Operation and Testing of A Micro Heat Engine

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ABSTRACT

The operation and testing of an external-combustion, micro heat engine, the P^3 micro engine is presented. In particular, measurements are given for low frequency operation of the micro heat engine. Production of electrical power by a dynamic micro heat engine is demonstrated. The prototype micro heat engine is an external combustion engine in which thermal power is converted to mechanical power through a novel thermodynamic cycle. Mechanical power is converted into electrical power through the use of a thin-film piezoelectric membrane generator. This design is well suited to photolithography-based batch fabrication methods and is unlike any conventionally manufactured macro-scale engine. A peak-to-peak voltage of .84 volts, and power output of 1.5 microwatts have been realized at operating speeds of 10 Hz.

Keywords: MEMS Power, Micro heat engine, piezoelectric generator.

1 INTRODUCTION

High energy density micro power generation systems are needed for a growing number of portable electronic and MEMS devices. The energy densities of existing electrochemical batteries are too low (around 1 kJ/g) to sustain the power needs of MEMS devices for long periods [1]. A typical liquid hydrocarbon fuel holds around 50 kJ/g in its chemical bonds [2]. However, the development of a micro-scale device that can efficiently convert this chemical energy into useful electrical power is challenging. Among the micro-scale concepts to generate electrical power using the chemical energy of hydrocarbon fuels now being explored are fuel cells, static heat engines and dynamic heat engines.

On the macro-scale, dynamic heat engines have achieved greater success than either fuel cells or static heat engines. This success is in large part because dynamic heat engines are more fuel flexible than fuel cells and have achieved higher conversion efficiencies than static heat engines. For these reasons, a variety of designs for micro-scale dynamic heat engines have been advanced. These include a gas turbine (Brayton cycle) engine [3,4], a micro rotary internal combustion (Otto cycle) engine[5] and a micro heat engine based combustion driven reciprocating liquid piston (Otto/Diesel cycle)[6]. Each of these dynamic heat engines are internal combustion engines.

Work at WSU has been directed toward the development of a MEMS power system based on a dynamic heat engine that is driven by an external heat source, the P^3 micro heat engine [7,8]. Since micro-manufacturing methods excel at producing many identical copies of two-dimensional structures, the engine design is a modular, two-dimensional architecture. The P^3 micro engine produces electrical power by employing a three-part strategy. First, thermal power is conducted into the P^3 engine from an external heat source. Second, thermal power is converted to mechanical power through the expansion and compression of a two-phase working fluid by the oscillation of a flexible membrane. Third, mechanical power is converted into electrical power through the use of a thin-film piezoelectric (PZT) generator.

2 MICRO ENGINE DESIGN

The design of the P^3 micro heat engine is based on a two-dimensional modular architecture. An individual module or unit-cell engine consists of a cavity filled with a saturated, two-phase working fluid, and bounded on the top and bottom by thin membranes. The top membrane of the cavity is a thin film piezoelectric membrane generator.

Heat is alternately conducted in and out of the two-phase working fluid, through the thin membranes capping the cavity at top and bottom. As heat is conducted first into and then out of the working fluid, the quality and volume of the saturated mixture first increases and then decreases. As a consequence, the upper membrane, which is fabricated of a piezoelectric thin film, acts like a piston in a conventional large-scale engine. Instead of sliding in and out, however, the piezoelectric thin film membrane flexes in and out. In this way, the piezoelectric membrane acts alternately as a generator/expander and as an actuator/compressor during the engine cycle. The useful output of a unit cell engine is the electrical power generated by the piezoelectric membrane as it is strained during expansion of the two-phase working fluid, minus the power consumed by the membrane during the compression of the working fluid.

The working cycle of the micro heat engine may be approximated with four ideal processes: (1) compression, (2) isothermal, isobaric high temperature heat addition, (3) expansion and (4) isothermal, isobaric low temperature heat rejection.

Two key points are crucial to understanding working cycle and engine operation. First, the PZT membrane generator is a spring which stores both mechanical and electrical energy. During the expansion process, only the fraction of energy stored as electrical energy is extracted from the membrane generator as useful power. The balance of the energy, the strain energy, remains stored in the membrane generator to be used during compression. Second, the engine is designed to operate at resonance so that the energy stored in the spring during expansion is available for compression.

