AN INFORMAL SURVEY OF POWER MEMS

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Abstract: This paper briefly and informally reviews the rapidly growing field of Power MEMS. This term now broadly refers to microsystems designed to produce power or mechanical work. Ongoing research includes heat engines, mechanical-to-electrical-energy conversion devices, and propulsion engines.

Keywords: Power MEMS, microengines, energy conversion

INTRODUCTION

The term “Power MEMS” was first suggested by Epstein and Senturia [1] in 1996 to describe microsystems which generated power or pumped heat. Their particular interest was MEMS heat engines, specifically Brayton cycles (such as gas turbines) and Rankine cycles (such as steam engines) and subsystems thereof. The promise identified was microsystems whose power densities equaled or exceeded those of the more familiar large-scale devices. Since that time, the Power MEMS system has evolved into a broader concept which includes other traditional thermal cycles, new heat engine concepts which may only be attractive at microscale, energy harvesting schemes, and even micro-fuel cells.

Heat engines convert chemical energy into heat and then mechanical work. This mechanical energy may be used directly for applications such as vehicle propulsion or fluid pumping or converted into electric power. For example, propulsion is the goal of MEMS gas turbine and rocket engines, while MEMS gas turbine and internal combustion engines are being developed to power electric generators of various designs for electric power production. Power MEMS also encompasses heat engines which convert chemical energy directly to electrical energy, usually using the thermoelectric effect. These devices may be intended primarily as power generators or may have a different primary function such as fuel reforming for fuel cells with the power generation (or scavenging) being a secondary consideration. Power MEMS also includes devices which convert mechanical energy into electric power. This includes such devices as a self-charging electric watch and heel strike power generators.

The literature of MEMS power systems tends to fall into two categories: (1) descriptions of the overall system concept and its realizations, and (2) progress in the enabling technologies needed to realize such system concepts. The objectives of this review paper are twofold. The first is to informally survey ongoing Power MEMS projects. The second is to note technology challenges common to many of the approaches which may form fruitful research areas.

POWER MEMS REVIEW

Power MEMS devices could be categorized in many different ways. For example they could be viewed by their function: electric power, mechanical power, fluid pumping, or propulsion. They could be viewed by the overall mechanical approach and construction: freely moving parts, flexing parts, or no moving parts. They could be viewed by the thermal environment: high temperature (for example, combustion-driven), ambient temperature (energy harvesting), and space (both high and low temperatures). They could be viewed by the manufacturing technique: batch-processed, foundry assembly versus various degrees of hand assembly. In this review, we have chosen to discuss devices by function, such as power generation, and then within the function, group them by general manufacturing approach. It must be emphasized that this review represents information available in the public literature at the time of writing. Rapid progress can be expected in this field.

ELECTRIC POWER GENERATION

Electric power generation is currently the primary focus of Power MEMS devices, with output power levels ranging over a broad spectrum. At the higher power range (of order 1-50 watts), Power MEMS devices are envisioned to provide portable power for computers and other personal electronics, with both military and commercial applications. At the lower power range (of order 1 milliwatt), Power MEMS devices could power remote sensors or actuators. For the device to be practical, it must perform better than available batteries, with the performance metric typically being some form of energy density. The high expected energy density of microscale
heat engines results from the high chemical energy density of fuels relative to batteries, coupled with sufficiently high chemical-to-mechanical and mechanical-to-electric conversion efficiencies for the device and the relatively small mass of microscale devices that result from scaling. Three types of electric power generation devices are discussed in this section: dynamic heat engines, direct energy converters and mechanical energy scavengers.

