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Development and Analysis of a Liquid Piston Stirling Engine †

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Abstract: Stirling engines are a type of reciprocating external combustion engine that uses one or more pistons to perform useful work with the help of some external heat. The Fluidyne design, also known as the liquid piston Stirling engine, uses liquid as pistons contained in a cylinder that entraps a working gas. Stirling engines are low efficiency engines that can utilize waste and low-grade thermal energy to pump water or do work at a small scale. Excellent opportunities to address difficulties with energy security, water dissipation, and greenhouse gas emissions are provided by the employment of these low-grade waste heat recovery techniques. This research will cover effects of changing water levels and using a mixture of different working liquids of low heat of vaporization on engine performance. Temperature, pressure, amplitude of oscillation variation with time and pumping volume were determined with Vernier sensors and tracking software. This study confirms correlation between working liquid volume and heat of vaporization on engine performance.

Keywords: Stirling engine; pumping; sustainability; low-grade heat; Fluidyne engine; external combustion engine

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1. Introduction

The liquid piston heat engine offers unparalleled potential to both renewable and waste-heat recovering methods because of its low manufacturing and operational costs [1]. The flexible geometry of the engine holds a fluid and a gas in place [2]. The components are inexpensive and simple to manufacture [3]. Stirling engines operate on a Stirling cycle [4,5]. The manufacturing costs of a liquid piston Stirling engine are extremely low. However, the full potential of such a simple energy conversion device is still underexplored considering that it could be used in areas with limited maintenance and availability of materials [6]. A better understanding of the engine's performance parameters is provided by this research. These are affected by fluid vaporization and volume of working liquid [3,7]. Additionally the pumping volume for each case has been measured.

2. Design

Fluidyne is divided into 4 segments which are labelled in Figure 1 with the testing apparatus shown in Figure 2. The dimensions of the model are given in Figure 3 [8]. The hot end is made of copper, the cold end with clear PVC (Polyvinyl chloride) tube and the regenerator with polyethylene foam with a pumping line attached at the hot end. Heat is supplied via a hot air gun with a 2000 W rating. Vernier temperature and pressure sensors are used for measuring values of air at cold end [9].

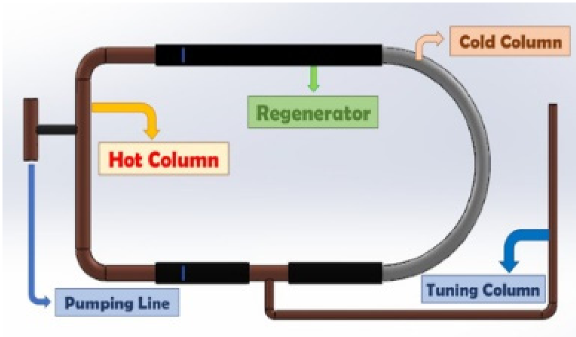

Figure 1. CAD model with segments.

Figure 2. Testing apparatus.

Section Name	Length	External Diameter	Internal Diameter
Regenerator	33 cm	1.3 cm	0.65 cm
Cold End Portion	38.1 cm	1.5 cm	1.3 cm
Hot End Portion	22.9 cm	1.3 cm	1.3 cm
Displacer Portion	33 cm	1.3 cm	1.3 cm

Figure 3. Dimensions of segments.

3. Results and Analysis

The effect of changing working liquid volume and liquid column vaporization on engine performance was analyzed. For heat input, a heat gun was utilized with a rated power of 2000 W. The amplitude of oscillation of the liquid, which is the displacement covered by the liquid from its initial to its final position in the tuning column, are measured using tracker software.

3.1. Effect of Working Liquid Volume (Water Is Used Only)

In order to analyze how an engine's working liquid volume affects performance, tests were carried out with volume of the working liquid (water) varied as 100 mL and 80 mL. The effects of the varied volumes were studied with respect to oscillations amplitude and stability, pressure and temperature variations in the cold end, and the pumping power at that volume was found. Vernier temperature and pressure sensors were used to record these values, which are illustrated in Figures 4 and 5.

