DESIGN AND CONSTRUCTION OF A SOLAR-POWERED FLUIDYNE TEST BED

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ABSTRACT

Liquid piston Stirling engines (sometimes termed “fluidynes”) have been studied extensively and applied in a variety of energy conversion applications. They are attractive for low capital costs and simplicity of construction. In addition, their operation as external combustion engines allows for flexibility in primary energy sources which is a distinct advantage when a low-cost or free source of heat can be paired with their minimal construction costs. Disadvantages of these devices include relatively low efficiency and low power density. A solar-powered fluidyne test bed was constructed and operated at the University of Colorado at Colorado Springs. This test bed was composed of a fluidyne engine which was constructed from copper pipe and plastic tubing along with temperature and pressure instrumentation. The system was designed to be powered by a Fresnel lens concentrating solar energy. The concentrated solar energy from the Fresnel lens provided ample power to operate the test bed, and tests were run in a wide variety of conditions. Indicated work of this unloaded engine was shown to agree well with a simple theoretical model of a Stirling cycle.

INTRODUCTION

This paper describes a solar powered liquid piston Stirling engine test bed developed at the University of Colorado at Colorado Springs. The construction and operation of the test bed was intended to serve two purposes. First, it was used to demonstrate direct solar-powered operation of a Fluidyne with sunlight concentrated directly on the Fluidyne cylinder rather than on a remote heat exchanger. In addition, it was used to characterize some aspects of the operational thermodynamic cycle. The test bed was only intended as a platform to explore feasibility and thermodynamic characteristics, not as a practical, power producing engine. Hence, electrical generation equipment was not included.

Liquid piston Stirling engines, sometimes referred to as “fluidyne” engines, use liquid pistons rather than solid ones used in conventional engines. Conventional engines ordinarily use solid pistons requiring the design, manufacture, and maintenance of sliding mechanical seals. Solid seals not only require relatively high tolerance manufacturing, they also require periodic replacement thereby increasing the maintenance cost throughout the life of the engine. Liquid piston engines do not require the manufacture or maintenance of mechanical seals which decreases the manpower and manufacturing costs. Additionally, the nature of the liquid piston allows for unconventional piston cylinder shapes which might be needed in certain applications. Fluidyne engines do not require the use of valves and advanced timing controls for engine operation. In fact, most fluidyne engines require very little complex machinery for operation and can be manufactured with relatively few tools and materials. This low capital option for energy conversion makes the fluidyne appealing for certain applications in which simple manufacture, free or low cost heat, and minimal maintenance are available [1]. While the fluidyne engine may have a viable future in some applications, the device’s low thermal efficiency and poor specific power limit its use to situations with cheap or free energy sources [2]. This includes, but is not limited to, pumping applications in developing countries or remote areas where frequent maintenance and attention may be unavailable.

One configuration for a fluidyne engine consists of a closed U-tube partially filled with liquid and connected at the bottom to a second tube also partially filled with liquid as shown in figure 1. This variety is termed a merged, alpha-type fluidyne. The liquid partially filling the U-tube acts as a displacer piston which moves a working gas from a hot side heat exchanger to a cold side heat exchanger. These heat exchangers are denoted as H and C in figure 1. When the gas in the working space shifts from side to side, it is heated and cooled causing the system pressure to increase and decrease. In the bottom of the U-tube, a second liquid column connects with the liquid in the U-tube. In one possible configuration, the second column (known as the output column, tuning column, or tuning line) remains open to atmospheric pressure. As the system pressure rises and falls, the liquid in the output column
moves up and down accordingly. This oscillatory motion not only provides a means to extract work, it also provides the necessary feedback to oscillate the displacer piston in the U-tube, if the fluidyne is designed correctly.

The primary advantage of the fluidyne lies in the simple construction and operation of the device. The device itself requires little maintenance as the failures of mechanical seals do not apply. Some disadvantages of the fluidyne engine are fluid friction, poor heat transfer characteristics, and the phase changes of the liquid columns that occur at high temperatures [1]. Additionally, even the most recent fluidyne designs have a low power density in relation to their size [2].

