POWER GENERATION AT THE MICRO SCALE

W. M. YANG, S. K. CHOU, C. SHU, and Z. W. LI
Department of Mechanical Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260

H. XUE
Department of Mechanical Engineering, California State Polytechnic University, 3801 West Temple Avenue, Pomona, CA 91768, USA

The present work is to show the development of micropower systems or power MEMS characterized by thermal, electrical and mechanical power density of 1–20 Watts in sub-centimeter-sized packages. Three kinds of typical micro power systems, namely, the micro-gas turbine engine, the MEMS rotary micro engine, and a micro thermoelectric system, are described in this paper. A novel microthermophotovoltaic (micro-TPV) system, which is being developed in NUS, is also introduced in this work. The system uses hydrogen as fuel and is able to deliver electrical power in the order of watts in a package less than 1 cubic centimeter in volume. The main components of the system are a heat source, a selective emitter, and a photovoltaic (PV) array. The performance of the system is largely affected by the materials of the emitter and the PV cells. When the emitter is made of Co/Ni-doped MgO, and the PV cells are made of GaSb, a 4.4 W electrical power output can be expected.

Keywords: Power MEMS, Microthermophotovoltaic, selective emitter, photovoltaic cells

1. Introduction

With the increasing demand for smaller scale and higher energy density power sources, a continued reliance on traditional batteries, combined with their relatively low projected energy densities, create serious logistical mission constraints. It is well known that hydrocarbon fuels have energy densities in the order of 10-100 times greater than the best batteries. Therefore, taking advantage of the high energy density of chemical fuels to generate power becomes an attractive technological alternative to batteries. This urges emerging of a new class of MEMS devices, power MEMS characterized by thermal, electrical and mechanical power density of 1–20 Watts in sub-centimeter-sized packages. Furthermore, the advantages of hydrocarbon fuels include inexpensive, more constant voltage, no memory effect, and instant recharge.

The potential application of micropower devices is numerous. The demands for portable electronics such as laptop computers and cell phones have been accelerated in recent years. In defense industries, an individual soldier requires lightweight and compact sources of electric power and microclimate control. Micro power is also critical for unmanned micro air and space vehicles.

However, development of micropower devices capable of chemical/electrical conversion with a net power output at the micro scale involves in some significant technological challenges. First, compared to conventional combustor, there is a shorter residence time for mixing and combustion at the micro scale. Second, the surface-to-volume ratio is proportional to the inverse of the hydraulic diameter of
combustor. At the micro scale, due to the high surface-to-volume ratio, heat losses through the wall increase drastically, which tends to suppress ignition and quench the reaction. Third, the stern operating environments propose higher requirements to materials of microreactors.

2. State of micro power devices

During the past ten years, several kinds of micropower devices have been developing around the world. Micro turbine engine is one of the typical micropower devices being developed in MIT [1]. The baseline engine design is illustrated in Figure 1. The engine mainly consists of a supersonic radial flow compressor and turbine connected by a hollow shaft. A thin film electric induction starter-generator is mounted on a shroud over the compressor blades [2]. The system is targeted to operate at a tip speed of 500 m/s. And with a compressor pressure ratio of 4.5:1, it may be capable of producing 10-20 watts in a micro combustor of 0.04 cm$^3$ in volume. The tip speed of 500 m/s means a 2.4 millions rpm rotor speed, which represents a great challenge to the fabrication and assembly of the system. So far, no prototype engine has been reported to produce a net power output.

MEMS rotary engine is another kind of micro power devices proposed by the University of California at Berkeley [2], see Figure 2. The system consists of 7 parts: front plate, epitrochoid housing, back plate, rotor, internal gear, spur gear, and shaft. Two bearings, mounted in the front and back plate, position the shaft. The engine with a displacement of 0.078 cm$^3$, is targeted to produce a power output of 13.9 W, at a speed of 30000 rpm. Due to some reasons such as fabrication and assembly, the prototype engine also did not generate expected net power output. Only a 2.7 W net power output was reported for a MEMS rotary engine with a displacement of 0.348 cm$^3$ [2].

The above two kinds of micro power devices have a high-speed shaft, which increases the difficulties of fabrication and assembly drastically. To eliminate the moving parts, Sitzki et al [3] from University of Southern California developed a micro thermoelectric device, see Figure 3. The system consists of a combustor, counterflow heat exchanger and thermoelectric elements that are
embedded in walls between cold incoming reactants and hot outgoing products and are used to generate electricity power output. The system is targeted to generate a 0.1 W electricity power output in a volume of 0.04 cm$^3$. Compared to the first two kinds of micro engines, the power density generated by the micro thermoelectric system is significantly lower, but with much higher reliability since no moving part is involved.