A power supply can be constructed of a single unit-cell engine or an array of many unit cell engines combined together. This modularity gives great flexibility in the assembling of energy conversion devices. Combined in parallel, the unit cell engines are driven by the same temperature difference. Combined in series, the unit cell engines form a cascade so that each unit cell engine is driven by a fraction of the total temperature difference across the entire cascade. Heat is transferred to and from an engine via a thermal switch.

3 PROTOTYPE FABRICATION

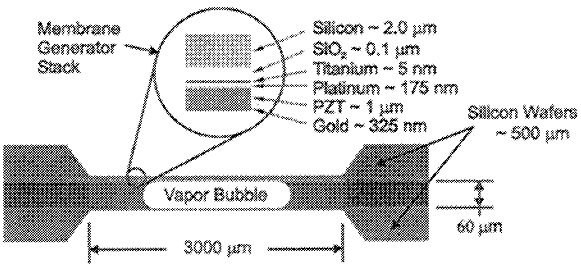

Fig. 1. Cross section of engine.

The fabrication of a prototype unit-cell heat engine, a "proof of concept" device, is illustrated in Fig. 1, which shows a cross section of the device. The prototype micro heat engine consists of three components: a top thin-film piezoelectric membrane generator, a middle spacer which defines the engine cavity, and a bottom silicon membrane. A two-phase mixture of the working fluid, Fluorinert, fills the engine cavity.

The upper and lower membranes are fabricated from (100) silicon wafers. On the back side of the wafer, photolithography defines the square membrane shape within the oxide layer; and an oxide etch exposes the bare silicon. EDP (ethylene diamine pyrocatecol) is then used for an anisotropic wet etch to create pyramidal cavities in the silicon wafer. Membrane thickness is controlled with a Boron etch stop. Silicon membranes with side lengths ranging from 1.45 to 4.0 mm and thicknesses ranging from 0.5 to 3.0 μm have been fabricated.

The silicon membrane now serves as a substrate on which to fabricate a generator stack. A bottom electrode of 5 nm of titanium followed by 175 nm of platinum is deposited on the silicon in a sputtering process. PZT is then spun onto the platinum in a sol-gel process [9]. One layer of PZT (at 90 nm per layer) is spun onto the wafer and pyrolized at 450 °C for two minutes to burn off organics. Two more layers of PZT are deposited in the same manner, after which the total of three layers of PZT are crystallized

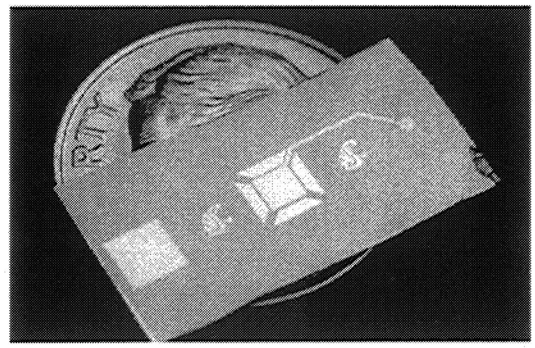

Fig. 2. Completed piezoelectric membrane generator.

at 700 °C for 10 minutes. Thicknesses of PZT between 250 nm and 2 μm can be readily achieved. A 5 nm layer of TiW is sputtered, followed by a 325 nm layer of gold to make the top electrode. Photolithography is used to pattern the top electrodes and the PZT, which allows contact to the bottom electrode and improves membrane durability.

The engine cavity is defined through the use of a spacer between the membrane generator and heater membrane. Presently that spacer is fabricated out of semiconductor tape. The diameter of the engine cavity is determined by the size of the hole cut in the tape. The cavity depth is determined by the thickness of the tape, nominally 60 microns thick. An engine is assembled, by clamping a spacer between a membrane generator and a heater membrane. The cavity thus formed is filled with the working fluid, Fluorinert.

In the final micro heat engine, thermal switches will be used to execute the heat addition and heat rejection from hot and cold sources. In the first realization of this engine however, thermal switches have not been incorporated. For engine testing heat is periodically applied to the silicon membrane to simulate the action of a thermal switch. There is no active heat rejection.

4 RESULTS

A test facility has been developed to characterize the performance of the micro heat engine and its components [10]. An interferometer is used to measure the deflection of the thin film membranes. A silicon membrane with an embedded micro resistance temperature detector (RTD) is used to measure temperatures inside the engine during operation. Pressure in the engine can be determined from the deflection of the lower, silicon membrane [11]. The voltage output of the PZT membrane generator is measured by connecting voltage taps to the top and bottom electrodes of the PZT stack.