West [3] provided a comprehensive look at the history and state of the art of fluidyne engines. More recently, Fauvel et al. explored the mechanism by which the tuning line supplied feedback to the displacer piston either via hydrodynamic coupling, hydrostatic coupling, or a combination of both [2]. In the experimental study, Fauvel et al. concluded that the plain ended termination point yielded the best results with a phase lag of 49°, suggesting that the coupling mechanism from this type of fluidyne was a nearly exactly equal contribution of hydrostatic and hydrodynamic coupling [2].

The following year, 1990, Fauvel, Walker, and Reader published another article which addressed the response of both the displacer piston and tuning line to a varying system pressure [4]. In the same year, Fauvel and West published an article which corroborated experimental data from Fauvel’s previous experiment with analytical data obtained from differential equations describing the piston motion [5].

A few years later, Fauvel and Yu presented another study specifically addressing the design and effectiveness of a barrel-type fluidyne [6]. This study differed from Fauvel’s previous studies by focusing more on a practical design of a fluidyne instead of scientific understanding. In 2004, an article published by Orda and Mahkamov described an empirical study of different water pumps, collecting efficiency and pumping capacity data [7]. The study involved three different prototypes; the first employed the use of a heated element in a concentric cylinder design, the second utilized flat-plate solar collectors in a U-tube design, and the third design improved the second design with a more compact form. All three fluidyne models contained a solid displacer piston in between the hot and cold side columns which was attached to a spring to aid in cycling the liquid back and forth. While Orda and Mahkamov only presented experimental data from their own fluidyne designs, their study presented physical data of solar-heated fluidyne engines which can operate under the varying conditions of solar collection and pumping needs.

A study published by Slavin, Bakos, and Finnikov concentrated on the development of fluidyne engines for medium power electricity generation [8]. The group conducted a computer simulation which analyzed a more complex fluidyne that contained multiple valves and chambers. Another study by Özdemir and Özgüc [9] attempted to formulate a mathematical model based on hydrodynamic and thermodynamic equations and compared that model to an actual experiment. Similar to the Slavin et al. study, the model was built on hydrodynamic and thermodynamic equations, except for the additional interfacial conditions that occur in a wet fluidyne (evaporation and condensation). The simulation data supported the experimental prototype, however the authors did comment that the weakness of the model was the modeling of the interfacial mechanisms.

An article published in 2009 reflected on the benefits of using a liquid piston Stirling engine as a mobile hydraulic power supply option [10]. The authors mostly discussed the efficiency benefits of the Stirling engine and the cost breaks associated with using liquid pistons in them. The qualitative discussion included the application of this engine to automotive powerplants, robotics, construction equipment, irrigation pumping in developing nations and the Stirling engine’s potential use as a heat pump.

**SYSTEM DESCRIPTION**

The test bed was to be powered by the sun using a 50’ by 37” Fresnel lens. To maintain the use of commercially available products, the displacer piston was constructed of 1” diameter piping. The tuning column tubing consisted of ½” tubing.

A piece of 1” nominal diameter PVC was cut to 9” in length, filled with sand, then bent 180° with a heat gun. Both ends of the pipe were fitted with 1” female threaded slip joints using PVC cement. The heat exchangers were made using 1” Type L copper pipe each cut to 6” in length. The ends of the copper pipes were sweated with 1” to 1”, cup to male NPT threaded adapters using 56% silver brazing alloy. On the tops of the copper pipes, 1” to ½” female to female galvanized steel adapters reduced the ends of the copper pipes so that ½” male to 3/8” male compression fittings could be attached. Brass ferrules were used to attach 3/8” nominal diameter copper tubing to complete the working space. A 3/8” brass compression fitting tee was attached at the top of the working space. The tuning line junction was formed using a combination of copper and CPVC. A 2.5” section of ½” nominal diameter CPVC 4120 was chosen because of the inner diameter and relatively thin walls. A 2” piece of ½” nominal size Type K copper tube was inserted approximately 1” into the CPVC. The CPVC was chosen to serve as an adapter that formed a compression seal with the copper as well as a good seal with the PVC U-tube. The remaining exposed copper piece served as a mount that the ½” vinyl tuning line could be attached with a hose clamp.

