Developments Towards a Liquid Piston Stirling Engine

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The Stirling engine possesses numerous natural benefits such as functioning from any heat source, quiet operation, and high theoretical efficiency. The limited success of Stirling engines has been partially due to the near-adiabatic operation in the working chambers, necessitating external heat exchangers that add dead space, difficulty sealing low-molecular weight gases at high pressure, and non-ideal piston displacement profiles. As a solution to these difficulties, a liquid piston is proposed that allows the compression and expansion chambers to be designed for a high heat transfer rate. The heat transfer in these chambers can be increased through geometry changes, allowable by the ability of a liquid column to fill an irregular volume. Through a simplistic example, it is demonstrated that a liquid piston can improve the heat transfer rate in the working chambers by 3.5 orders of magnitude over a conventional piston. Creating near-isothermal operation in the working chambers eliminates the need for costly external heat exchangers, while creating a secondary path to transfer heat in and out of the chamber through the liquid. The elimination of the external heat exchangers decreases the dead space in the engine, increasing power and efficiency. The liquid piston also eliminates sealing a gas with sliding seals. Finally, the displacement of the liquid pistons can be carefully controlled in a number of ways to closely match the ideal Stirling cycle.

I. Introduction

THE Stirling cycle engine has numerous natural benefits over other heat engines. A prime benefit of the engine stems from the ability to operate from any heat source including continuous combustion of sustainable fuels, solar energy, factory waste heat, geothermal energy, or numerous other sustainable energy sources. Due to the external combustion, a Stirling engine produces little noise, allowing its use in locations that are not preferable for internal combustion engines, such as in homes or buildings for electric power generation or other noise sensitive areas such as submarines. The Stirling cycle also has the theoretical efficiency of the Carnot cycle, creating tremendous development potential.

Despite significant research efforts, the Stirling engine has suffered from a few shortcomings that have prevented greater success. Current Stirling engines are expensive to produce, primarily due to the complex heat exchangers, which are required to heat and cool the gas outside of the working chambers. The need for external heat exchangers is a result of near-adiabatic operation in the compression and expansion chambers, reducing efficiency and power. The addition of external heat exchangers also increases the “dead space” of the engine, defined as engine volume not displaced by the pistons. Dead space reduces the pressure fluctuation, decreasing power and efficiency.

Achieving high power density in a Stirling engine requires high gas pressure and the use of low atomic weight gases such as hydrogen and helium. Sealing these gasses with a mechanical piston is a significant design challenge. While numerous designs have been proposed to solve this problem, the majority of the approaches create a significant trade-off between gas leakage and sliding seal friction.

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The displacement profile of mechanical pistons in kinematic and free-piston Stirling engines leads to additional performance limitations. The majority of current Stirling engines deviate significantly from the ideal Stirling cycle due to approximate sinusoidal piston displacement. This results in a reduction of the area contained within the pressure vs. volume profile, reducing the power output of the engine by not reaching the extreme corners of the ideal cycle.

II. Liquid Piston Operation

As a solution to poor heat transfer in the working chambers and issues of sealing low molecular weight gases at high pressure, a liquid piston system is proposed. A liquid piston is a column of liquid that enters and exits the fixed volume working chambers and allows direct compression or expansion of the gas. Because a liquid can conform to an irregularly shaped volume, the working chamber can be designed to maximize the heat transfer between the gas and the interior geometry by increasing the surface area to volume ratio. Furthermore, the liquid piston eliminates sealing and friction concerns associated with a sliding piston seal.

An existing application using a liquid piston in a Stirling engine is a low-power water pumping engine. The liquid piston in this engine typically consists of a U-shaped tube filled with water that oscillates and acts as the displacer piston, forcing the working gas to move between the hot and cold sides of the engine. During the expansion stroke, water is forced out of the hot side of the tube, creating the pumping action. Water is added to the engine through a check valve during the compression stroke. The primary research in this area has focused on tuning the oscillating frequency of the water columns and designing the engines for operation in rugged environments [1-3]. Further Stirling engine concepts [4,5] and Stirling heat pump concepts [6,7] can be found in patents. These works have not utilized the liquid piston to improve the heat transfer between the gas and the working chamber.

