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Development of a MEMS-Based Rankine Cycle Steam Turbine For Power Generation: Project Status

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Abstract

This paper summarizes de challenges, prospects, and status of the on-going project to develop a MEMS-based microturbine device that implements a steam Rankine power cycle for portable power generation. First, the device configuration is motivated by a discussion of the unique characteristics of the Rankine cycle. Progress to date on the development of the rotating and thermal subsystems is then presented along with areas of future work.

Keywords : Micro power generation, Microturbine, Micropump, Two-phase flow

1 - INTRODUCTION

Over the past decade, various projects have been initiated to create miniature heat engines, such as micro gas turbine engines ([1]-[2]), internal combustion engines (rotary [3] or piston [4]), and thermally-actuated piezoelectric power generators [5]. Within this effort, we have undertaken the development of a microturbine device that implements the Rankine vapor power cycle using silicon microfabrication and microelectromechanical systems (MEMS) technology. This centimeter-scale device will miniaturize and integrate all the components required for power generation, forming a power-plant-on-a-chip. Fed by a small fuel tank, this microturbine device would act as a portable electric power source, effectively replacing or complementing rechargeable batteries broadly used today in consumer electronics, power tools, distributed sensors, or robots. If developed with sufficient efficiency, fuel-burning micro heat engines could increase the autonomy, range, and/or performance of applications currently using batteries. The operating principle of this device is also amenable to harvesting energy from waste heat. One can therefore envision dime-size engines heated by the sun that endlessly power environmental sensors or engines extracting heat from the exhaust gases of automobiles to drive on-board electronics.

To evaluate the potential of a new technology for such applications, a quantitative understanding of the device performance and limitations is required. We have therefore undertaken the project of developing the core technology for a microfabricated Rankine device to demonstrate its feasibility, understand its limitations, and create a knowledge base for the design of such devices. In this paper, we present a progress report on the development to date, along with the challenges and prospects of the technology.

2 - DEVICE DESCRIPTION

The configuration for a complete micro Rankine power source consists of a heat source (burner with fuel tank or waste heat), a cooling mechanism (cooling fan or other heat removal approach), the MEMS-based micro Rankine device and power electronics. The Rankine device itself consists of a steam-driven turbine that entrains a liquid pump and an integrated generator, along with a compact evaporator and a condenser. These components implement the Rankine power cycle, used in the vast majority of fossil-fueled or nuclear electrical power plants. The working fluid (typically water) is pressurized in liquid state, evaporated with the addition of heat from the external source, expanded through the turbine to provide mechanical power, and condensed back to liquid state. The proposed concept consists of miniaturizing and integrating the Rankine device using lithography, deep reactive ion etching, and aligned bonding of silicon and glass wafers (Figure 1, [6]). The device takes a planar form with dimensions on the order of $1cm^2$ x 3 mm thick. Previous system-level studies suggest that an output electrical power of 1-12 W could be possible with overall energy conversion efficiencies ranging from 1-10% [7].

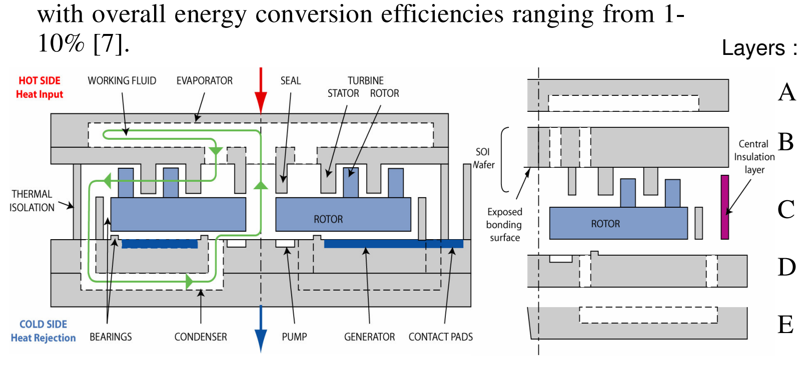


Figure 1 - Schematic cross-section of the Rankine steam turbine device formed of five micromachined layers.