The fluidyne engine was mounted on two vertical rods attached to a 1/2” plastic base so the unit could be transported easily as one unit. The framed Fresnel lens was mounted on a wooden stand made of various lengths of 2” by 4” wood. The lens pivoted on its arms that were the length of the focal length. The design allowed the fluidyne to remain positioned in the same location on the lens stand allowing the focal point to remain positioned on the hot side of the heat exchanger, even as the lens was raised and lowered to face the sun. Figures 2 and 3 show the fluidyne engine and lens stand respectively. A
The sampling rate was limited by the capabilities of the computer. With all the instrumentation in place, the data acquisition system could sample approximately every 120 milliseconds.

TEST ERROR

For the two thermocouples, the differential pressure transducer, and the level measurement device, the random and systematic errors used to determine the measurement uncertainty were estimated by operating the instrumentation at steady laboratory conditions.

In the LabView data acquisition program, each thermocouple reading was composed of the average of 10 samples for each data point in order to minimize the random error. More samples could have minimized this error, but would have required more processing time and decreased the sampling rate of the instrumentation. The fluctuations have a standard deviation of 0.0325°C which was used to calculate the overall uncertainty of the temperature readings. The standard deviation of the cold side thermocouple was 0.0297°C.

While both thermocouples showed random error, the difference in the average of the two readings indicated the system bias or systematic error. This resulted in a system bias of 0.1°C. To find the total uncertainty in temperature differences, the sum of squares for each of the errors was calculated as shown in Equation 1.

\[
\text{Error} = \sqrt{\text{Random}_{\text{Hot}}^2 + \text{Random}_{\text{Cold}}^2 + \text{Systematic}^2}
\]

(1)

Using Equation 1, the total error for the thermocouples was calculated to be ±0.1°C.

The random error of the differential pressure transducer was found in the same way. The standard deviation of the pressure readings was 0.003 PSI. The output of the pressure transducer was composed of an average of 10 readings for each data point. Because the pressure transducer was the differential style, both ports were left open to the atmosphere to determine the systematic error. The sum of squares calculation yielded a total uncertainty of 0.010 PSI for the pressure readings.

### Table 1: System Dimensions

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INSTRUMENTATION

The instrumentation system consisted of two thermocouples, a differential pressure transducer, a level measurement device, and a data acquisition system. The data acquisition system was made up of a Gateway Solo Pro 9300 computer using LabView with a Keithley KPCMCIA-16A1AOH data acquisition card.

The two thermocouples were manufactured by Omega Engineering, Inc., catalog number 5TC-TT-T-24-72. The type “T” thermocouples were made of 24 gauge wiring, Teflon coated, and 72 inches long. The thermocouples were placed at the top of the main copper cylinders to avoid getting splashed with water from the displacer piston. The thermocouples recorded the temperatures of both the hot and cold cylinders. The temperatures helped establish the general state of the working space during engine operation. Additionally, temperature fluctuations recorded from the thermocouples helped approximate piston movement so the phasing of the different liquid pistons could be determined.

The differential pressure transducer, catalog number PX139-005D4V from Omega Engineering, Inc., measured the pressure inside the working space relative to the atmospheric pressure measured with a separate port attached to the device. The differential pressure transducer was used because the pressure inside the fluidyne engine’s working space worked against one side of the tuning column which was open to atmospheric pressure on the other side. A differential pressure transducer accounted for any changes in atmospheric pressure on the open end of the tuning column. The relatively high speed of pressure propagation justified the assumption that the pressure was always in quasi-equilibrium across the working space. The pressure measurements were intended to primarily determine the pressure oscillation amplitude and phase but were also used to determine the indicated work and form the PV traces.

The fluctuations have a total uncertainty of 0.010 PSI for the pressure readings.

The pressure measurements were intended to primarily determine the pressure oscillation amplitude and phase but the systematic error. The additional 83 Ω resistor was wired in series with the parallel circuit to limit current to 15 milliamps from the 5 Volt power supply. Before testing each day, the voltage across the electrodes was calibrated with various tuning column heights in case the conductivity of the water changed during the testing period. The measurement of the tuning column height helped determine the phasing of the liquid pistons as well as the working space volume during engine operation.