Actuation and control of the liquid pistons displacement profile is possible in multiple ways depending on the domain of power output. One power output option is direct hydraulic power. Through the use of valves, the displacement and timing of the expansion and compression pistons can be directly controlled. Furthermore, a hydraulic accumulator can store a portion of the expansion work to reuse during the compression stroke. An efficient and power-dense hydraulic power source, such as the liquid piston Stirling engine, has numerous applications including: hydraulic hybrid vehicles, construction and agricultural equipment, mobile robotics, and hydraulic hand tools to name a few.

A second power output option is a rotating shaft. The work of the liquid pistons can be transferred to a shaft in multiple ways; one appealing option is a radial mechanical piston with either a crankshaft or a cam interface to the rotating shaft. In this configuration, shown with a cam in Fig. 1, a mechanical piston converts the pressure in the liquid into a force, which is applied to the shaft. Through design of the cam profile, the displacement profile of the piston is controlled, enabling operation near the ideal Stirling cycle. Changing the phase angle between the expansion and compression cams modulates the cyclic pressure in the engine, controlling the power output.

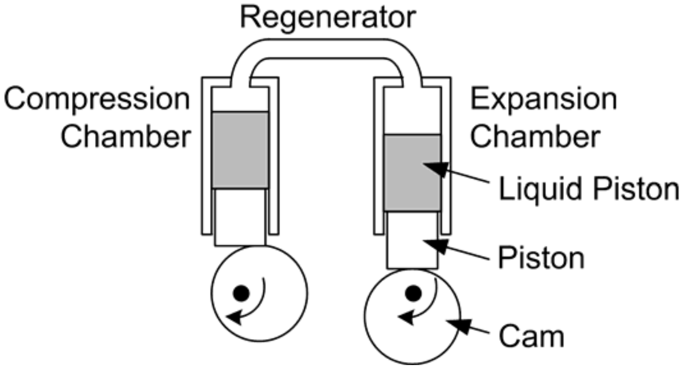

Figure 1. Cam driven liquid piston Stirling engine. *Design of the cam profile allows direct control of the displacement function of the expansion and compression pistons. The engine power is modulated by controlling the timing of the two cams and thus the pressure fluctuation. Note*

that the internal geometry of the chambers occupied by the liquid pistons is designed to maximize the heat transfer between the gas and the chamber while minimizing the viscous drag.

The seal between the mechanical piston and the liquid piston can be achieved in multiple ways. As demonstrated through hydraulic motor design, tight tolerance mechanical pistons are a low-leakage and low-friction solution. A second option is to incorporate a metal diaphragm, such a proposed by Schreiber and Geng [8]. A third option is the use of a roll-sock diaphragm that eliminates leakage by maintaining a fabric reinforced elastomeric seal. The authors are currently exploring a concept to design a roll-sock diaphragm system where the cross-sectional area of the piston varies with stroke to enable further control of the displacement profile of the liquid piston.

A third possible output power option for future development is an electric generator. By using a conductive liquid for the liquid piston, a magneto-hydrodynamic generator can be created that converts the kinetic energy of the liquid column into electricity in the presence of a magnetic field.

III. Benefits of a Liquid Piston Stirling Engine

A. Heat Transfer

The primary benefit of implementing a liquid piston in a Stirling engine is the dramatic improvement in heat transfer within the working chambers. The heat transfer is improved by changing the internal geometry of the working chambers to increase the surface area to volume ratio. For a demonstration of the possible improvement in convective heat transfer, consider the following simplified example.