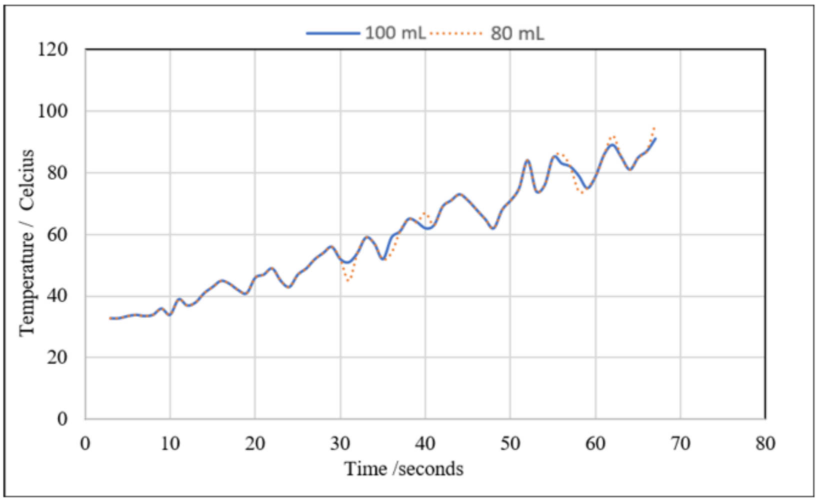

Figure 4. Temperature vs. time curve.

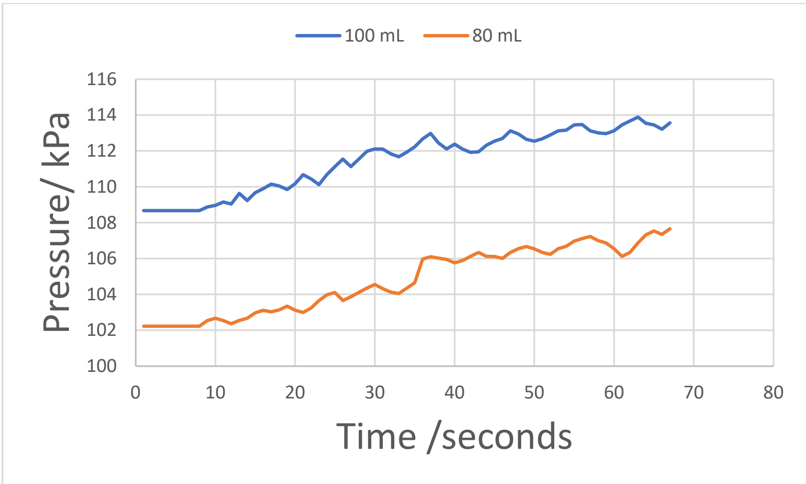

Figure 5. Pressure vs. time curve.

The oscillations produced in the tuning column were analyzed for both volumes using tracker 6.0.10 software, and the variation of amplitude with time is illustrated in Figures 6 and 7.

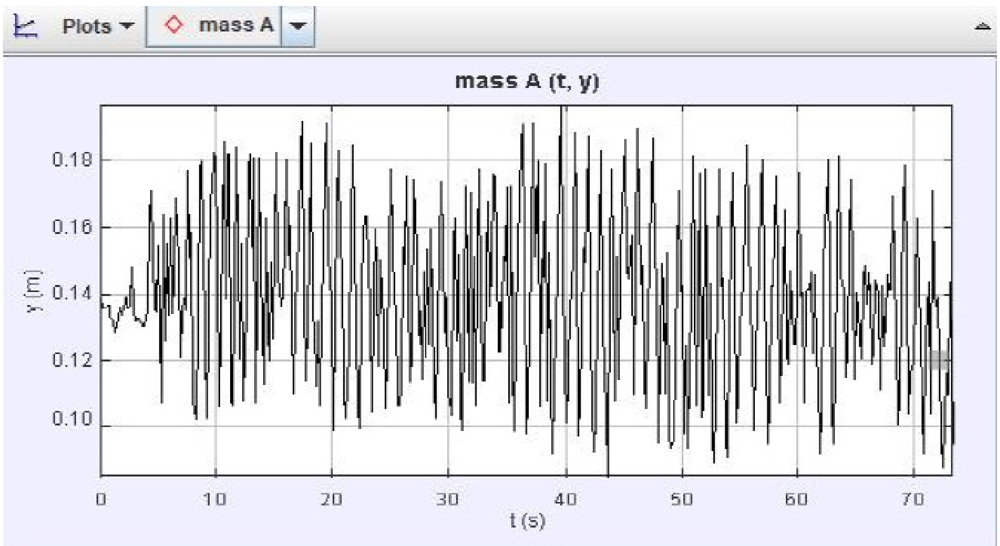

Figure 6. 80 mL volume.