Microscale Dynamic Heat Engines

Batch Process-Based Devices

Heat engines derived from traditional silicon-based batch-processed microfabrication is where the field of Power MEMS began. Since MIT began a program to microfabricate a Brayton-cycle-based gas turbine generator, several other groups have initiated programs investigating microscale Brayton-, Rankine- and Otto-cycle heat engines. In developing highly integrated complex devices that push the limits of microfabrication, such as the devices discussed in this section, the designers have several paths that they can take. For instance, one decision that is critical to the ultimate process flow is the degree to which manual assembly will be incorporated. Manual assembly will likely not be practical for a commercial product and it introduces an increased risk of device contamination. However, it can greatly simplify the process flow and allow for integration of materials and subsystems that are not currently possible with a pure batch-processed flow at a MEMS foundry. The devices discussed in this paper include varying degrees of manual assembly.

One of the first Power MEMS devices started was the gas turbine engine project at MIT. This effort focuses on developing the technologies needed for practical propulsion and power production at the 10-100 watt scale [44]. The first turbojet engine demonstration design is shown in Fig. 1. The centrifugal compressor and radial turbine rotor diameters are 8 mm and 6 mm respectively. The compressor discharge air wraps around the outside of the combustor to cool the combustor walls, capturing the waste heat and so increasing the combustor efficiency while reducing the external package temperature. The rotor is supported on a journal bearing on the periphery of the compressor and/or turbine and by thrust bearings on the rotor centerline. Thrust bearings on the centerline and a thrust balance piston behind the compressor disk support the axial loads. The balance piston is the air source for the hydrostatic journal bearing. The thrust bearings and balance piston are supplied from external air sources. The design peripheral speed of the compressor is 500 m/s so that the rotation rate is 1.2 Mrpm. External air is used to start the machine. With 400 micron tall airfoils, the unit is sized to pump about 0.36 grams/sec of air, producing 11 grams of thrust or 17 watts of shaft power. A cutaway engine chip is shown in Figure 2. In this particular engine build, the airfoil span is 225 microns and the disks are 300 microns thick. Both electric and magnetic generator technologies are being developed to use the shaft power to produce electricity. Later versions of the engine are to have the generators integrated into the engine.

Berkeley has been the leading proponent of an Otto-cycle based rotary (Wankel) engine [2,3]. As a proof of concept, the Berkeley group initially built a mesoscale rotary engine out of steel with a rotor diameter of 12.9 mm, machined with wire EDM. This device has spun at 9300 rpm with a measured mechanical shaft power output of 4 W. Berkeley is now developing a microscale rotary engine with a 2.4 mm diameter silicon rotor (Fig. 3). This device will include an integrated magnetic electric generator. Rotors are fabricated separately from the stator and the generator stator includes inserted discrete components, thus high-precision manual assembly is required. The silicon engine includes a silicon carbide

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Figure 1: H₂ demo engine with conduction-cooled turbine constructed from six silicon wafers.

Figure 2: Cutaway H₂ demo gas turbine chip.

Figure 3: SiC coated MEMS Wankel engine components [2].
coating on the rotor that acts as an oxidation barrier and provides wear resistance, a deep 900 micron etch requiring straight sidewalls, and an integrated apex sealing system to reduce circumferential leakage. Berkeley is also developing a thermal package and other ancillary equipment required for this device. The 2.4 mm diameter device is expected to produce ~10-100 mW of mechanical power, and arrays of devices would be used to obtain desired levels of power.

In contrast to the Berkeley and MIT efforts, which are primarily scale reductions of macroscale machines, Washington State University is developing a heat engine based on the expansion and compression of a saturated two-phase working fluid driven by an external heat source [4,5]. This engine, known as the P3, utilizes an external heat source to convert the working fluid to a gas (Fig. 4). The resulting expansion of the fluid flexes a silicon membrane. A thin piezoelectric film on the flexing membrane produces electric power. The engine would operate near the resonant frequency of the membrane (of order 1000 Hz) to obtain peak power. This engine can work over small or larger temperature differences. Thus, this device could be used in an energy-scavenging situation or with an external combustor. Modeling predicts a chemical-to-mechanical efficiency of about half that of the Carnot efficiency. Each of these engines would be a relatively low power device (micro-milliwatt), and cascades/arrays of devices would be used to achieve the level of power desired for a given application.

