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Performance analysis of a miniature free piston expander for waste heat energy harvesting

C. Champagne, L. Weiss *

Institute for Micromanufacturing, Department of Mechanical Engineering, Louisiana Tech University, Ruston, LA 71272, United States

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ABSTRACT

Initial experimental analysis of a small-scale Free Piston Expander (FPE) is presented. In final form, the FPE will be a MEMS-based device capable of operation from low temperature waste heat sources. Currently, a millimeter scale device is constructed and tested to yield insight into critical operational parameters for use in later design and testing.

Operating conditions are examined to increase operational performance. Piston stroke length and repeatability are considered. Optimized variables include piston length and mass, FPE shape and size, input pressure, and lubrication. Construction of this testbed device is via concentric copper tubing, allowing an effective baseline study of these determining parameters.

Results show that, while thick lubricants seal well in static configurations, piston motion is decreased in dynamic testing, indicating leakage. By contrast, reduced viscosity lubricants prove ineffective as sealing agents during static conditions, however, yield increased piston motion in dynamic testing with little leakage around critical piston sealing surfaces. The trends established by the study of varying viscosity lubricants hold true for pistons of increasing mass and length as well. A mixture of isopropanol and water performed well in these tests, and represented a low viscosity sealing fluid, which was used in later repeatability tests. Repeatability tests were performed in a closed dynamic environment on FPE designs with multiple cross sectional shapes and areas. Results from these tests show that circular FPE's are more precise than square FPE's. The final closed system tests yield a pressure–volume curve indicative of an engine cycle as a first look at thermodynamic cycle operation from the FPE.

1. Introduction

Future population growth and energy consumption place a growing demand on efficient energy use as a whole. Demand for both increased efficiency and environmental responsibility is increasing and will continue as global population expands. The U.S. Department of Energy has predicted that, compared to 2006 levels, global energy demand will increase up to 44% by 2030 [1]. This places high demand on the development of alternative energy sources as well as increased emphasis on clean, affordable energy production. Increased energy sustainability is of critical importance to these efforts. In 2010 alone, the United States consumed 98 quadrillion BTUs of energy while the transportation sector was responsible for more than 28% of that total [2].

There is significant research underway across a wide variety of fields to address these growing challenges. Traditional sources of clean energy like solar, wind, and geothermal are of increasing interest. Another potential source for power production is through sources like waste heat. Waste heat is thermal energy that is rejected to the surrounding environment as a result of a larger process. Automotive exhaust heat is one example. It has been estimated that typical Otto Cycle efficiency is on the order of 35%. The bulk of the remaining energy is rejected via cooling or exhaust sources [3]. This represents a source of significant opportunity for thermal scavenging. Through the capture and reuse of this thermal energy, overall efficiency is increased and energy consumption reduced.

There have been several approaches to this type of energy scavenging. Among these has been the investigation and application of thermoelectric generators (TEGs). Dependent on the Seebeck effect, these represent a solid-state solution to energy scavenging with no moving parts [4]. Although materials have varied, early examples relied on poly-SiGe or pure poly-Si [5,6]. Temperature gradients of 5–10 K were utilized to produce electricity from the TEG. A drawback to this approach has been the general efficiencies associated with TE devices. Typical efficiency for a standard TEG is on the order of 5–10% [7]. This presents an opportunity to study other, alternate devices.

Small scale heat engines have been under investigation by a variety of researchers for a number of years. One of the first examples was a micro-scale steam engine produced by Sandia National

* Corresponding author.
E-mail address: lweiss@latech.edu (L. Weiss).

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Labs in 1993 [8]. Other investigators have pursued high-speed rotational designs reliant on the Brayton, Rankine, and Otto Cycles [9–13]. These have typically been powered by high temperature sources, on the order of several hundred degrees Centigrade. Lower temperature operation of Rankine-type devices have been proposed as Organic Rankine Cycle (ORC) systems [14,15]. These operate across lower temperature gradients more consistent with waste heat sources. Unlike true Rankine Cycles, ORC devices utilize refrigerants like HCFC-123 due to the lower temperature sources. A common challenge to the micro-scale operation of any of these systems is the associated high speed rotation. Bearing wear and stability concerns are among the engineering technical challenges [16]. Other challenges relate to fluid viscosity acting on the small scale turbine blades [9]. Despite these challenges, work continues on these unique small-scale devices [11].

An alternate approach to high speed rotation has focused on flexing-expanding membranes [17–19]. In this approach, a cavity was filled with refrigerant that boiled at temperatures on the order of 50 °C. Two micron thick membranes surrounded the cavity top and bottom. Heat was introduced through the lower membrane causing the refrigerant to evaporate. This increased the internal pressure and drove membrane expansion. This approach successfully eliminated high speed rotation and allowed operation from lower temperature thermal sources. A drawback was the need for an external thermal switch to periodically introduce heat to the lower membrane [20]. This allowed the engine to cycle and perform useful work.