3 - CHALLENGES AND BENEFITS OF THE RANKINE CYCLE

Cycle characteristics - Since this device is based on a thermodynamic cycle, the predicted performance values are greatly dependant on the heat source and sink temperatures. High evaporator temperatures are preferable, which consequently suggests pressures as high as 10 MPa (critical point of water is at 22.1 MPa, 375°C). Superheating the working fluid beyond the saturation temperature (up to 400-800°C) can significantly increase the cycle efficiency and is commonly done is large scale power plants; this approach is also adopted for the proposed Rankine microturbine. The maximum temperature is however limited by the material properties, since heat must be provided to the working fluid through a heat exchanger, unlike gas power cycles (such the Brayton and Otto cycles in gas turbines and internal combustion engines) which generate heat through combustion directly in the working fluid.

Since the Rankine cycle is characterized by relatively high operating pressures, the static structure must be designed with sufficient mechanical strength. The turbine must also expand this large pressure ratio, forcing the design towards a multistage configuration. For conservative aerodynamic designs, we expect that it is possible to extract approximately 1W per stage for 24 mg/s mass flow of steam, and that a maximum of 5 concentric stages per rotor can be well matched. Higher power levels (or higher pressure ratios for the same flow rate) are possible with multiple rotors per chip [7].

Another important characteristic of the Rankine cycle is the potential for closed loop operation. It can operate on pure, filtered working fluid to prevent potential blockage of small clearances with particles or fouling in the microchannels. Management of two-phase flow in a closed microsystem comes with its own set of challenges. Achieving complete evaporation (droplet-free) and superheating before the vapor enters the turbine are critical. The compact volumes envisioned preclude gravity separation of liquid and vapor phases. The condenser exhibits a similar technical challenge, with the requirement of preventing vapor from entering the pump. The closed-loop configuration also introduces the need to remove high heat fluxes from the condenser side of the chip (up to 50W / cm^2), which can be achieved with forced convection over optimized heat sinks [8]. Alternate external cooling approaches would however be preferable, such as evaporative cooling or conduction into a larger structure.

Losses - Losses in the system also directly impact the overall device efficiency, and must be minimized. These losses can be separated in three main categories, all of which become increasingly challenging at small scale: 1) core component efficiencies; 2) power consumption of auxiliary components (such as bearings, seals, or cooling fans); and 3) heat loss within the components, or bypassing the cycle (such as heat leakage through the static structure).

Fortunately, many characteristics of the Rankine cycle are favorable, compared to other cycles. First, the working fluid is compressed in liquid form, which dramatically reduces the power requirement. For example, the pumping power is less than 1% of the turbine output power hence pump efficiency is not critical. A spiral groove viscous pump has been developed for this application, with a maximum efficiency of 5% and exit pressures up to 8 MPa. Second, the external heat source and moderate maximum temperatures in the device (up to 400-600°C) facilitate the thermal management issues. For example, it is possible to use micromachined SiO_2 substrates to adequately isolate the evaporator from the condenser, by restricting the contact area to less than 10% of the chip area. An all-silicon device does not appear viable due to the high thermal conductivity of Si ($k_{Si} > 100\ k_{SiO2}$). On the other hand, the Rankine cycle requires extensive sealing and low friction bearings. For example, liquid must be prevented to enter the outer region of the rotor otherwise viscous drag would become overwhelming (large area and tangential velocities). To keep the turbine efficiency high, it should operate at Reynolds numbers above 500 [9]. This implies minimum rotor diameters on the order of millimeters and tangential speeds in 100's m/s. High speed operation of microturbomachinery is therefore a prerequisite to achieve acceptable efficiency.

4 - ON-GOING RESEARCH ACTIVITIES

Development of a complete and integrated Rankine microturbine power plant-on-a-chip appears as a daunting task. We have started down this path by focusing on the core Rankine microturbine device, and more specifically, on the *rotating* and *thermal* subsystems. Key technologies and concepts are being demonstrated and developed using test devices for each subsystem. A MicroTurboPump is currently under fabrication to explore the multistage microturbine, the spiral groove viscous pump, the thrust and journal bearings, the seals, and the fabrication approach. The evaporator is also pursued as a distinct component. Unfortunately, modeling of two-phase flow in microchannels is not at a state that permits the design of such a component, so the development approach is mostly experimental. The last portion of this article focuses on these two subsystems.