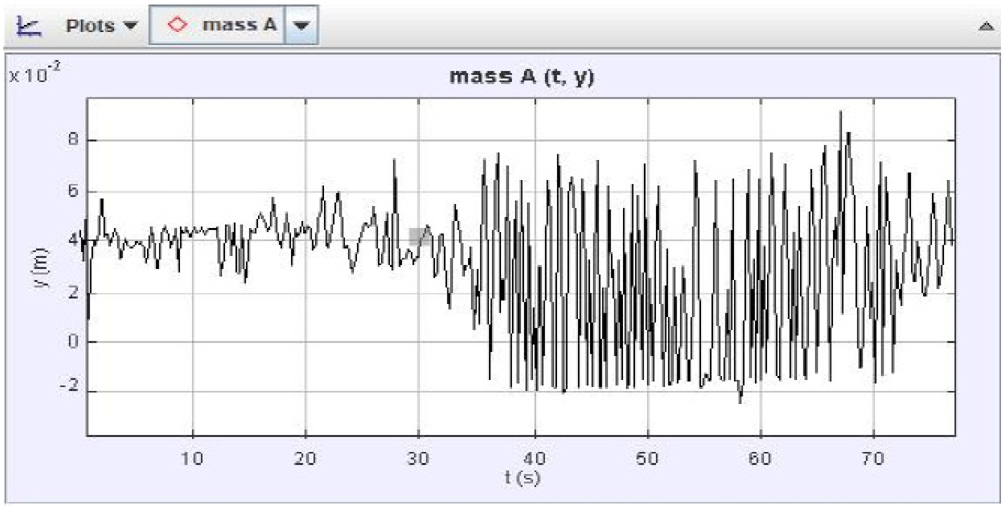

Figure 7. 100 mL volume.

To determine the pumping rate, we added a water reservoir under the pumping line, and a test tube of 20 mL capacity was connected to the upper part of the pumping line. The time required to fill the test tube was measured with a stopwatch. The time was measured from the instance the oscillations became prominent and stable summarized in Table 1.

Table 1. Pumping data for different working fluid volume cases.

Liquid Volumes (mL)	Pumped Volume (mL)	Time (s)
100	20	22
80	8	25

The analyzation of the graphs showed that the temperature variations for the cold end remained similar in both 80 mL and 100 mL working fluid volumes. This is strongly justified and implied by the constant heat input to the hot end in the system. The pressure variations for the 100 mL volume case lye in the range 108–114 kPa while for the 80 mL volume case the variation majorly existed between 102–107 kPa. This implies that although the pressure varied by equal values in the cold end, the magnitude of the pressure trend in the cold end for the 100 mL case was more than that for the 80 mL case. This is also reflected and supported by the pumping data regarding both cases.

Frequencies of oscillations for both cases were similar; however, for the case of 100 mL, the amplitudes were higher with respect to the 80 mL oscillations. The frequency of the oscillations remained a factor of engine geometry and heat input.

For a lower volume of water engine, the starting time was less than that for a higher volume of water; hence, for a lower temperature differential, the amount of working gas should be higher compared to that of working liquid. A similar outcome was proven by Mahdy [10].

3.2. Effects of Liquid Column Vaporization

The next part of the research is to notice the effects on engine performance by the vaporization of liquid. For this purpose, an alcohol that is Ethylene Glycol is used to achieve variations of vapor pressure to know the relationship between fluid vaporization and engine performance. Vapor pressure was determined using Raoult's law after the fluids were mixed volumetrically, as illustrated in Tables 2 and 3.

$$P_{solution} = X_{solvent} \cdot P_{solvent} \tag{1}$$

$$X_A = \frac{n_A}{n_A + n_B} \tag{2}$$

Table 2. Heat of vaporization (kJ/mol) and vapor pressure.

Liquid	Heat of Vaporization	Vapor Pressure (100 °C)
Water	40.66	87,726
Ethylene Glycol	65.60	2466

Table 3. Calculated vapor pressure.

Mixtures	Ratio	Vapor Pressure
Glycol, Water	20–80	70,180
Glycol, Water	40–40	43,863
Glycol, Water	50–10	14,621

Temperature and pressure values were recorded for three mixtures (100 mL, 80 mL and 60 mL) at cold end, as illustrated in Figures 8 and 9.