In this present work, a Free Piston Expander (FPE) is considered for use with low temperature thermal sources as a means for thermal energy scavenging. Advantages include a lack of rotating parts as well as the ability to operate within a thermodynamically "open" system. In this manner, the device may generate useful power output from a continuous stream of pressurized working fluid, similar to a rotating device. Previous works on small-scale free piston engines have relied on internal combustion in an Otto Cycle approach [21,22]. Some inherent challenges include the surface area quenching effects of miniature combustion.

This paper considers an alternative free piston approach that eliminates combustion as the driving force, relying instead on external combustion from a boiler to produce pressurized vapor, or steam, to drive the engine. The boiler operates from low temperature waste heat sources while the FPE provides the final power output. The device itself is capable of expanding pressurized working fluid through the motion of a linear piston. Once expanded, the piston returns to its initial point through a changing pressure balance within the piston bore. This cycle has been discussed in detail in previous work [23]. Fig. 1 illustrates the basic concept.

In Fig. 1, the piston is bounded by two membranes that provide work output. Pressurized working fluid is introduced to the intake port, yielding a piston motion towards the primary membrane and exhaust port. A unique piston skirt ensures the intake port closes as the piston moves from the starting position. The primary membrane expands as the piston compresses the volume, driven by the initial pressure input from the intake port. The piston begins to return toward the second membrane as forcing pressure drops and the exhaust port is opened. Upon return to the starting position, the piston is again exposed to pressurized vapor and the cycle repeats.

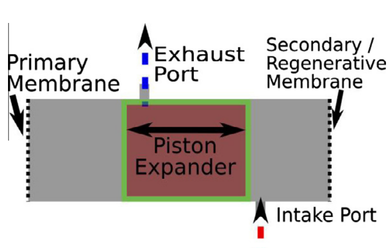

Fig. 1. Free piston expander setup.

In final constructions, pressure will be provided by a unique micro-boiler currently under development [24]. The FPE itself will be a fabricated device capable of production as part of typical MEMS batch fabrication processes [18]. In this present work, initial experiments and characterizations are performed on a larger, millimeter scale device to yield important insight to future production and design. This also represents a low cost approach to achieving a useful device. Dimensions and design of the present, millimeter scale FPE rest on the foundation established through prior modeling effort [23]. This study aided in operating expectations based on factors like potential friction due to liquid shear or operating pressure. It was expected that experimental efforts would diverge from this initial modeling due to an increase in base piston diameter, however.

As with the prior modeling effort, in this new experimental work the FPE utilizes pressurized air to simulate steam pressure from a boiler system in a controlled and repeatable manner. In this manner, overall operation of the FPE is simplified and basic piston motion from pressurized air is studied based on parameters that include mass, forcing pressure, and sealing/lubricating liquids around the piston itself. Based on these results, future work will progress toward microscale development and batch fabrication of this unique device.

Understanding and characterization of piston motion is critical in this device as part of the larger energy scavenging and power output system. Optimizing piston motion is of particular importance to the operational parameters of the FPE, as decreasing frictional losses will increase the overall efficiency of the system and alter fundamental characteristics like stroke length, velocity, and acceleration within the FPE. Three different experimental setups were used for determining characteristics of piston motion and lubricant ability to facilitate this motion. Multiple lubricants were examined for two primary aspects: the ability to seal around the piston and prevent leakage, and the ability to promote piston movement. Experiments were established to determine how much of a leakage barrier a lubricant would provide for a given size and shape of a piston, and to show how much a given lubricant would impede the motion of a piston given variations in piston length and mass. Experimental results were supplemented by an analysis of piston motion using a well established model of fluid dynamics.

2. Experimental methods

To assess the performance of lubrication within a FPE system on an experimental basis, three experimental test setups were performed. The first experimental setup tested the performance of a lubricant in a static system: i.e. no piston motion. A pressure difference was induced across a piston while the piston was held static, and sealing of the lubricant was measured using a pressure sensor on the side of the bore not directly connected to the pressure input. The rate at which the opposite side became pressurized gave an indication of the sealing abilities of lubricant in a static environment. The second test showed the sealing of a piston in a dynamic environment by allowing the piston freedom to move linearly within the bore. The piston was sealed on one side and open on the opposing side. An impulse pressure was induced on the sealed side, allowing the piston to move. The piston motion was recorded with a laser vibrometer and the impulse pressure was recorded with a pressure sensor. In a final test, the piston was fully sealed in the bore and an impulse pressure was utilized to initiate motion