The working chambers of a Stirling engine are subdivided into many small diameter vertical cylinders, which are occupied by the working gas and simultaneously displaced by the liquid piston. A comprehensive analysis of the convection heat transfer requires accounting for the non-uniform fluid velocity, developing flow, pressure waves, and thermal gradient across the gas. For a rough estimate of the heat transfer rate, a first order study will use a fully-developed pipe flow analysis. The flow regime is determined from the Reynolds number:

$$\mathrm{Re} = \frac{\dot{x}_m \delta}{\nu} \tag{1}$$

where $\dot{x}_m$ is the mean gas velocity, δ is the characteristic length, which is the diameter of the piston, and ν is the kinematic viscosity. For pipe flow, a Reynolds number less than approximately 2300 indicates laminar flow, a Reynolds number greater than 4000 indicates turbulent flow, and intermediate values signify transitional flow [9].

To determine the convection coefficient, the average Nusselt number can be expressed in terms of the Reynolds and Prandtl numbers by:

$$Nu = \frac{h\delta}{k} = a\,\mathrm{Re}^m\,\mathrm{Pr}^n \tag{2}$$

where Nu is the Nusselt number, h is the convective heat transfer coefficient, k is the thermal conductivity, Pr is the Prandtl number, and a, m, and n are constants. Across a wide range of operating temperatures, the Prandtl number is approximately 0.7 for most gases. The three constants in Eqn. (2) vary with flow regime and have been determined both empirically and experimentally. For laminar flow in a pipe, $a = 0.664$, $m = 1/2$, and $n = 1/3$. For turbulent flow, $a = 0.023$, $m = 0.8$, and $n = 0.3$ [9]. Solving Eqn. (2) for h yields:

$$h = \frac{k}{\delta} a\,\mathrm{Re}^m\,\mathrm{Pr}^n \,. \tag{3}$$

The heat transfer rate from the gas to the chamber is calculated using Newton's law of cooling:

$$\dot{Q}_{conv} = hA\left(T_s - \overline{T}_g\right) \tag{4}$$

where $\dot{Q}_{conv}$ is the heat transfer rate, A is the surface area of the chamber, T_s is the surface temperature of the chamber, and $\overline{T}_g$ is the average gas temperature. Recognizing that a given chamber volume with a defined stroke can be created with fewer large diameter cylinders or many small diameter cylinders, the surface area per volume ratio is described as:

$$\frac{A}{V} = \frac{2\pi rl + 2\pi r^2}{\pi r^2 l} = \frac{2}{r} + \frac{2}{l} \tag{5}$$

where r is the individual cylinder radius and l is the length of the working chamber.

For the example, the compression side of a Stirling engine will be considered, represented by the parameters presented in Table 1. The example compression chamber will use helium as the working gas at a temperature of 300 K and a pressure of 10 MPa. For individual cylinder radii less than 0.8 mm, the flow remains laminar, while cylinder radii above this size results in turbulent flow. For reference, the Reynolds number for a 0.1 mm radius cylinder is 236, while the Reynolds number is 70,000 for a 30 mm radius cylinder.

The increase in the heat transfer coefficient due to decreasing the individual cylinder radius is readily apparent in Fig. 2. The improvement in the heat transfer rate due to decreasing the cylinder radius is demonstrated in Fig. 3, which is a log-log plot of the convection coefficient multiplied by the surface area to volume ratio as a function of radius. In both of these Figures, a distinct step is present at the transition to turbulent flow, resulting in a decrease of the heat transfer rate. On the lower right of Fig. 3, a circle marks the value for a single conventional cylinder with the bore diameter equal to the stroke. The square placed in the upper left of the plot, represents a reasonable cylinder radii to balance the improvements in heat transfer with the increased viscous drag, as discussed in a previous work by the author [10]. For this specific condition using Paratherm NF® as a liquid piston, the viscous pressure drop is approximately 69 kPa (10 psi). The difference between these two points is an increase in the heat transfer rate of 3.5 orders of magnitude as a result of increasing the surface area to volume ratio.

Table 1. Parameters for heat transfer example problem.