The instrumentation was sampled using the data acquisition card which was controlled by a program made in the National Instruments LabView environment. The sampling rate was limited by the capabilities of the computer. With all the instrumentation in place, the data acquisition system could sample approximately every 120 milliseconds.

The level measurement device was fabricated from two pieces of welding rod (1/16” diameter ER70S-2) which acted as electrodes inserted in the water in the tuning column. The water level changed the resistance across the electrodes. The electrodes were wired in parallel with a 510 Ω resistor. An additional 83 Ω resistor was wired in series with the parallel circuit to limit current to 15 milliamps from the 5 Volt power supply. Before testing each day, the voltage across the electrodes was calibrated with various tuning column heights in case the conductivity of the water changed during the testing period. The measurement of the tuning column height helped determine the phasing of the liquid pistons as well as the working space volume during engine operation.

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The tuning column line had to be calibrated daily using recorded voltage values across the electrodes when the level was steady at 0", 8", 16", 24", and 32" above the mean tuning column level. The random error was found in the same manner as the other instrumentation. Again, each data point represents the average of 10 samples to minimize the random error. The random error in the measured voltage corresponded to an uncertainty in height change of 0.0108".

Using the sum of squares method shown in Equation 4, the tuning column height uncertainty was calculated to be $\pm 1.814"$. The tuning column height was also used to determine the working space volume. This tuning column height uncertainty resulted in a working space volume uncertainty of $\pm 0.356 \text{ in}^3$.

RESULTS

Testing took place from 9 July 2010 until 6 Aug 2010 at 38° 53' 30" N, 104° 48' 14" W. Weather conditions fluctuated during the testing period including various ambient temperatures, wind, and cloud cover conditions. While these conditions affected the output of the experiments, they are the same parameters that would affect a solar power fluidyne engine intended for practical use.

One of the primary goals of this project was to demonstrate the use and function of a solar powered fluidyne. The Fresnel lens supplied ample solar power for the fluidyne. Using an estimation of the sun’s typical incident power of approximately 900 W/m², the 1.2 m² lens could provide approximately 1080 W of power. The final design was tested with a heat gun prior to solar powered testing which showed that the 1000W provided by the heat gun could generate water level oscillations of approximately 8" in the tuning line. This would occur after a few minutes and required the heat gun to remain steady within 1 inch of the hot side cylinder. The solar power from the Fresnel lens was able to generate much larger oscillations after a few seconds once the lens was focused properly on the hot side cylinder. The radiative heat transfer of the lens proved to be a much more effective heat transfer mechanism than the forced convection from the heat gun. Since fluidyne engines without evaporation suppression typically operate with very low efficiencies, they must reject most of the power input into the system. In order for the fluidyne engine to reject this heat and operate steadily, the materials must be able to withstand the high temperatures required to sustain this high rate of heat rejection. During testing with the Fresnel lens, the experiment would have to be stopped periodically because otherwise the slowly rising temperatures would cause the PVC and other heat sensitive parts to melt. Thus, the system never operated at a true steady-state, however, the change was slow enough that quasi-steady performance data could be gathered over sustained periods.

In order to maximize the power concentrated by the Fresnel lens, the fluidyne was positioned at a distance so that the focal point was located on the hot side cylinder. If the sun’s rays were out of focus on the cylinder, the radiative flux was decreased and some of the power physically missed the hot side copper pipe. This loss of radiation incident on the cylinder occurred if the fluidyne was 1 to 2” fore or aft of the focal length. Thus, the lens and fluidyne apparatus had to be positioned carefully in order to maximize the solar input. Additionally, the lens face had to be positioned perpendicular to a line of sight to the sun in order to focus the sun’s incident radiation to a spot at the focal length. The sun’s movement made the above obstacles more difficult. Even if the lens were perpendicular to the sun, and the focus was aimed directly on the hot side heat exchanger, the apparatus would have to be repositioned several times per hour. In order to make this more convenient, the lens stand was designed to pivot at a distance equal to the focal length so that the fluidyne would be able to remain stationary with respect to the stand. Though the lens was made of a light-weight plastic, the 20 pound lens/frame apparatus and 35.5” focal length created a large moment at the pivot arms of the lens stand. A full sized camera tripod supported the weight of the lens to hold it stationary during testing. Periodic adjustment consisted of a rotation of the whole apparatus and a height adjustment of the camera tripod supporting the lens.

