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Investigations of a new free piston expander engine cycle

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ABSTRACT

This work examines the design and operation of a new, small-scale FPE (Free Piston Expander) engine that operates using low temperature waste heat sources to produce useful power output. The FPE is based on a sliding-piston architecture that eliminates challenges associated with MEMS-based rotating systems. A nonlinear lumped-parameter model is derived to study the factors that control the performance of the FPE engine and its unique operating cycle. This basic analysis considers a closed cycle operation of the FPE with low thermal or heat inputs and dimensions on the order of several millimeters. Key system design and operating parameters such as piston mass, external load, and heat input are varied to identify conditions and trends for optimal performance. The model indicated the pressure-volume diagram resembles a constant pressure cycle for a certain set of operating conditions but is also condition dependent. Increased heat inputs to the FPE reduced the engine natural or operating frequency while increasing the power output. Thermal efficiencies of the FPE are shown to be predictably low, on the order of 0.2% due to the small heat input and operating temperature gradients associated with waste heat. Key design features are identified that reveal FPE efficiency, operating frequency, and output power are dependent on piston mass, external load, input heat-rate, and duration of heat input.

1. Introduction

There are many significant challenges that influence energy supply, policy, and future consumption trends. At the heart of these challenges is increased worldwide energy consumption. The U.S. EIA (Energy Information Agency) has predicted that world consumption will increase 56% by 2050 compared to 2010 levels [1]. In the midst of the predicted energy consumption growth exists a competing need to reduce GHG (greenhouse gas) emissions [2]. There is acknowledgment that renewable energy supplies will provide a growing contribution to worldwide energy needs, however, traditional non-renewables will remain a significant source for the foreseeable future [1]. This indicates a continued need for traditional cycle efficiency and thermal management improvement [3].

Thermodynamic cycles operating from non-renewable sources include the standard Otto cycle with average efficiency of about 35% [4]. The majority of energy is lost to the surrounding environment as low temperature waste heat via heat rejection. This reality is similar for other industrial-based uses of energy [5,6]. Through the capture and reuse of rejected 'waste' energy, it is possible to both increase the operating efficiency of the base cycle as well as reduce GHG (Greenhouse Gas) emissions [5].

The work in this article examines the design and operation of a new, small-scale engine designed to operate from these low-temperature sources using a unique thermodynamic cycle. The FPE (Free Piston Expander) engine operates via modified steam cycle, similar in nature to an ORC (Organic Rankine Cycle), or even direct thermal or heat input. Through focus on a small, millimeter-scale engine, it is possible to use the device across multiple types of thermal sources and applications. For example, a single device may be utilized to scavenge small thermal energy amounts for individual sensor power. By contrast, many FPE engines may be combined in parallel to scavenge thermal energy from larger, industrial size sources.

A microfabricated boiler as well as heat exchangers and other required system components are already under investigation to support the FPE. Thapa et al. investigated a unique MEMS-based boiler using both experiment and computational analysis [7]. Heat exchanger research has been conducted using traditional microfabrication materials and methods, like silicon [8]. In this work, the use of capillary channels was the primary means for fluid

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transport. Relatedly, unique materials and fabrication processes that included electroplated porous nickel [9] or copper [10] have been under development. The option of thermal energy storage for a system of this type has also been investigated using paraffin wax as the storage media [11]. The nature of the FPE and the harvesting system itself allows different working fluids to be substituted for application to a variety of sources and real-world applications.

As part of this scavenging system, the FPE produces useful power output that may be either mechanical or electrical depending on setup and application need. In final form, electrical output may be achieved through the use of piezoelectric materials that flex as a result of piston motion [12] or via linear generator output. The FPE represents a small-scale device with many key dimensions on the order of millimeters. Many components of the device, however, are consistent with common microfabrication techniques and advantages [13].

One of the traditional challenges of power generation on the MEMS or microscale has been the effective management of combustion processes [14]. The feasibility of sustained combustion has been limited by high surface area to volume ratios that exist within miniature combustion systems [15]. Wang et al. investigated the miniaturization limit on internal rotary combustion engines [16]. Miniaturization of these devices considered losses including mass loss by seals as well as thermal losses. Reduced compression ratio reduced mass loss, or “blow-by,” leading to increased efficiency as length scales diminished. The ability to maintain effective operating pressures and low-loss internal sealing remains a key challenge.

For this reason, some research has pursued devices and approaches that are based on external power sources that drive output. These approaches and devices take many forms that have included phase-change actuators that rely on external thermal inputs [17]. Pneumatic actuators have also been of interest on the small scale as a further alternative [18]. Phase change steam engines have also been investigated including a micro Newcomen device [19].