Parameter	Symbol	Value	Units
Mean Gas Velocity	$\dot{x}_m$	3	m/s
Kinematic Viscosity (Helium at 300K and 10MPa)	ν	1.27x10-6	m2/s
Thermal Conductivity (Helium at 300K)	k	0.150	W/m/K
Stroke Length	l	60	mm

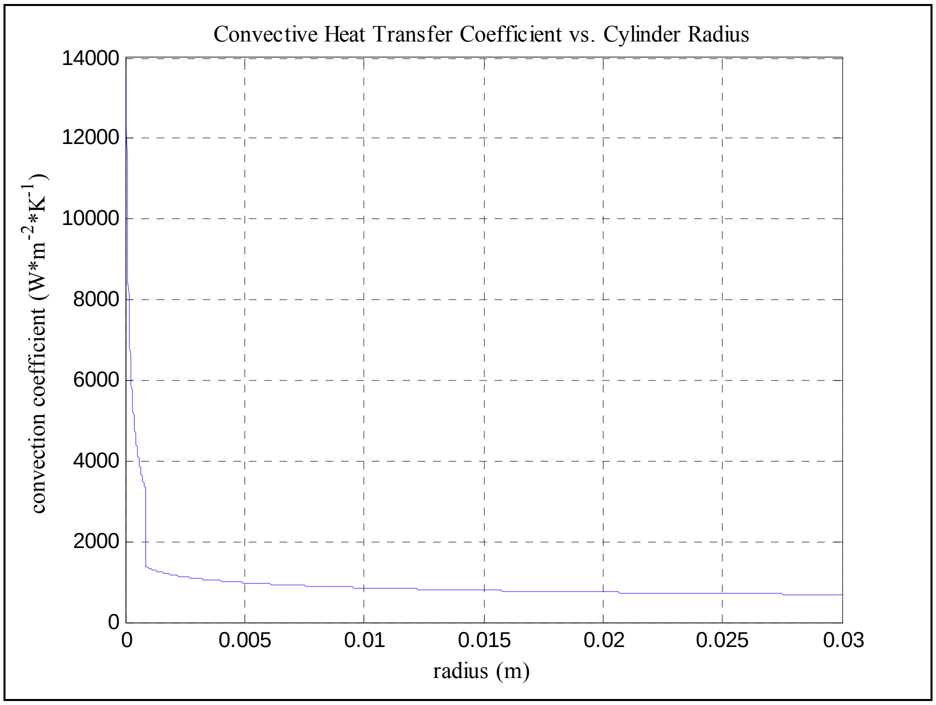

Figure 2. The convective heat transfer coefficient demonstrates a significant decrease with increasing cylinder radius. The discontinuity in the curve is due to the transition to turbulent flow at larger cylinder radii.