3. Development of micro-TPV system

To get a relative high output power density and high reliability, we proposed a new power MEMS concept, micro-TPV system, see Figure 4. The system mainly consists of: (1) a heat source, (2) a micro flame tube combustor (The wall can be made of gray body emitting materials such as SiC etc, or selective emitting materials such as Co/Ni-doped MgO$^4$, etc), and (3) a photovoltaic array made of low band-gap materials such as GaSb$^5$, GaInAsSb$^6$ and so on. The emitter is used to convert heat from combustion into radiation, while the PV cells array functions to convert radiation into electricity. It does not involve any moving part. Its fabrication and assembly are relatively easy. As a result, it can be more commonly used in commercial electronics and micro devices.

The most challenging issue in microcombustor design is to keep an optimal balance between sustaining combustion and maximizing heat radiation output. According to the cubic-square law, when the size of a microcombustor decreases by a factor of 100, the surface-to-volume ratio will increase by a factor of 100, thereby enhance the heat flux through the wall drastically, which makes the study of micro-TPV system particularly attractive in terms of power density output per unit volume. However, sustaining combustion will be largely affected by the increased heat losses due to the high surface-to-volume ratio, which tends to suppress ignition and quench the reaction. To optimize the structure of microcombustor, 3-D numerical simulation and experimental works have been carried out. The results indicate that a micro cylindrical combustor with a backward facing step is one of the simplest but effective structure for micro-TPV application. An average temperature of 1265 K have been obtained along the wall of a micro SiC combustor with 3 mm in diameter, 16 mm in length and 0.11 cm$^3$ in volume.

A mathematical model has also been developed to predict the performance of the micro-TPV system. The short-circuit current of PV cells can be calculated by$^5$

$$J_{sc} = qF_{cs} \int \frac{W(\lambda, T)Q(\lambda)d\lambda}{hc/\lambda}$$

(1)

where $q$ is the electrical charge, $F_{cs}$ is a geometrical factor that compensates for the distance from the source to the cell which is set equal to 1 for this calculation, $W(\lambda, T)$ is the spectral distribution radiated by an emitter, $h$ is the Planck's constant, $c$ is the speed of light, $\lambda$ is the wavelength, $T$ is the temperature of emitter, and $Q(\lambda)$ is the quantum efficiency as a function of wavelength for the cell.
The open-circuit voltage, $V_{oc}$, can be determined by

$$V_{oc} = \frac{kT_c}{q} \ln\left[\frac{J_{sc}}{J_0} + 1\right]$$  \hspace{1cm} (2)

where, $T_c$ is the working temperature of PV cell, $J_0$ is the reverse saturation current of a p/n junction and $k$ is the Boltzmann's constant.

The voltage at maximum power point, $V_{mp}$, can be obtained by solving

$$V_{oc} = \frac{kT_c}{q} \ln\left[1 + \frac{qV_{mp}}{kT_c}\right] + V_{mp}$$  \hspace{1cm} (3)

Then, the maximum power $P_m$ can be got by

$$P_m = \frac{qJ_{sc} (V_{mp})^2}{(kT_c + qV_{mp})}$$  \hspace{1cm} (4)

Combined with the experimental results of SiC emitters, GaSb PV cells \cite{5} and GaInAsSb \cite{6} PV cells, an electrical power output of 0.74 W and 1.17 W can be expected for GaSb PV cells and GaInAsSb PV cells respectively.

Furthermore, if we replace the SiC emitter with a Co/Ni-doped MgO selective emitter, then an electrical power output of 4.4 W and 2.9 W can be expected for GaSb PV cells and GaInAsSb PV cells respectively. This indicates that selective emitter can improve the performance of micro-TPV system drastically.

4. Conclusions

Four kinds of micro power devices are introduced in this work. Micro turbine engine and MEMS rotary engine have higher output power density, but experience more difficulties in fabrication and assembly. Micro thermoelectric device and micro-TPV system have higher reliability due to the elimination of moving parts, but generate lower power density output. When the emitter is made of Co/Ni-doped MgO, and the PV cells are made of GaSb, a 4.4 W electrical power output can be expected in a micro combustor of 0.11 cm$^3$ in volume, so Micro-TPV system is a good choice in balancing reliability and output power density.

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References

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