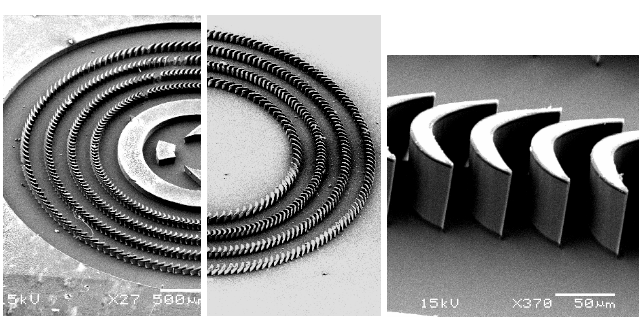
4.1 - Rotating subsystem – MicroTurboPump

A test device to develop the rotating subsystem of the proposed Rankine microsystem has been defined and is currently being fabricated. It will provide a platform for model validation and experimental development of rotating components. The layout of this test device is similar to the proposed Rankine device, but it includes various additions to appropriately characterize its performance. It should be noted that the generator is not integrated in the test device, but instead the turbine's mechanical power is dissipated by a viscous load. A region of small clearance at the outer periphery of the disk was intentionally added to provide significant drag and therefore allow the turbine to operate at typical power levels. The thrust bearings are nominally self-pressurized from the turbine inlet gases. Here, an additional hydrostatic bearing is added in the viscous load area and the journal bearings are externally fed and controlled. To reduce drag in the journal bearing, it would be preferable to locate it on a central shaft, acting on the inner radius of the rotor disk. Unfortunately, design and stability modeling for such microbearing technology is not sufficiently advanced, so we have chosen to use previously demonstrated configurations [10]. The journal bearing will therefore initially be located on the outer periphery of the rotor disk and operated hydrostatically, i.e. from pressurized gas or vapor source.

Unlike the proposed Rankine microturbine, this test device will operate on an open cycle with separate streams for the turbine and pump to allow component mapping. The turbine inlet conditions are reduced to 200°C and 4 atm (with atmospheric exhaust) to alleviate the thermal isolation issues and simplify the device fabrication.

The test device configuration was chosen to be modular, such that various rotors can be tested in the same static structure. Top layers and bottom layers of the device will be bonded separately, dies will then be separated, the rotor will be manually inserted, and the halves held into contact for testing. The device is designed not to require a good seal at the interface between both halves. Alignment is provided by mechanical pin-in-key features directly etched into the wafers.

The multistage turbine configuration requires interdigitated rotor and stator blade rows, which unfortunately, complicates the fabrication. The stator is built from a silicon-on-insulator wafer (SOI) with 50 micron blades etched through the top silicon. The exposed surface of the substrate becomes the mating area for the other half of the device; complete removal of the silicon over all of the chip area is required, expect for the blades and the alignment pins. Scanning electron microscope images of the deep reactive ion etched (DRIE) turbine blades are shown in Figure 2. Blades are 50 microns tall and approximately 100 microns in chord. The short chord was necessary in order to allow multiple concentric stages on a single 4mm diameter rotor, without stage matching problems. Also, a transparent Pyrex wafer is used for the top layer to allow direct observation of the central portion of the rotor and visualization of liquid flow at the exit of the pump. Multiple static pressure measurement taps are also integrated in the device to measure the turbine inter-row pressures and gas bearing pressures.



(a) Rotor (b) Stator (c) Rotor blades

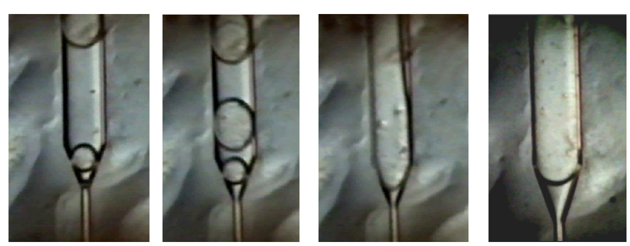
Figure 2 - SEM image of a radial, multi-stage microturbine formed by DRIE.

Two main seals are also required to keep the liquid water at the inner radius of the rotor, one on the pump side and one on the turbine side. They consist of spiral groove seals, similar to the pump, that balance the pressure differences across it and ideally negate the leakage flow. In order to mitigate the uncertainty related to leakage, the seals were over-designed.

As these lines were written, most of the wafer processing was completed for the five layers of the MicroTurboPump, and a completed device is expected by the end of the year.