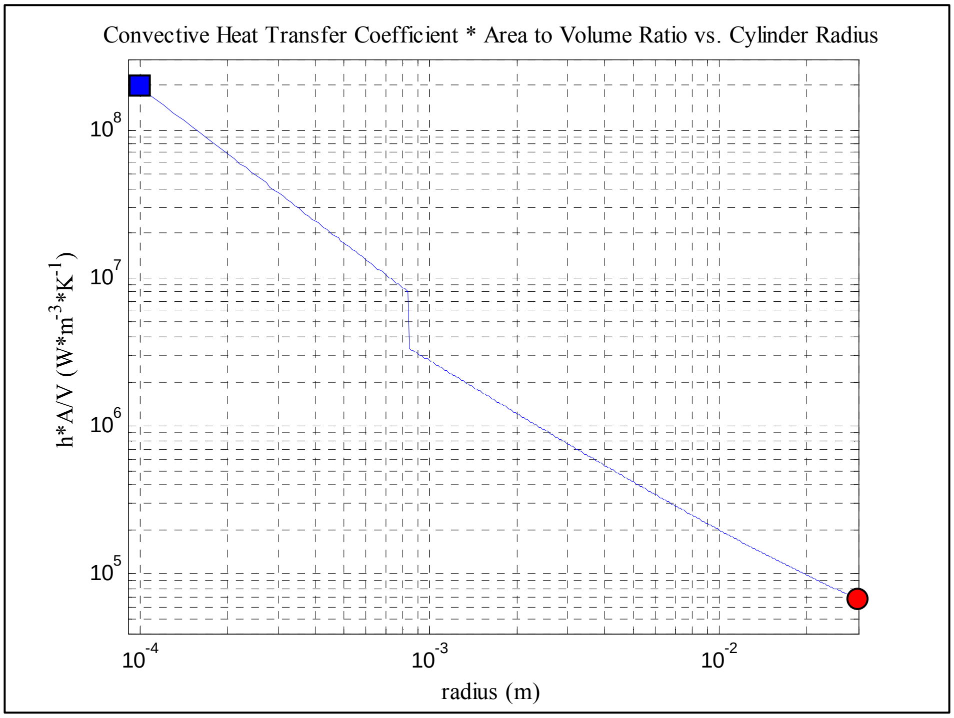

Figure 3. Log-log plot of the convective heat transfer coefficient multiplied by the area to volume ratio as a function of the cylinder radius. The circle in the lower right denotes a single cylinder with the diameter equal to the stroke. The square in the upper left denotes many 0.1 mm diameter cylinders. The sharp drop in the curve represents the transition to turbulent flow.

The drastic increase in the convective heat transfer rate within the working chambers allows the auxiliary heat exchangers found in conventional Stirling engines to be eliminated. Eliminating the heat exchangers reduces the dead space in the engine, which increase the compression ratio and thus the power. The combination of increasing engine power and decreasing the system volume improves the overall power density. Furthermore, experimental and analytical research has shown that increasing the dead space, especially on the hot side of the engine, decreases the engine efficiency [11-13]. Eliminating the complex external heat exchangers will also considerable decrease the manufacturing cost of the engine.

As discussed by West, previous attempts at improving engine efficiency by marginally increasing the heat transfer in the working cylinders yielded negligible results due to the transient heat transfer losses from operating between adiabatic and isothermal conditions [14,15]. It is expected that the 3.5 orders of magnitude improvement in the heat transfer rate will enable near-isothermal behavior in the working chambers, and thus a significant improvement in engine efficiency.

The above example created a high surface area to volume ratio through the use of many small diameter cylinders. This was done primarily to enable the simplification of a pipe flow analysis. In actual application, the surface area to volume ratio can be increased through a variety of internal geometries such as wire mesh, fins, or fine wire bundles.

In a conventional Stirling engine, heat entering or leaving the gas must be transferred through heat exchangers or the chamber wall. The liquid piston system also allows heat to be transferred into and out of the working chambers through the liquid. For example, on the expansion side of the engine, the liquid column can be heated directly. When the liquid column fills the working chamber, as occurs during every cycle of the engine, heat from the liquid is transferred to the internal geometry of the chamber. When the liquid piston retracts, the gas enters the space previously occupied by the liquid piston and the heat is transferred to the working gas.

B. Piston Displacement Profile

The ability to design the piston displacement profile is another major benefit of the liquid piston Stirling engine. As previously discussed, the approximately sinusoidal piston displacement profiles of the majority of conventional kinematic and free-piston Stirling engines compresses the area within the pressure vs. volume plot, decreasing the work output per cycle. By tuning the displacement profile of the liquid pistons through cam design or valve control, the cycle can be extended to the corners of the ideal cycle. The sinusoidal cycle overlaid with the ideal cycle is presented in Fig. 4. By closely approximating the ideal cycle through piston displacement tuning, the engine power and efficiency are increased.

