MISTIC - Micro Stirling Heat Engines for Thermal Energy Harvesting

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Abstract. This paper reports on the fabrication and validation of the piston assembly for a new micro heat engine based on the Stirling cycle, (MISTIC - Micro STIrling Clusters), intended for electric power generation by harvesting low temperature waste heat ($\leq 200^\circ$C). Here, we define the requirements, develop the fabrication processes and fabricate piston assemblies to show the feasibility. Static and dynamic response of the pistons show that high quality factors ($Q>100$) are achievable with the polymer structures and the natural frequencies of adjacent pistons can be matched (within 4 percent), two characteristics required to allow start-up of the engine. We also demonstrate an electromagnetic actuator that is capable of individually exciting the pistons to further facilitate start-up.

1. Introduction

Current waste heat recovery systems typically rely on the Seebeck effect, which efficiency is typically low [1]. The Stirling cycle is an attractive alternative since its potential efficiency is higher and it can benefit from scaling effects [2]. In this work, we present the Micro Stirling Cluster (MISTIC), a free-piston Stirling micro-engine dedicated to thermal energy harvesting from low temperature heat dissipating systems ($\leq 200^\circ$C). The device consists of a stack of layers that encloses an array of mm-scale pistons with polymer membranes and planar heat transfer chambers, as shown in figure 1. One side of the stack is in contact with the heat sources while the other side is cooled. The heart of the device is an array of cylindrical magnets supported on both ends by polymer membranes, forming free-pistons. This core layer is sandwiched between planar heat exchangers to form chambers on the cold and hot side of each piston. When gas in the hot chamber is heated and expands, it applies a pressure force on the membrane, which pushes the membrane towards the cold side. Over time, if the system symmetry forces are enough, the pistons motions synchronize with each other with a phase of $120^\circ$, implementing the Stirling cycle. This novel Stirling engine configuration was analyzed previously [3, 4], leading to the requirements for start-up and the current design.

This paper presents the fabrication process developed to build a MISTIC prototype and the experimental characterization of the core piston component. We first discus the material
properties and geometry to achieve the required mechanical and thermal characteristics. Then, we present the entire bonding and assembly method developed and implemented especially to build a MISTIC prototype. Static and dynamic characterization of the pistons will be presented, validating the proposed fabrication approach and device configuration.

In addition, we designed and built an external electromagnetic actuator (EMA) to compensate the losses during its start-up phase. Preliminary tests showed the ability of the actuator to drive the micro-engine’s magnetized pistons.

2. Requirements

To meet the initial goal of demonstrating the start-up of a MISTIC engine, certain fabrication and operation requirements must be met. From a dynamics perspective, the pistons should have a sufficient quality factor to exhibit resonance (more than 10) and adjacent pistons should have similar natural frequencies. Thermally, the heat exchangers must allow fast heating or cooling of the working fluid (kHz range) with minimal pressure drop. Also, the materials had to remain stable over the operating temperature range from 20°C to 200°C. Mechanically, the assembly should sustain an internal pressure up to 5 bars and be sealed to retain the working fluid (He).

The electromagnetic technology used for the actuation led to integrate magnetized pistons between the membranes. The heat exchanger layers (HXs) that cover the membranes must not shield to magnetic field and should avoid the induction of undesirable eddy currents that would warm involuntarily the cold side of the prototype. To better characterize the device operation during testing, the membranes could also be instrumented with strain gauges (SG) and/or the piston displacement measured optically, with transparent heat exchangers. Internal temperature measurement should also be tracked, so the integration of RTDs is desirable.

3. The MISTIC micro-engine

The prototype is made of three sub-assemblies (figure 1): the hot exchanger, the cold exchanger and the core composed of two polymer films, two baseplates, the frame, three pistons and 6 kapton shims. The heat exchangers are made of a sapphire plate (thermally conductive and transparent) and an alumina sheet with a cut out for the chamber and fins. The working gas is helium. To ensure that the working chambers’ sealing is hermetic enough to sustain 5 bars of gas pressure, a thin PDMS layer was applied on the membranes as a gasket.

Figure 1. a) CAD exploded view of the Stirling micro-engine layers; b) Top view of a MISTIC; c) Sectional A-A view, 90° rotated.
3.1. Fabrication processes for individual components

The fabrication approaches developed for the various parts are summarized in figure 1. The two baseplates, the six kapton shims and the HXs parts have all been directly cut on an excimer laser (LPKF protolaser U3), part way from both sides. The laser path width was 20µm, giving a good accuracy for the cut. The pistons are made of N40 magnet, mechanically milled to reach a length of 2.3mm ± 5µm. The frame was mechanically machined in ceramic (Macor).

