MOTION ANALYSIS OF LIQUID PISTON ENGINES

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Abstract: Engines and pumps are common devices that have become important sources of power to operate machines used in everyday life. Many of these machines need complex technology for proper operation. However, some of these can be operated by using simple mechanical processes. Liquid piston fluidyne engines are such devices that are a simpler version of Stirling engines. In this work, a simple test rig using this concept has been designed. Various experiments were done to test the device, and future recommendations on improvements have been presented.

Keywords: engines, liquid, piston, fluidyne

1. INTRODUCTION

During the industrial revolution of 18th century, the steam engine became a primary source of power. However, this device has its own drawbacks. Its maximum efficiency is at the most 2%, and there were many accidents involving explosions. This prompted engineers to look for alternative sources of power like Stirling engines.

A Stirling engine is a hot air engine operating on the principle that air expands on being heated and contracts on being cooled. These devices have zero exhaust and are external combustion engines, hence wide variety of fuels can be used to run a Stirling engine that include alcohol, bio-products or waste gases, etc. These engines are suitable for operations that have following requirements [1]:
- Constant power output;
- Noiseless operation;
- Long startup period;
- Low speeds.

Development of Stirling engine is widely attributed to the Scottish scientist Sir Robert Stirling. The first version of this engine developed in 1815 was heated by fire and air cooled. Figures of some of these early versions are presented in coming sections (Figures 1 and 2).

Later Erickson in the year 1864 invented the solar powered engine to heat the displacer tube at the hot side. The heat was obtained by use of solar reflectors. First alpha type engine was built in the year 1875 by Rider. Reader and Hooper proposed the first solar powered heat engine for irrigation purposes in the year 1908. Following this Jordan and Ibele designed a 100W solar powered engine for pumping of water. In year 1983 a low-temperature difference Stirling engine was patented by the White having an efficiency of about 30 %. Colin later presented a design with a low-temperature difference of 15 °C and Senft published specifications of an engine with a very low-temperature difference of 5 °C between hot and cold ends [1].
Some of following events can be considered as important milestones in the design and development of a Stirling engine for use as a pump:
- 1688: Thomas Savery develops a drainage pump that was a liquid piston machine;
- 1909: Development of Humphrey pump;
- 1931: Malone designed and developed an engine with regenerative cycle similar to a Stirling engine;
- 1965: Philips Company patented a Stirling engine;
- 1977: The metal box company develops Stirling engine for irrigation purposes in Harwell lab;
- 1985: McDonnell designed an engine with parabolic reflectors to focus solar energy thus achieving a high temperature of 1400 °C (Figure 3).

The basic principle of a fluidyne is similar to a Stirling engine [3]. A gas when is heated expands and if its expansion is confined, its temperature rises [4]. This can be understood more easily by following operations as shown in upcoming figures (Figures 4 - 8).
Initially the displacer piston is at centre, with half of the gas in the hot side and other half of gas in the cold side of the cylinder. The pressure gauge is at the neutral position.

As the displacer piston moves towards the cold end, the gas is displaced towards the hot end by the connecting tube, its temperature and hence pressure goes up as indicated by the gauge.

As the piston moves towards the hot side, the gas is displaced towards the cold end, its temperature and hence pressure falls. The changes in the displacer pressure can be used to drive another piston known as the power piston [5]. When the gas pressure is high, the power piston moves towards the open end of the cylinder, hence doing some work that can be used to pump water or rotate a crankshaft.
However, when the gas pressure is low, the power piston returns towards its original position for which work is needed which is lesser than the work available from the previous stroke [6]. Hence, there is an excess of energy that can be used for pumping operation or other tasks.

![Diagram of a displacer piston in a cylinder (cold side) with labels: 1 - Hot side; 2 - Displacer; 3 - Cold side; 4 - Pressure Gauge; 5 - Working piston.]

By clever and innovative engineering, some of the power available from the power piston can be used to drive the displacer piston, and so to create a variable pressure heat engine.

2. EXPERIMENTAL SETUP

Tests were done on a liquid piston engine having specification as represented in Table 1 and general layout as seen in Figure 9. Ethyl alcohol was used as a fuel for heating the hot end of the column and to generate pressure fluctuations. A plastic tube was used as displacer column connecting at both ends by a thin Brass pipe that acts as air column. Two mild steel balls were used as non-return valves to control the flow of fluid in pumping column. Pressure and temperature data were recorded using horizontal manometer and thermocouple attached at the hot end of test rig as shown in Figure 10.

![Diagram of the experimental setup with labels: 1 - Reservoir; 2 - Cold end; 3 - Frame; 4 - Support; 5 - Hot end; 6 - Air column; 7 - Connecting column; 8 - Pumping column; 9 - Collecting cup.]

To study the variation of pressure and temperature of the air column with time, standard procedure was used. First balancing of the level of manometer with knob was done, so that air bubble is at centre. The alcohol flame was then lit up, and one end of manometer was connected with the gap provided in the hot air column. Experimental data was recorded at various time intervals.
Table 1. Engine specifications.

| Parameter                        | Value   |
|----------------------------------|---------|
| Pumping Column Height(H)         | 150 mm  |
| Pumping Column Diameter (D)      | 3.9 mm  |
| Diameter of Air Column(d)        | 50 mm   |
| Length of Air Column (l)         | 180 mm  |
| Diameter of Displacer Column(δ)  | 6.3 mm  |
| Length of Displacer Column(L)    | 300 mm  |
| Length of Connecting Column(k)   | 60 mm   |
| Diameter of Connecting Column(β) | 3 mm    |

3. RESULTS AND DISCUSSION

The time period of fluid oscillations and power required to do pumping working was calculated from the known design parameters.

