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POWER MEMS AND MICROENGINES

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SUMMARY

MIT is developing a MEMS-based gas turbine generator. Based on high speed rotating machinery, this 1 cm diameter by 3 mm thick SiC heat engine is designed to produce 10-20 W of electric power while consuming 10 grams/hr of H_2. Later versions may produce up to 100 W using hydrocarbon fuels. The combustor is now operating and an 80 W micro-turbine has been fabricated and is being tested. This engine can be considered the first of a new class of MEMS device, *power MEMS*, which are heat engines operating at power densities similar to those of the best large scale devices made today.

Keywords: Heat engine, turbine, generator.

INTRODUCTION

Currently, society finds it most economical to produce electrical power centrally on megascale (with turbines producing on the order of 100 MW) and then distribute it to individual users. Cooling is likewise centralized whenever possible (building-wide, complex-wide). MEMS may change this model. We propose herein a new class of MEMS devices, *power MEMS*, characterized by thermal, electrical, and mechanical power densities equivalent to those in the best large-sized machines produced today, thus producing powers of 10 to 100 watts in sub-centimeter-sized packages. Based on classical thermodynamic cycles (Brayton, Rankine, etc.), such devices would have significantly different behavior than, but equivalent performance to, their more familiar full-sized embodiments. They could see widespread application as mobile power sources, propulsion engines, and coolers. However, the realization of power MEMS presents new challenges both to micromachining and to the traditional mechanical and electrical engineering disciplines of fluid dynamics, structural mechanics, bearings and rotor dynamics, combustion, and electric machinery design. This paper delineates the technology challenges of power MEMS, suggests promising approaches, and describes the work on-going at MIT in this area.

Thermodynamic Considerations

Thermal power systems encompass a multitude of technical disciplines. The architecture of the overall system is determined by thermodynamics while the design of the system's components is influenced by fluid and structural mechanics, and by material, electrical and fabrication concerns. The physical constraints on the design of the mechanical and electrical components are often different at microscale than at more familiar sizes so that the optimal component and system designs are different as well. Most thermodynamic systems in common use today are variations of the Brayton (air), Rankine (vapor), Otto, or Diesel cycles. The Brayton power cycle (gas turbine) was selected for the initial investigation based on relative considerations of power density, simplicity of fabrication, ease of initial demonstration, ultimate efficiency, and thermal anisotropy.

A conventional, macroscopic gas turbine engine consists of a compressor, a combustion chamber, and a turbine (driven by the combustion exhaust) that powers the compressor, and can drive machinery such as an electric generator. The residual enthalpy in the exhaust stream provides thrust. A macroscale gas turbine with a meter diameter air intake generates power on the order of 100 MW. Thus, tens of watts would be produced when such a device is scaled to millimeter size if the power per unit of airflow is maintained. When based on rotating machinery, such power density requires (1) combustor exit temperatures of 1300-1700 K; (2) rotor peripheral speeds of 300-600 m/s and thus rotating structures centrifugally stressed to several hundred MPa (the power density of both fluid and electrical machines scales with the square of the speed, as does the rotor material centrifugal stress); low friction bearings; high geometric tolerances and tight clearances between rotating and static parts; and thermal isolation of the hot and cold sections.

These thermodynamic considerations are no different at micro- than at macroscale. But, the physics influencing the design of the components does change with scale, so that the optimal detailed designs can be quite different. Examples include the viscous forces in the fluid (larger at microscale), usable strength of materials (larger), surface area to volume ratios (larger), chemical reaction times (invariant), realizable electric field strength (higher), and manufacturing constraints (planar geometries).

ENGINE DESIGN

There are many thermodynamic and architectural design choices in a device as complex as a gas turbine engine. These involve trade-offs among fabrication difficulty, structural design, heat transfer, fluid mechanics, and elec-

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trical performance. Given that the primary goal of this research effort is to demonstrate that a high power density MEMS heat engine is physically realizable, the design philosophy adopted is that the first engine will be as simple as possible, trading performance for simplicity. For example, the addition of a heat exchanger transferring heat from the turbine exhaust to the compressor discharge fluid (a recuperated cycle) offers many benefits including reduced fuel consumption and relaxed turbomachinery performance requirements, but it introduces additional design and fabrication complexity. Thus, the baseline design is a simple cycle gas turbine generator. While this engine is the simplest of gas turbines, it is an extremely complex and sophisticated MEMS device. Arriving at a satisfactory design requires heavy dependance on simulation of the mechanical, thermofluid, and electrical behavior to achieve the required levels of component performance and integration.