In any thermodynamic cycle analysis, the work output strongly depends on the temperatures of the heat source and sink with which a system communicates. In an ideal Stirling cycle, the working fluid is isothermal during expansion and compression. In this operating engine, the temperature readings from the hot and cold thermocouples did not measure the same temperature in the working space at any one point in time. Thus, a temperature gradient exists across the working space at all times. In spite of this gradient, it still might be expected that air closest to the sources would affect the work of the cycle. The greater the temperature difference of the hot and cold sides of the working space could contribute to larger amounts of indicated work since the temperatures of the hot and cold source directly affect the work of the cycle.

Figure 5 shows about 20 seconds of temperature data from a single test. During this segment, the temperature fluctuations on the hot side were about 4 deg C, and the temperature fluctuations on the cold side were approximately 12 deg C. As expected, the temperature fluctuations from the two thermocouples are out of phase with one another.

Figure 6 displays pressure (left scale) and working volume (right scale) over the same period as figure 5. It can be observed that the gauge pressure drops below zero in each cycle indicating a slight vacuum in the working space. As necessary to function as a heat engine, the pressure and volume are out of phase. The P-V relationship is plotted for the same data in figure 7. The enclosed area represents the work of each cycle. This engine was operated without any external load for this phase of testing. Therefore, the indicated cycle work is only overcoming internal friction and other losses. Figure 8 shows only the first four cycles plotted with different symbols in order to make the details of the cycle work more visible. Also overlaid in figure 8, shown with a heavier line and no symbols, is a simple P-V prediction based on sinusoidal motion of the displacer piston and output piston with 90 degree phase difference, and scaled to fit the measured volume and pressure.
fluctuations. The overall agreement is forced by the scaling, however, the scaling allows a comparison between the shapes of the measured cycle and the idealized P-V shape. It can be seen that the measured data has a more concave shape during compression and a more convex shape during expansion than the prediction. This may be attributed to the measured phase difference between the displacer and output column being close to 75 degrees while the theoretical model assumed 90 degrees.

Figure 9 shows the cycle work, in lbf-in, for the data displayed in figures 5-7 as well as data for an additional 30 seconds. The work fluctuated, apparently randomly, by about 15% around the mean cycle work. No clear correlation was evident between the cycle work and other cycle parameters.

Figure 10 demonstrates, for the first six cycles of the data presented earlier (for clarity) a plot of the temperature difference between the hot side and the cold side, overlaid onto a plot of the measured pressure. It can be seen that the temperature difference fluctuations are exactly in phase with the pressure fluctuations. This confirms that the dynamic mechanical response of this unloaded engine closely tracks the thermodynamic expansion of the working fluid.

CONCLUSION

The instrumented solar-powered fluidyne test bed demonstrated consistent and repeatable operation. The Fresnel lens used provided ample energy to power the Fluidyne. Efficient heat transfer via concentrated radiative heating by the Fresnel lens put more heat into the system than could be effectively rejected to the atmosphere at the cold side, so the system typically ran unsteadily and needed to be periodically stopped in order to avoid overheating. Nevertheless, quasi-steady data over periods of several minutes could be collected. Indicated work of the engine was collected with pressure and volume measurements. Since the engine was unloaded, this work only overcame frictional losses. The shape of the indicated work in a cycle was compared to the shape of a simple thermodynamic expansion and compression in a Stirling cycle with the same volume and pressure range imposed. The shape was found to differ slightly, and this was attributed to the difference in phasing. Finally, it was found that the dynamic mechanical response of the unloaded engine showed no delay from the thermodynamic expansion due to temperature changes.

REFERENCES


Figure 1. U-tube fluidyne schematic
Figure 2. Fluidyne engine
Figure 3. Fresnel lens and stand
Figure 4. Dimensions of the test bed
Figure 5. Measured Temperatures

Figure 6. Pressure/volume fluctuations and phasing
Figure 7. P-V plot over multiple cycles

Figure 8. P-V Plot Detail
Figure 9. Work per Cycle

Figure 10. Pressure and Temperature Difference