Membrane generator performance is tested independently of the engine in a bulge test facility [10]. The PZT membrane is subjected to a periodic pressure wave to simulate engine operation. The PZT membrane deflection and voltage output are monitored during testing.

The membrane generator voltage output is proportional to the strain produced in the thin film PZT membrane when it is deflected. As shown in Fig. 3, by adding successive layers of PZT (90 nanometers per layer), the PZT output at a given deflection can be substantially increased. At 40 μm of deflection 12 layers of PZT produced 0.47 V, while 18 layers of PZT produced 0.70 V (a 49 % voltage increase). The majority of data throughout this paper refers to a membrane generator with 1.08 μm thick PZT (or 12 layers). The ability to deposit more layers of PZT during sol-gel

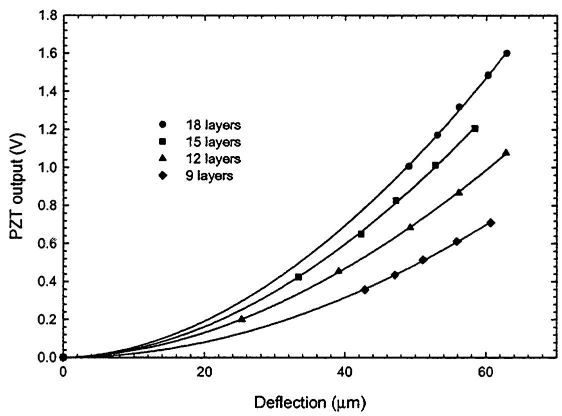

Fig. 3. PZT output versus deflection for various layers of PZT.

fabrication gives incremental control of device voltage output and power production and provides a method to optimize membrane generator performance.

Dynamic testing of the engine is performed by subjecting the engine to a periodic heat pulse that results in deflections of the PZT membrane. In Fig. 4 the engine is being driven by a 10 Hz, 50% duty-cycle heat pulse. The PZT membrane generator produces 800 mV peak to peak. Temperatures vary over 8 °C during engine operation as shown in Fig. 5.

The power produced by a prototype micro heat engine can be determined by dissipating the electrical output from the membrane generator across a load resistance. A variable load resistor is used to match the impedance of the generator. Figure 6 shows the voltage drop across the load resistor and the power produced versus load resistance. A peak power of 1.51 microwatts is seen at a load resistance of 190 kohms for an engine running at 10 Hz. Increasing the voltage to the heater driving the engine to 2.8 volts increased the maximum power generated by the engine to 2.1 microwatts.

These data represent the first demonstration of electrical power production from a dynamic micro heat engine. The target operational speed for this engine is 500 to 1000 Hz with power outputs in the range of 0.1 to 1 mW. Power output can be increased by: (1) optimizing the PZT membrane generator characteristics, (2) increasing the

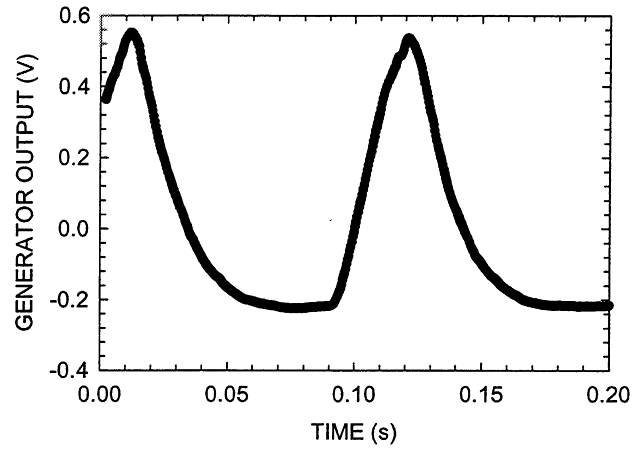

Fig. 4. Voltage output (V) during engine operation at 10 Hz.