There are several other devices being developed, with somewhat less published information available. Georgia Tech is developing a silicon-based, combustion-driven, free-piston engine (two-stroke cycle) with integrated electric generator [6,7]. Korea Advanced Institute of Science & Technology is working on a similar free-piston-type engine fabricated from photosensitive glass wafers (Fig. 5) [8,9]. Ritsumeikan University has proposed and begun fabricating a resonant reciprocating Otto-cycle-based engine [10]. Muller and Frechette [11] have analyzed and shown the potential for microfabricated Rankine-cycle steam engines for power generation.

**Other Dynamic Heat Engine Devices**

The need for higher energy density portable power generating devices has led several groups to try to miniaturize large-scale engines using more traditional fabrication methods. These devices do not conform to batch processing, violating one of the seeming selling points of MEMS, and thus require a high degree of manual assembly. For instance, a team led by Tohoku University and Ishikawajima-Harima Heavy Industries is developing a microscale gas turbine generator [12-14]. This device is similar in cycle to the MIT microengine, although it is fabricated out of metals and ceramics using small-scale high precision milling. The rotor has a centrifugal compressor and radial inflow turbine with diameters of 10 mm, connected by a shaft with a diameter of 4 mm. The shaft has a herringbone pattern etched into it, providing a hydrodynamic gas bearing to support the rotor. The target cycle for this device has an electric output of 100 W and an overall chemical-to-electric efficiency of about 5%. University of Tokyo is investigating a similar device, having initially built a 10X model (~80 mm rotor diameter) [15]. M-Dot Aerospace is also developing a similar device [16]. Stanford has developed a 12-mm-diameter silicon nitride rotor containing a centrifugal compressor and radial inflow turbine [17]. The silicon nitride rotor is fabricated by a mold SDM (shape deposition manufacturing) process, and includes a shaft that is supported by ball bearings. This rotor has been demonstrated up to 420,000 rpm, with a design speed of 800,000 rpm.

Katholieke Universiteit Leuven is also developing a microscale gas turbine generator, however their device is EDM machined from stainless steel with an axial flow turbine and centrifugal compressor [18]. The turbine has a 10 mm diameter and the compressor a 20 mm diameter. The turbomachinery is connected by a shaft that is supported by ball bearings. This device has been operated as a turbine-driven generator, producing 44 W of electric power with a compressed air-to-electric efficiency of 16%.

Aerodyne Research is developing a two-cycle, free-piston engine, referred to as the MICE (miniature internal combustion engine) [19]. The device is fabricated in
metal. A 10 W electric output version is 15 mm in diameter by 45 mm long. This engine has produced net electric power output operating with propane. A scaled-up version of this device capable of 500 W is planned. University of Michigan is developing an internal combustion swing engine, which is essentially an oscillatory rotating free-piston engine [20]. The device currently under development is sized to produce 20 W of electric power burning butane. The device is fabricated from steel using wire EDM with a 16 mm long swing arm. The estimated device chemical-to-electric efficiency is 14%. University of Central Florida has analyzed a miniature rotary Wankel engine that is scaled somewhat larger than the device being built by Berkeley [21]. The rotor for this device is 14 mm in diameter and 9 mm thick, sized to produce 20 W of electric power burning JP8. They suggest that this device could be fabricated with either stereolithography or EDM.

University of Tokyo studied the scaling of a Stirling engine to microscale size [22]. They conventionally fabricated an engine from metal with size of order a few cubic centimeters that developed a mechanical power output of 10 mW when the hot side of the engine was raised to 373 K. They suggest that such a device could be used as a micro-actuator or a micro-heat pump, and discuss how this device could be reduced further in scale to be amenable to microfabrication.