A secondary challenge has been the ability to fabricate and operate high-speed rotational systems that include Brayton or Rankine cycle devices [20]. Key among the challenges to this approach is the limitation of decreasing rotor size [21]. Below key threshold values, the Brayton cycle and Rankine cycle require alternative designs for typical viscous flows.

Rankine cycle efforts have leveraged the advantage of external combustion for the high speed system. System design and modeling [22] as well as fabrication of critical components like microturbopumps [23] have been conducted. Silicon was the material of choice for these efforts, relying on advanced MEMS and microfabrication techniques. Limitations have paralleled those present in high temperature Brayton cycle efforts and include layer stress reliefs in the fabrication process, external thermal boundary controls, and gap geometry during operation [24]. When applied to a lower temperature energy source, as is the case with many waste heat sources, the use of the ORC (Organic Rankine Cycle) has also been studied on the small scale [25]. This approach removes challenges associated with elevated temperature operation, however, remains an engineering challenge for fabrication and production.

Microengines without rotation have included microbubble actuators utilizing capillary channels [26] and membrane-based thermal actuators that produced mechanical power output through internal phase change of a low boiling point working fluid. The unique nature of this membrane-type design was further studied for operation approaching the Carnot cycle [27].

In experimental efforts, the ability of the membrane-based actuator to operate at resonant frequency generated a unique working cycle as a result [28]. The general form of these devices utilized one lower membrane with thickness on the order of 1 μm and an upper membrane of similar thickness, separated by a cavity volume about 75 μm thick. The cavity was filled with working fluid that boiled at low temperature. External heat was added through the lower membrane to generate liquid to vapor phase change. This resulted in increased device volume. When operated at resonant frequency, the pressure and volume changes inside the cavity rose and fell 90° out of phase, producing the unique thermodynamic engine cycle. This unique engine and process was modeled by Bardaweel et al. [29].

Free Piston Engines have been the subject of research and general application for decades on the large scale and in a variety of applications [30]. These engines traditionally consist of a piston within a bore that is free to move between the cycle top-dead-center (minimum volume) and the bottom-dead-center (maximum volume) without mechanical linkage or constraint that is typical of traditional reciprocating engines. This variable compression ratio feature allows fuel flexibility. Applications have varied on the larger scale with internal combustion as the primary driving force. Mechanical outputs have included hydraulic pressure with the free piston used as a linear motion pump [31] as well as electrical power generation. Unique solutions to valve timing and modeling have been investigated due to the lack of rotating components in the basic FPE design [32].

This lack of rotation has made the FPE of interest to the small-scale because it works around many of the aforementioned micro-power challenges. Further, the driving force may be either internal or external combustion. This makes its use attractive for sources like waste heat. Various prior approaches have been executed in both modeling and experimental efforts. Early efforts were presented by Aichlmayr et al. and considered internal combustion in a HCCI (homogeneous charge compression ignition) approach [33,34]. This test reaffirmed the challenge to provide precise control of the combustion environment to limit cold surface quenching and manage heat release even in this non-rotating, small-scale application. More recent work has considered the uses of a catalyst wall within the combustion chamber of a micro-FPE that relies on HCCI [35]. This numerical effort showed a basic improvement in energy conversion though a decreasing compression ratio due to advanced ignition versus a non-catalytic design. Indicated power output was also increased via this approach. Bai et al. continued efforts at HCCI modeling and established a unique model that predicted the required kinetic energy of the piston to achieve ignition [36]. As with other combustion-centered free piston work, controlling factors included projected sealing leakage as well as accurate equivalence ratio mixing.

Zhang et al. studied a novel ‘swing engine’ piston approach that moved the free piston in an arc [37]. FPSE (Free Piston Stirling Engines) have also been considered and modeled with respect to scaling and operation [38]. Among the opportunities for this design was increased power density, however, energy loss through heat as well as sealing within the engine were among the challenges. Additional approaches include replacing the traditional piston-cylinder assembly with a compliant architecture to facilitate the free-piston motion [39]. In this regard, nonlinear lumped parameter engine models and prototypes have been tested to predict engine dynamics and engine performance [40,41].

Initial results of an external combustion, low-temperature steam cycle FPE (Free Piston Expander) engine have also been investigated with bore dimensions on the order of a few millimeters [42]. A laser-vibrometer was used to track piston position in the bore as a function of forcing pressure. The natural frequency of the device was approximately 33 Hz.

The past decades have seen continuous progress and the inherent challenges of power production on the small-scale. In the