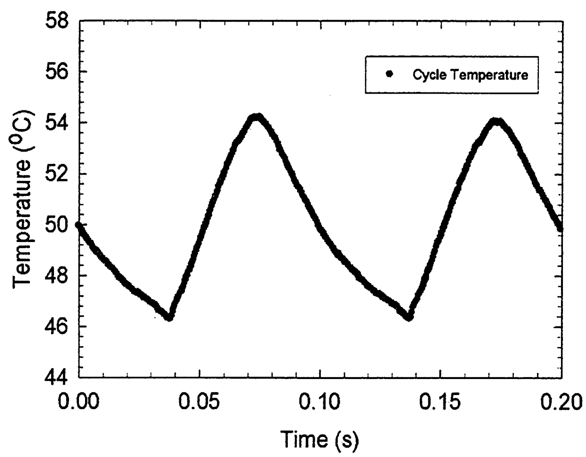

Fig. 5. Temperature inside engine cavity (°C) during engine operation at 10 Hz.

speed of operation, and (3) incorporating a thermal switch. The voltage produced by a PZT membrane generator when strained is crucial to the engine performance. The PZT thickness is directly related to the voltage output. Membrane generator output voltage increases linearly both with PZT layer thickness and with PZT maximum strain. This demonstrates one clear path to increasing the voltage output of the membrane generator. As the operating frequency of the engine increases, the power produced increases for two reasons. First, as operating frequency increases more power cycles are completed in a unit time. Second, as the resonant frequency for the engine is approached, the membrane undergoes larger deflections for the same applied force. As a result, as the operating frequency approaches the resonant frequency, large increases in power are realized. The resonant frequency can be modified by changing the properties of the PZT generator stack and membrane geometry. A thermal switch, which is now under development, is necessary to allow

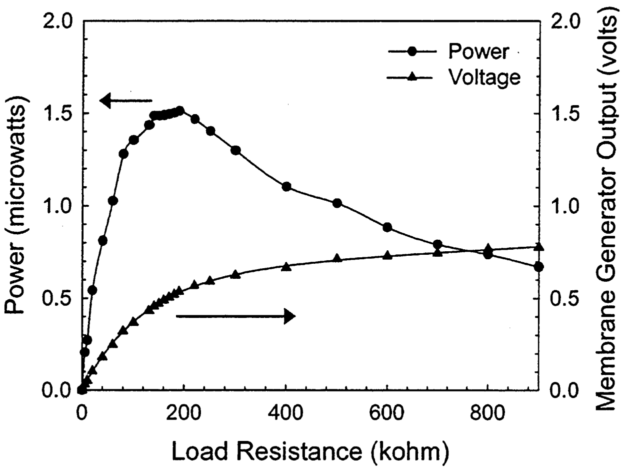

Fig. 6. Power and voltage versus load resistance during engine operation at 10 Hz.

faster engine speeds and to realize the full cycle outlined earlier in the paper.

As discussed above, operation of the engine at the system resonance is desired for maximum power output. The resonant frequency of the engine can be tuned by placing a resonant cavity above the membrane generator [11]. Currently resonators that control engine resonance between 150 and 400 Hz are in use. The electrical output of a membrane generator of an engine with such a resonator is shown in Fig. 7. The plot shows the open circuit peak-to-peak voltage as a function of engine cycle frequency. A resonant peak occurs near 240 Hz. Incorporation of a thermal switch will allow operation at higher engine speeds and thus engine resonance will be tuned upward.

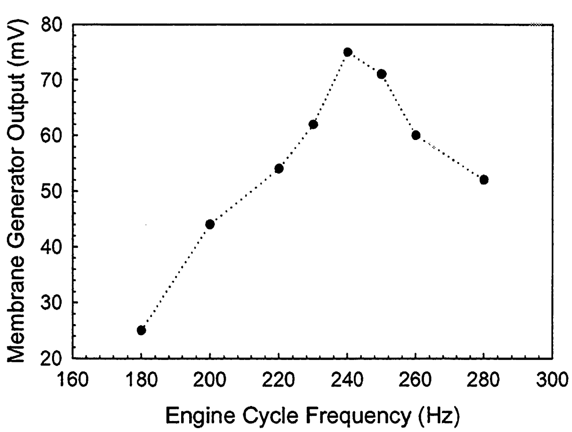

Fig. 7. PZT membrane output versus engine cycle frequency.

5 CONCLUSIONS

The design, fabrication and testing of a micro heat engine for MEMS power has been presented. The micro heat engine is an external combustion engine, in which thermal power is converted to mechanical power through the use of a novel thermodynamic cycle. Mechanical power is converted into electrical power through the use of a thin-film piezoelectric membrane generator. This design is well suited to photolithography-based batch fabrication methods, and is unlike any conventionally manufactured macro scale engine. Measurements of PZT membrane voltage, temperature and deflection made during engine cycling have been presented.

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