The membranes consist of polyimide sheets, on which RTDs and strain gauges are first fabricated, then the membrane shape is cut by laser. The thin film sensors are deposited by subsequent evaporation of 50nm Cr, 450nm Al, 50nm Cr, through a laser cut alumina shadow mask.

![Figure 2. Fabrication processes for the MISTIC parts](image)

3.2. Bonding and assembly

Figure 3 shows the dedicated process used to bond two parts together, while the complete assembly sequence is illustrated in figure 4. The parts were bonded with an epoxy (B-4811, Reltek) selected for its high temperature resistance and very good adhesion on ceramics and polymers. An iron jig with three alignment pins is used to align the parts while they are bonded, while also avoiding magnetic interaction between the magnetized cylinders during this assembly phase.

![Figure 3. Aligned bonding method for two layers](image)

Considering the small size of the device, the capillary forces of the epoxy are significant during the cure and can lead to unwanted migration of the epoxy. Hence, it is important to find the minimal thickness of epoxy to avoid to plug any aperture. Also, we need to maintain the surface flatness between the two parts. A successful bonding is characterized by ≤ 10µm of epoxy thickness and ≤ 10µm of total thickness variation, measured on 5 random points.
4. MISTIC characterization

4.1. Characterizations of the piston static and dynamic response

To validate that the proposed configuration and fabrication process can lead to adequate pistons, static deflection tests as well as dynamic responses tests were conducted on the prototypes. The force versus displacement of the core piston assembly was tested under static loading conditions using a texture analyzer (TA.XTPlus). We noticed that the membranes can support a displacement of 400 $\mu$m pp of the piston at room temperature, without plastic deformation. Also, we observed that close to the piston’s neutral position, the membranes had a small non linear deformation range. Hence, Kapton shims are added to each end of the cylindrical magnets to prestress the membranes during the assembly, leading to a linear behavior at zero displacement.

We also performed preliminary dynamic characterization of an assembled core. In order to do so, we used a piezoelectric actuator (figure 5.a) to shake the pistons and observe their response (figure 5.b). We used an optical probe (Philtec D12), in addition of the strain gauges, to see the movement of the pistons trough the sapphire windows. The three membranes exhibited natural frequencies of 1135$\pm$50 Hz and quality factors above 100. These results confirm that the polymer membranes can exhibit low mechanical dissipation and that the fabrication and assembly method leads to pistons with very similar resonance frequencies. In fact, the results are also consistent with the analytic models made by Formosa [3].

4.2. The electromagnetic actuator

Although inertial excitation is convenient for individual piston characterization, starting the engine requires out of phase excitation of the pistons. Electromagnetic transduction was selected
since it leaves the MISTIC design largely unchanged. Besides, it can operate at high temperature, carefully choosing the curry temperature of our magnet. The magnetic E-core design illustrated in 6 was computed on FEMM software to find a shape optimizing the magnetic flow through the piston. So we fabricated a custom made actuator to fit in our prototype (figure 6.b). We choose to use two counter polarized coils to facilitate the actuation and the control sequences.

Figure 6. a) FEMM simulation of the piston behaviour under EMA drive; b) CAD view of a MISTIC micro-engine with 3 EMA ; c) Measurement of the forces applied by the EMA on a MISTIC piston

We measured the motion of a piston, without HXs, under the EMA drive. The first results demonstrated that it was able to produce forces up to 400mN peak to peak(pp) on the piston (figure 6.c) at the resonance frequency. In these tests, the average current inside the coils was 200mA. Furthermore, this force was enough to reach 70-80% of the maximal piston stroke, which is fixed by the dimensions of a working chamber (5mmx200µm).

5. Conclusion
This MISTIC prototype is the first of its kind to have been designed and fabricated by dedicated and reproducible bonding and assembly processes, aiming to implement the Stirling cycle in a miniature, planar configuration. First characterizations on assembled pistons show that they have good quality factors and matching resonant frequencies between the cylinders. In addition, the custom made electromagnetic actuator has been able to drive the micro-engine pistons individually, which will be helpful to start-up the engine. Once the engine will be operational, it will also allow the generation of electrical power from the engine. This work therefore validates key elements required to start-up and harvest energy using a Stirling micro heat engines.

References
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