Frequency $f$ of oscillations is given in terms of angular frequency of vibrations ($\omega$) by equation (1).

$$f = \frac{\omega}{2\pi}$$

which can be further expressed in terms of length of displacer tube (L) as equation (2).

$$f = \left(\frac{2g}{L}\right)^{1/2} / 2\pi$$

The time period of fluid oscillations is given by equation (3).

$$T = \frac{1}{f} = 0.63 s$$

Pumping rate ($Q$) can be expressed in terms of area of delivery column ($A$) and height of column ($H$) as equation (4).

$$Q = A(2gH)^{1/2} = 8.19 cm^3 = 8.19 \times 10^{-6} m^3 / s$$

The power needed to pump water is given by equation (5).

$$P = \rho \times Q \times g \times H = 1000 \times 8.19 \times 10^{-6} \times 9.8 \times 0.15 = 0.012 W$$

Fig. 10. Experimental setup for finding pressure and temperature.
Table 2. Variation of pressure and temperature of the air with time.

| Reading (mm of Hg) | Temperature (K) | Time (s) |
|-------------------|-----------------|----------|
| 730               | 296             | 0        |
| 988               | 298             | 300      |
| 912               | 300             | 320      |
| 1216              | 305             | 340      |
| 912               | 306             | 360      |
| 1368              | 308             | 380      |
| 760               | 310             | 400      |
| 1444              | 311             | 420      |
| 745               | 312             | 440      |

Table 2 shows results of pressure and temperature variations recorded at regular time intervals. Temperature of air in the engine was found to increase with time as it gains more and more heat from the burning fuel. The pressure was found to fluctuate with time as it moves back and forth from the hot side towards cold side alternatively through the connecting air column. Peak pressure was found to be around 1400 mm Hg whereas the peak temperature was found to be around 39°C indicating poor heat transfer to the working gas (air). In order to reduce heat losses, the connecting column was covered with PTFE insulation layer (PTFE tape). Further in order to improve the heat transfer rate, connections having bigger length and diameter of displacer column tube can be used so that more mass of air is able to gain heat from the burning fuel (Figure 11).

![Calculation of the length of stroke](image)

Fig. 11. Calculation of the length of stroke: 1 - No heat; 2 - Heat applied.

Calculation of stroke of the water column was difficult due to quick oscillations. However, it was theoretically found using ideal gas laws and observing temperature and pressure at certain time intervals using manometer, stopwatch and thermocouple. According to gas law we have (equation (6)):

\[
P_1 V_1 / T_1 = P_2 V_2 / T_2
\]  

Hence displaced volume of fluid \((V_d)\) can be used to find stroke length of fluid \((S)\) as follows (equation (7)):

\[
V_d = V_1 - V_2 = 2(\pi / 4D^2)S
\]

Various values of stroke length \((S)\) can be seen in Table 3.
Table 3. Variation of stroke length with time.

| P1 (mm of Hg) | V1 (m³) | T1 (K) | P2 (mm of Hg) | T2 (K) | V2 (m³) | V1-V2 (m³) | S (mm) | Time (s) |
|---------------|---------|--------|---------------|--------|---------|------------|--------|---------|
| 733           | 22.6    | 296    | 988           | 298    | 16.8    | 5.8        | 25.6   | 300     |
| 988           | 16.8    | 298    | 912           | 300    | 18.32   | 1.52       | 6.7    | 320     |
| 912           | 18.32   | 300    | 1216          | 305    | 13.96   | 4.36       | 19     | 340     |
| 1216          | 13.96   | 305    | 912           | 306    | 18.68   | 4.72       | 20.85  | 360     |
| 912           | 18.68   | 306    | 1368          | 308    | 12.53   | 6.15       | 27     | 380     |
| 1368          | 12.53   | 308    | 760           | 310    | 22.7    | 10.17      | 45     | 400     |
| 760           | 22.7    | 310    | 1444          | 311    | 11.99   | 10.71      | 47     | 420     |
| 1444          | 11.99   | 311    | 745           | 312    | 23.31   | 11.32      | 49.8   | 440     |

4. CONCLUSION

The stroke length of the device was found to be in the order of below 50 mm which is very low due to various poor heat transfer, leakage, viscous and frictional losses [7-11]. To increase the engine efficiency some of following improvements can be made in the current design:

1) Use of bigger diameter displacer tubes-it ensures the greater amount of air flowing between the cold and hot side. This can lead to a larger amplitude of oscillations due to higher pressure, but smaller compression ratio whereas smaller tubing results in a larger compression ratio.

2) Use of regenerator

The regenerator acts as a thermal sink, releasing and absorbing heat at various stages hence increasing the efficiency of the engine. Most common method of heat storage is to obstruct the flow of working fluid by use of metallic mesh, porous material, array of tubes, but this may cause flow losses.

3) Better heat exchange-in order to enhance the heat exchange at the hot end, electric resistance heater can be used instead of fuel burning heater.

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