Direct Energy Converters

The devices discussed in this section convert thermal energy directly to electricity, and are thus heat engines as well. However, they have no moving mechanical parts. These devices range from higher power devices that include combustors to lower power devices that scavenge thermal energy from their environment. All of these devices use thermoelectric elements to produce electricity. Thermoelectric power generation benefits at small scale due to the increase in surface area-to-volume ratio; however, thermoelectric generator conversion efficiency tends to be well less than that of dynamic heat engines. USC is developing a “Swiss Roll” counterflow heat exchanger and combustor using electrochemical fabrication processes (Fig. 6) [23,24]. They have demonstrated both gas phase and catalytic combustion in their devices with an enthalpy flux of order 50 W at microscale size. This implies that with reasonable conversion efficiency from thermoelectric elements, such a device could produce order 1 watt of electric power. A group at MIT has demonstrated a silicon-based thermoelectric power generator with integrated catalytic combustor [25]. This device has operated to 500°C with a chemical-to-electric efficiency of 0.02% and 75 mW power out. A group at University of Michigan has also demonstrated a catalytic combustion-driven thermoelectric power generator at the microwatt level [26]. Matsushita Electric Works and Tohoku University have demonstrated a catalytic combustion-driven thermoelectric power generator producing 138 mW electric power and a claimed chemical-to-electric conversion efficiency of 3% [27]. Others are developing microscale thermoelectric generators as well [28,29]. Several groups are developing microscale thermoelectric generators aimed at converting waste heat to electric power [30,31]. The thermal gradients here tend to be low and the resultant power goal is of order microwatts.

The MIT group has also developed a thermophotovoltaic MEMS micro-power generator producing 1 mW of electric power with a chemical-to-electric efficiency of 0.08% (Fig. 7) [32]. The potential for microscale thermophotovoltaic devices has also been investigated at UNLV [33].

![Figure 6: Heat exchanger and Swiss Roll type burner intended for power generation system [24].](image)

![Figure 7: Vacuum insulated combustion system as a thermophotovoltaic power system [32].](image)
Mechanical Energy Scavengers

Similar in application to the thermoelectric waste heat converting devices discussed in the previous section, several groups are working on mechanically-based energy scavenging systems. As scavengers, these devices tend to produce low levels of electric power, of order microwatts to milliwatts, depending on size and excitation level. Most efforts in this group aim to convert vibrational kinetic energy transferred to a mass within the device supported on springs to electric power. The electric generator can be electromagnetic by having the vibrating mass be magnetic [34-36], or it can be piezoelectric [37]. A novel scheme was investigated by a group at MIT who developed a microhydraulic transducer driven by a piezoelectric actuator (Fig. 8) [38]. By exciting the actuator, high pressures could be achieved within the transducer. Likewise, by applying pressure to the transducer (by a heel strike, for example), one should be able to extract electric power from the piezoelectric layer, perhaps as much as 1 watt from a 100 kg person.

Other Power MEMS Devices

Several other Power MEMS devices have been developed in which the goal was not electric power generation. A group at MIT fabricated a microscale electric motor-driven compressor [39]. This device had a 4.2 mm diameter rotor and was demonstrated to a rotation rate of 15,000 rpm and a shaft power of 0.5 mW. This device was designed to operate to higher speeds and power levels, and could serve as a platform for a blower, compressor, or pump. Honeywell and University of Minnesota are working on a free-piston knock engine for compressing air [40-43]. This engine was originally conceived as an electric power generator. However, following a development effort that explored silicon-based deep reactive ion etching, LIGA, and EDM, the researchers concluded that the fabrication tools in their current state did not have the precision necessary to achieve an engine-driven generator, but they were sufficient for an engine-driven compressor.

Several groups are developing microfabricated rocket engines. Both solid and liquid fuel engines have been demonstrated. The solid fuel engines consist of two-dimensional arrays of rocket propellant “pixels”. Each pixel, typically several tens of microns square, is ignited by its own, uniquely addressable, electrical squib. When fired, each pixel produces thrust in the micro-Newton range for a few milliseconds. The specific impulse (thrust per unit mass of propellant, a measure of fuel economy) of the units reported to date have been quite low (~ a few seconds). While each pixel can only be fired once, arrays with very large numbers of pixels can, in principle, be fabricated. One intended use of such thrusts is attitude control of very small (kilogram class) spacecraft. These solid propellant array microthrusters can be considered the most developed of the microrocket engines in that they have been flown and demonstrated in space. Future development may yield both much larger arrays and much improved fuel economy.