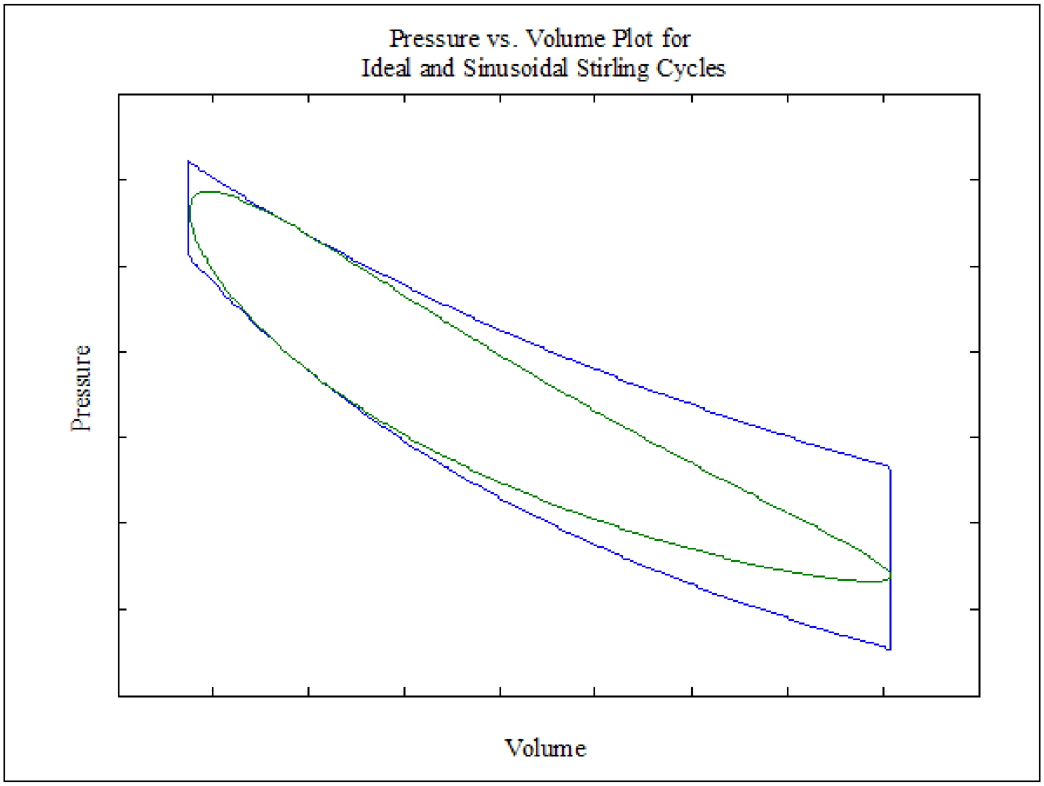

Figure 4. Pressure vs. volume plots for the ideal and sinusoidal Stirling cycles. The outer curve with the constant volume sections is the ideal Stirling cycle while the curve for the cycle with sinusoidal displacement of the expansion and compression pistons is the inner continuous curve. Note the increase in area contained within the curve for the ideal cycle, corresponding to an increase in work per cycle.

C. Liquid Piston Sealing

Another major argument for using a liquid piston in a Stirling engine is sealing high-pressure, low-molecular-weight gases without sliding seals. Because the power output of a Stirling engine is directly proportional to the average gas pressure, high power engines need to operate at a high working pressure. The use of low molecular weight gases such as hydrogen and helium further augments the sealing challenge, often resulting in substantial energy loss due to sliding friction of linear seals [13]. This issue has been addressed in some engine designs through unique sealing methods, which often add cost and complexity [16]. The ability to increase the working gas pressure without increasing detrimental sliding seal friction enables further increases in engine power and efficiency.

Finally, because the liquid piston engine replaces high friction sliding seals with an oscillating liquid column, the wear on the engine is drastically decreased. This leads to a reliable and low maintenance engine with a long operational life.

IV. Complexities of a Liquid Piston System and Future Work

The liquid piston Stirling engine offers many exciting research challenges to enable its realization. The research topics revolve around the operation of the liquid piston and include issues from selection of the liquid to the behavior of the liquid column to the actuation of the liquid piston.