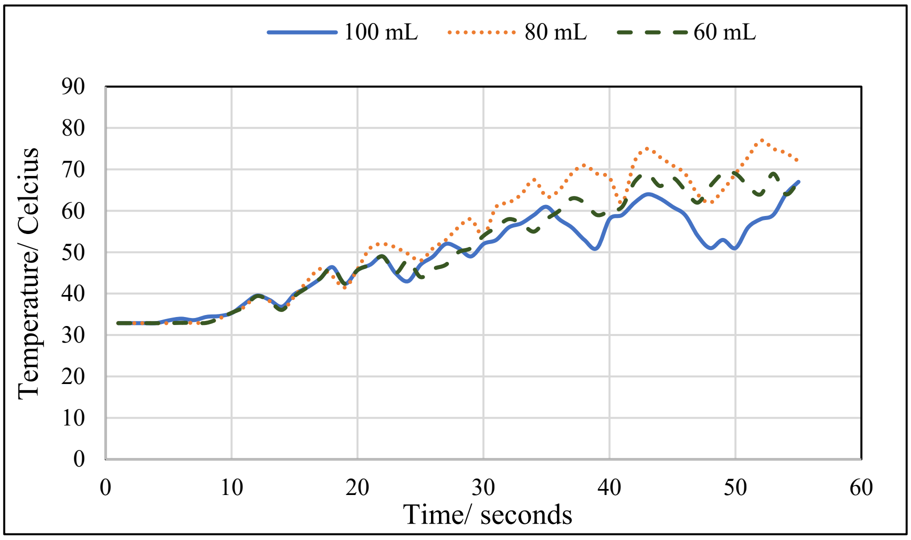

Figure 8. Temperature vs. time Graph for glycol mixtures.

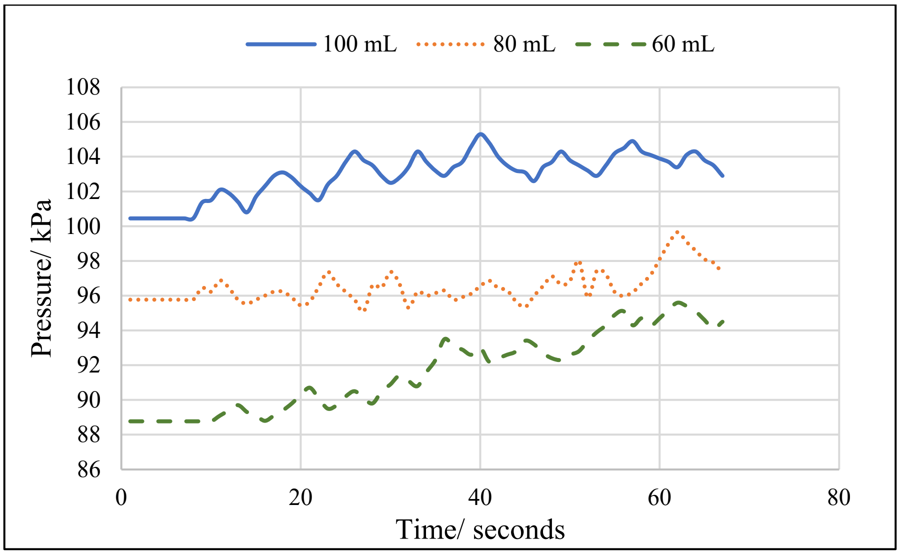

Figure 9. Pressure vs. time Graph for glycol mixtures.

The oscillations in the tuning column were also analyzed using tacker software for all the concentrations for the sake of comparison of oscillations under different operating conditions, as shown in Figures 10–12.

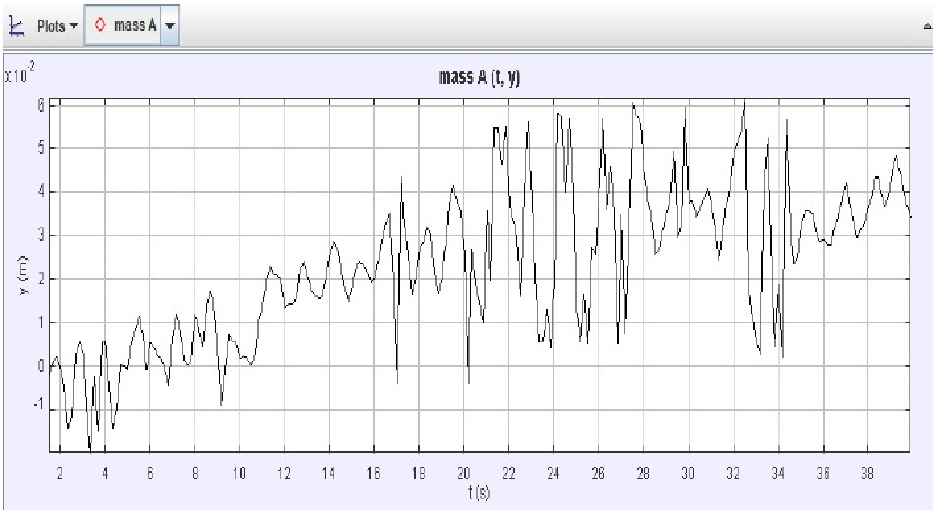

Figure 10. 100 mL mixture.