4.2 - Thermal subsystem

In parallel with the rotating subsystem development, an on-going effort aims at managing two-phase flows in microchannels to ultimately create an evaporator that provides a stable, constant flow of fully-evaporated and superheated steam. Previous investigations of two-phase flow have mostly focused on straight, uniform cross-section area microchannels, and have identified multiples undesirable phenomena, such as bubble formations, flow oscillations, and incomplete vaporization of the exiting fluid. One proposed approach to alleviate these problems consists of evaporating the liquid from a meniscus in a microchannel as opposed to allowing nucleation of bubbles typical of internal flow boiling, and to use surface tension to maintain the meniscus at a fixed location in the evaporator. The later can be achieved by surface treatments and/or shaped channel walls. To explore this concept, simple microchannels have been fabricated by deep reactive ion etching partway into a silicon wafer and bonding a glass cover plate to complete the channel. The channels consisted of pre-heating, evaporating, and superheating zones. They were heated with a resistive heater under the chip and the flow field was observed visually for different operating conditions and geometries. Under very specific operating conditions, stable meniscus evaporation or annular flow was observed in the non-uniform section of the channel, as shown in Figure 3. For a practical Rankine device however, completely evaporated steam and superheated is required over a wide range of operating conditions, hence further development is required. Porous materials will also be investigated.



(a) T_a (b) $T_b>T_a$ (c) $T_c>T_b$ (d) $T_d>T_c$

Figure 3 - Evolution of the internal flow boiling patterns. Bubbles form at the expansion, grow to fill the downstream channel cross-section, then convect downstream (a). At higher wall temperatures, the frequency of bubble formation increases (b), reducing the spacing between them, until stable annular flow is achieved (c). Annular flow rapidly leads to completely evaporated stream downstream of the expansion as the temperature is increased further (d).

A key observation was the need to limit the wall temperature in the regions upstream of the evaporating zone, and allow wall temperatures to rise significantly above the boiling point in a downstream region for superheating. Calculations to date suggest that the use of a SiO_2 wafer is adequate to separate the pre-heating and superheating regions. A thermal test device is currently under development based on this approach. It will be used to evaluate the effect of channel wall shaping, surface treatment, and controlled wall temperature distributions.

5 - OTHER RESEARCH NEEDS

Achieving a complete integrated power plant-on-a-chip will require additional research efforts on topics not discussed above, such as micro-combustors, electromagnetic machinery, and multiple basic research topics.

Micro-combustors - Two types of combustors are envisioned to heat the device: a surface catalytic reactor that provides heat directly by conduction to the evaporator structure, or a burner that provides hot gases (products of combustion) that must initially transfer the heat through convection along the outer surface of the chip. This external component should provide a heat flux of 50-100W/cm^2 at wall temperature in the range of 400-800°C without the need for electrical power (or significantly less than 1W/cm^2). Air circulation could be induced by natural convection (buoyancy forces) and fuel supply by capillary forces.

Electromagnetic micromachinery – Conversion of mechanical power from the rotating disk to electrical power can be achieved with electrostatic or electromagnetic rotating machinery. The generator would be integrated in the multi-wafer device and located on the condenser side of the rotor, over a circular area of 1-2 mm radius. Magnetic generators appear preferable to electrostatic machines since they require a lower number of poles, hence larger pitch and larger clearances between the rotating and stationary parts. The generator should be capable operating at high speeds (100's of m/s tangential speed or 10's kHz) and be integrated within a multi-wafer fabrication process. The rotor structure should be capable of sustaining high centrifugal stresses and operate at moderately high temperatures. The rotor will reside at an average of the maximum and minimum cycle temperatures, hence in the range 200-400°C, which is acceptable for magnetic materials (below or near Curie temperatures). Compact external power electronics are also required to condition the generator output, preferably to DC for portable electronic applications.

Basic research - Further fundamental research will be needed in microturbomachinery (100's micron chord blades, $100<Re<10,000$), micro gas bearings and rotor dynamics, moderate Reynolds number viscous flows ($1<Re<1000$), meniscus evaporation at high rates and flow boiling, and conjugate heat transfer in microsystems (high heat transfer coefficients in small structures). Versatile micromachining techniques for high temperature materials (such as silicon carbide, SiC), and for low thermal conductivity materials (such as glass, SiO_2), would also be enabling.

6 - CONCLUSIONS

Although we have only started to address the myriad of technical challenged that must be overcome to create a micro steam turbine power plant-on-a-chip, the approach appears promising and our experience to date has not uncovered insurmountable barriers. The development effort initiated at Columbia University will be pursued at the Université de Sherbrooke (Canada), with a short term focus on the key subsystems and a long term goal to integrate them into a fully functional device. Multiple topics raised throughout this article will however remain unaddressed, providing exciting research opportunities. Technologies and microengineering sciences developed in the context of the Rankine power generator will also form a knowledge base for future design of a broader range of applications, such as micro-refrigeration systems for electronics or personal cooling, micro steam reformers for portable fuel cells, and hydraulic drives for miniature robots.

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