As discussed, increasing the surface area to volume ratio in the working chambers decreases the size of the flow passages. To maximize the efficiency of the liquid piston, the viscous frictional forces and the heat transfer must be optimized. Cursory work has already examined this issue from a steady-state fully-developed pipe flow analysis and found that a realistic optimal exists for the liquid piston chambers [10]. Due to the small size of the passages in the working chamber, the flow occurs at low Reynolds numbers, where viscous forces are dominant. To improve the understanding of liquid piston chambers, this work needs to be expanded to a computational fluid dynamics model that removes the simplified steady-state fully-developed assumptions. This model can then be used as a design tool for the Stirling engine.

As the operating frequency of the liquid piston Stirling engine is increased, surface instability, or splashing of the liquid column becomes a concern. Further work needs to be done to understand whether the surface tension of the liquid is sufficient to maintain the stability of the surface and how the geometry of the working chamber affects this issue. If this is deemed to be a problem that cannot be solved through geometry changes, other methods, such as baffles or other separators, can be used to remove the liquid from the working gas.

A second research issue arising from the direct contact between the liquid column and high gas pressure is gas entrainment in the liquid. In a hydraulic system, gas entrainment decreases the bulk modulus of the liquid and can lead to cavitation in low pressure areas of the system. This issue can be addressed through a variety of manners. First, the working chamber needs to be designed to minimize splashing of the liquid as discussed above. Second, the liquid needs to have a low gas solubility, to minimize the gas entrainment.

Another area requiring additional research is the selection of a liquid for the liquid pistons. The liquid must be stable across the temperature range of operation, have low viscosity to minimize viscous friction, have a high thermal conductivity, have low gas solubility, have a low toxicity, and be compatible with the other materials in the engine. The selection of a liquid for the hot piston is especially challenging due to the high desired operating temperature. A few liquid options being explored include coolants for high temperature reactors such as synthetic organic fluids, silicone fluids, and non-toxic eutectic alloys such as Field's metal which melts at 62ºC.

Because the temperature of the liquid in the expansion and compression chambers is drastically different, the liquid in the working chambers, especially the hot chamber, will need to be isolated from the hydraulic fluid to prevent loss of thermal energy. This isolation can be achieved with an insulated diaphragm that separates the liquid piston fluid and the hydraulic fluid while allowing transfer of pressure.

V. Conclusion

The Stirling cycle engine has numerous natural benefits over other engines, including the ability to operate from any heat source, enabling alternative energy options. A few technical challenges have prevented widespread success of the Stirling engine including manufacturing cost, limited power density, and efficiency values not reaching the theoretical potential. Prime sources of these limitations includes adiabatic operation in the working chambers necessitating expensive external heat exchangers that add dead space, non-ideal piston displacement profiles, and challenges sealing low molecular weight gases at high pressure.

Implementing a liquid piston in a Stirling engine provides a solution to the three primary limitations. Because a liquid can conform to an irregularly shaped chamber, the surface area to volume ratio in the working chambers can be greatly increased. This increase in surface area can result in increasing the heat transfer rate by 3.5 orders of magnitude over conventional working chambers. Creating near isothermal operation in the working chambers eliminates the need for external heat exchangers, increasing the compression ratio and thus increasing the efficiency and power density of the engine. The liquid also provides an auxiliary path to transfer heat in and out of the gas.

The nature of the liquid pistons also allows multiple domains of power output with direct control of the piston displacement profile. Power output domains range from direct hydraulic to rotating shaft to electrical power generation. These various interface domains all allow control of the displacement profile of the liquid pistons to approximate the ideal Stirling cycle, improving power and efficiency. Because of the direct pressure transfer from the liquid to the gas, the need to seal high pressure low molecular weight gases with a linear seal is eliminated.

While implementing a liquid piston in a Stirling engine has numerous advantages, there are multiple research challenges that need to be addressed. These challenges include modeling the behavior of the liquid piston with particular attention to the viscous forces, surface stability, and gas entrainment in the liquid. Furthermore selecting an appropriate liquid for the temperature range of operation with the desired characteristics is a significant challenge. Interfacing the high temperature liquid piston to the power output becomes an additional design challenge requiring some form of sealed insulator with minimal mechanical energy loss.

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