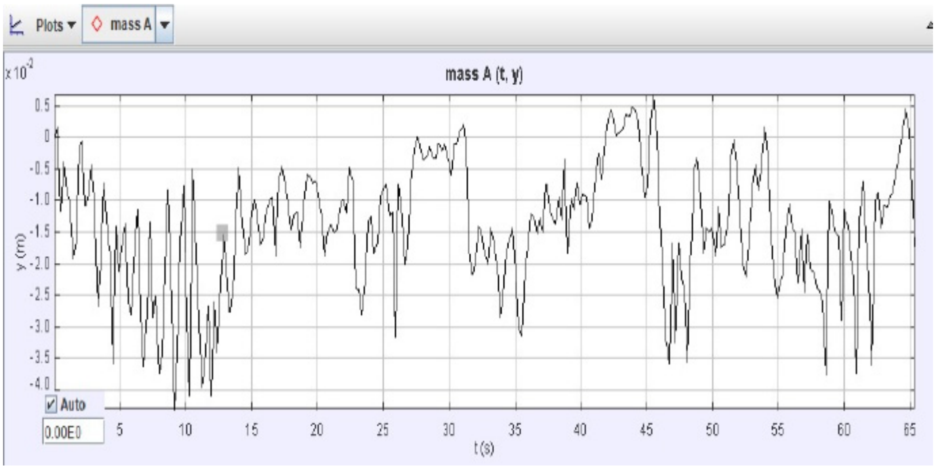

Figure 11. 80 mL mixture.

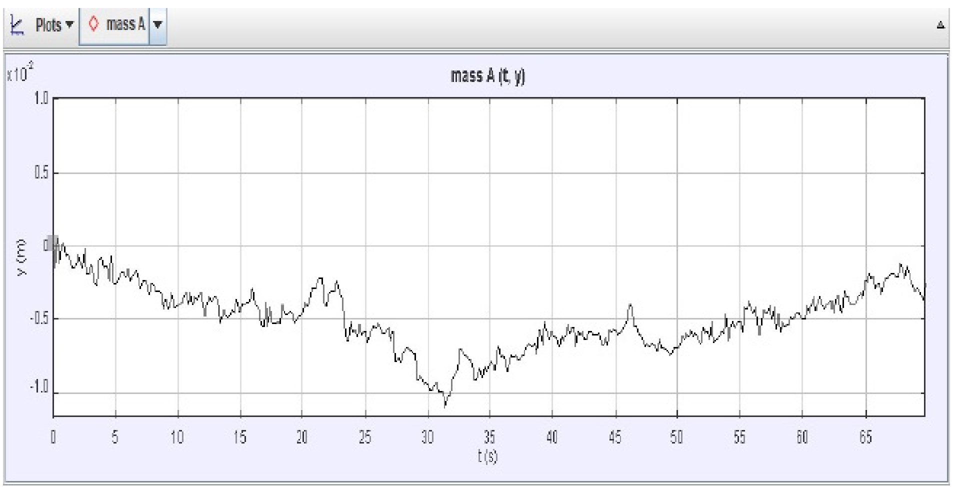

Figure 12. 60 mL mixture.

In all the cases, the source of heat input and conditions were kept the same, and experimental results show that although the range of pressure variation is the same, higher pressures are achieved with greater concentration of water than ethylene glycol. The temperature plots do not show a recognizable or definite trend, possibly because the heat input is maintained constant. The analysis of amplitude vs. time graphs from video tracker modelling and analysis software show that when the liquid columns are occupied with greater concentration of liquid, with higher heat of vaporization, the oscillations are somewhat more stable but with a much smaller amplitude. Compared to the mixtures with greater concentration of water in liquid columns, the graphs show that for a given hot column temperature, the rate of energy conversion into vaporization is higher for liquids having relatively low enthalpies of vaporization, which results in a larger oscillation amplitude. It was found that the engine's operating frequency was reliant on geometry but unaffected by input energy back when the working liquid was just water. The research indicated that there is some dependence of the engine's operating frequency on the composition of glycol mixtures. Similar research was conducted by Newlan, and the results were consistent with previous studies.

4. Conclusions

There is a strong correlation between engine output power and a high vapor pressure of the engine working fluid, suggesting that at a constant heat input, as the concentration of the lower heat of vaporization liquids rises, more energy may be transferred to mechanical work. This is in line with the results of Oyewunmi's research.

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