the number of oscillation it can produce before failure. This depends strongly on the stress and strain forces applied to the diaphragm material and limiting the maximum stress to below the material's threshold stress will produce an infinite number of oscillations. The maximum stress (radial and tangential) applied to the diaphragm at full deflection occur at the clamped edge part, which is given by:

$$\sigma_o = \frac{3r^2(1-\mu+\mu^2)^{0.5}}{4t^2}\Delta p \qquad [3]$$

Similarly, the operating frequency of the diaphragm was approximated by the fundamental natural frequency of oscillation of a vibrating circular plate with clamped at its edge, as follows [5]:

$$\omega_p = \frac{10.21}{r^2}\left(\frac{Et^2}{12\rho(1-\mu^2)}\right)^{0.5} \qquad [4]$$

The effect of the surrounding working fluid and clamping arrangement however reduces the oscillating frequency. To tune the diaphragm natural frequency, a corrective rigid mass is attached to the diaphragm at its centre.

3 THE TEST RIG AND PRELIMINARY RESULTS

A small proof of concept prototype diaphragm Stirling engine was built and testing is ongoing. Figure 4 illustrate a photograph of the engine test rig.

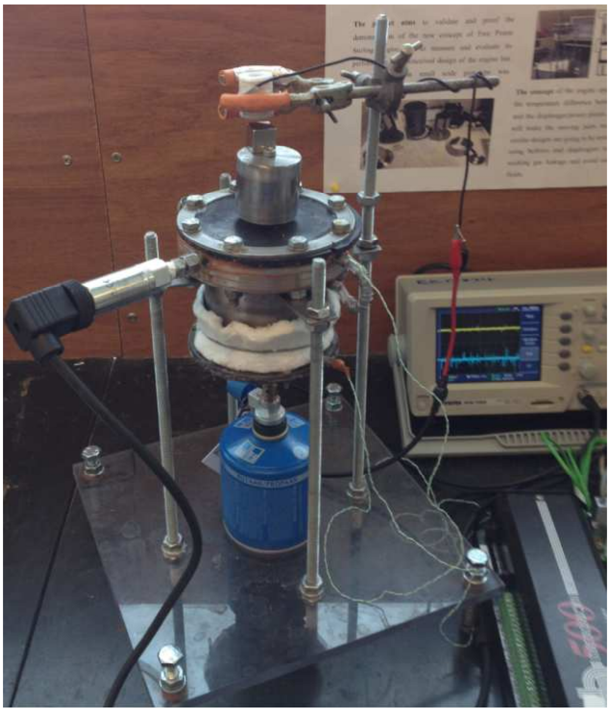

Figure 4: Engine housing casing

Starting the engine for the first time proved challenging as a number of design parameters need to be set correctly. In addition to satisfying the thermal parameters, the dynamic behaviour of the oscillating parts must be finely tuned including overcoming frictional and viscous damping forces as well as correcting the natural frequencies of the components. After the initial modifications, the engine self-starts reliably on application of sufficient temperature gradient between the heat source and the heat sink. Figure 5(a) shows the initial attempts at starting the engine where it shows that the diaphragm oscillation decay after a few oscillations. Eventually, the engine oscillation was sustained at a heat source temperature of about 250 °C and heat sink temperature of 40 °C. The operating frequency of the engine was measured at 15.4 Hz and a diaphragm stroke of 10 mm, as shown in Figure 5(b).

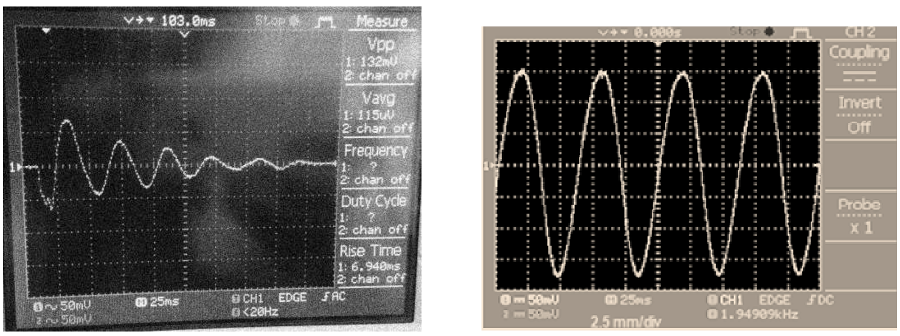

Figure 5: Diaphragm oscillation a) decaying oscillation b) sustained oscillation

The testing of the engine is still on-going and further recordings of compression space pressure and volume variation are shown in Figure 6. It can be seen that the two sinusoidal waveforms are have a phase shift angle of about 80° with pressure lagging.

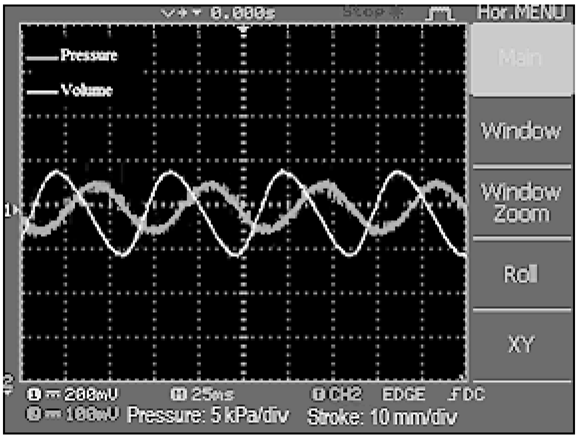

Figure 6: compression space pressure and swept volume variation

The power output of the engine was evaluated from the p-v diagram recording using a digital oscilloscope is shown in Figure 7. The pressure variation was determined using a pressure transducer and the volume swept from an LVDT that measures the diaphragm oscillation amplitude. It was estimated that the area enclosed by the p-v diagram amounts to a power output of about 0.10 W.

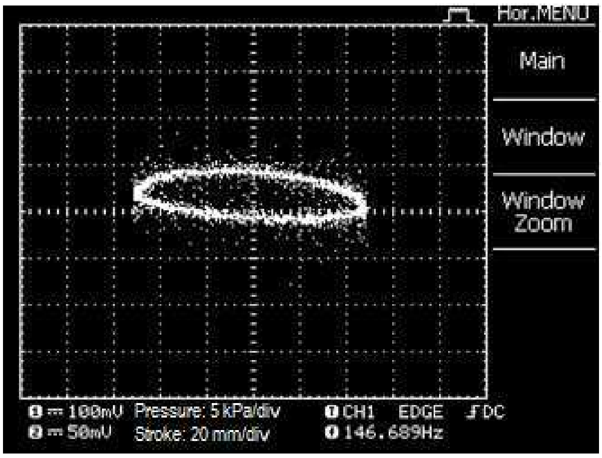

Figure 7: p-v diagram recording

4 CONCLUSION

A FPSE using a flexure bellows and elastomeric material diaphragm was designed and tested. The preliminary results demonstrate good operation stability and self-start up operation. Further work will be implemented to increase the power output through further tuning and enhancing heat regeneration. A load using diaphragm type water pump will also be tested for irrigation purposes.

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