At conventional large sizes, liquid propellant rocket engines offer the advantages of significantly improved fuel economy at the expense of complex tanks, piping, valves, etc. The same is true at the microscale where complexity can be traded with performance. The simplest fluid propellant thrusters simply exhaust cold gas to produce thrust. Breuer and colleagues at MIT have demonstrated thrust levels below a milli-Newton at specific impulses of a few tens of seconds. The next level up in rocket engine complexity and performance is the catalytic decomposition of a monopropellant such as hydrogen peroxide or hydrazine. At large sizes, specific impulses above 100 seconds are typical. The first such MEMS efforts reported were by the University of Vermont and the NASA Goddard Space Flight Center whose design was based on catalytic decomposition of hydrogen peroxide. The performance levels reported to date are low but should improve as device designs are refined.

One effort at MIT [44,45] is focused on bipropellant liquid rocket engines to realize thrusts of several Newtons and specific impulses comparable to those of the large engines, on the order of 300 seconds. This requires mass flows of several grams per second, and combustor conditions on the order of 100 atm at 3000K. To realize such performance, the motors are regeneratively cooled by the propellants. The complete propulsion system is under development, including combustion chamber and nozzle (Fig. 9), turbopumps, and control valves. Initial engines were designed for liquid oxygen and ethanol.

Figure 8: Microhydraulic power generator design for such uses as a heel strike generator [38].

Figure 9: Regeneratively cooled MEMS thrust chamber design to produce 15 N thrust [45].
propellants. More recently, the emphasis has shifted to long-term storable propellants, specifically hydrogen peroxide and JP-7. To date, thrusts of 1-2 N have been demonstrated at equivalent specific impulses of about 200 sec. Continued development should grow the performance to 10-15N of thrust at 280-300 sec specific impulse.

COMMON TECHNICAL CHALLENGES

While the concepts and approaches of Power MEMS vary widely, there are several common engineering constraints and challenges. In general, high power density and high efficiency are engineering goals for most such systems. This has several implications. For dynamical systems with rotating or reciprocating parts, high specific power - in fluid, mechanics and electromechanics - requires high translational speeds and therefore high frequencies. This in turn implies that such parts will be highly stressed, demanding a high degree of rigor in the mechanical design and manufacture. It also limits material choices to those capable of carrying the loads. In addition, friction can become a dominant issue in many rotating and translating systems so that lubrication and tribology are important. This is one reason why fluid or electromechanical bearings look attractive at very small size. For heat engines, high power density generally requires high pressures and velocities to realize high flow rates per unit area. Thus, the fluid design is important as well.

High efficiency imposes another set of requirements. Efficiency in heat engines is often coupled with temperature differences. Thus, high temperatures (such as in a combustor) are needed for the hot part of the system while low temperatures are needed for heat rejection. This has several implications. First, we need high temperature designs and materials. Second we must thermally isolate the hot and cold section of the device, something which is quite challenging at microscale, especially if a high thermal conductivity material such as silicon is used. Fluid leakage is an important concern as well. Large-scale devices, such as piston engines whose characteristic dimensions may be tens to hundreds of centimeters, already operate with clearances on the micron level, which implies that microscale devices need either tighter clearances or designs less sensitive to such imperfections.

It is important to view the above considerations as challenges rather than barriers. The value of clever engineering should not be discounted.

CONCLUDING REMARKS

This informal survey looks at the Power MEMS literature published at this time. This is a very rapidly moving field, with many new researchers. We would expect both significant progress in devices currently under development as well as new concepts and ideas to be explored. For example, there is much exciting work to be presented at this conference which is not represented in this review. The challenge, as in any new technology, is to bring advances to a point that they can be moved out of the laboratory, first into true product development and then on to users. In a field with this much potential, it may be a relatively short time before we see such progress.

REFERENCES