The baseline engine design is illustrated in Figure 1. The engine consists of a supersonic radial flow compressor and turbine connected by a hollow shaft. Gaseous H_2 fuel is injected at the compressor exit and mixes with air as it flows radially outward to the flame holders. The combustor discharges radially inward to the turbine whose exhaust turns 90 degrees to exit the engine nozzle. A thin film electric induction starter-generator is mounted on a shroud over the compressor blades and is cooled by compressor discharge air. Cooling air is also used to thermally isolate the compressor from the combustor and turbine. The rotor is supported on air bearings. The following sections briefly discuss component design considerations.

Materials and Mechanical Design

Conventionally-sized engines, constructed from titanium and heavily cooled nickel and cobalt-based superalloys, are stress-limited in the rotating components. Nonmetallics such as silicon (Si), silicon carbide (SiC), and silicon nitride (Si_3N_4) offer substantial improvement in strength-to-density ratio and temperature capability, but large parts with acceptable properties have proven difficult to manufacture from these materials. However, they are readily available in essentially flaw-free form for microscale fabrication so that significantly superior material performance is available for micro-heat engines than can now be realized in conventionally-sized devices. In addition, because of the small length scales required here, materials which are unsuitable for a large heat engine due to thermal shock considerations (*e.g*. aluminum oxide), would be usable in a microengine given a fabrication technology [1].

Silicon is suitable for the compressor (600 K) but cannot operate at the combustor discharge temperature needed (1300-1700 K) without cooling. SiC can operate uncooled but SiC fabrication technology is much less developed than that for Si. The baseline design assumes uncooled SiC for simplicity but a cooled Si design is also under study. The individual components are being demonstrated in Si while SiC manufacturing technology is being developed. Since the properties of such materials are a strongly influenced by the details of their fabrication, material testing is an integral part of this program.

Fabrication

The fabrication of a structure as large and complex as a micro-gas turbine generator poses several challenges. These include the production of features hundreds of microns deep, fillets to reduce stress on highly loaded parts, electrical properties for the motor-generator, the excavation of volumes

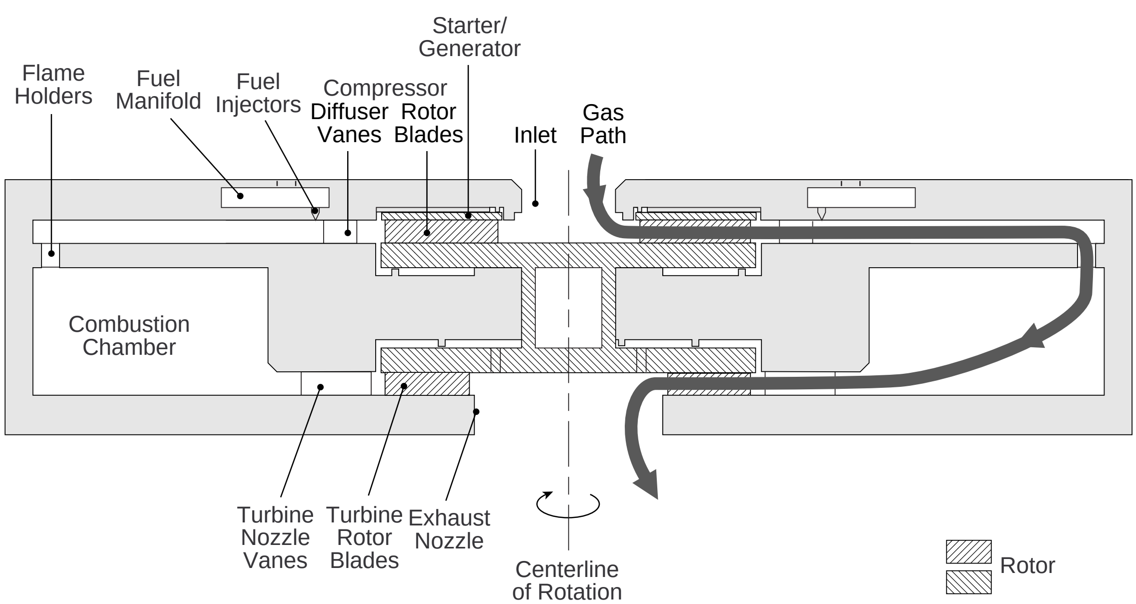

Figure 1: Micro-gas turbine generator cross-section.

millimeters across and hundreds of microns deep, and assembly and packaging. Since the initial component demonstrations are in silicon, early emphasis was placed here. Air flow requirements of 0.1-0.2 g/sec imply airfoil and passage heights on the order of 200-300 microns given the geometries of Figure 1. Deep reactive ion etching was used to produce the turbine shown in Figure 2, which has a 4 mm rotor diameter and 200 micron span blades. The rim of the 300 micron thick disk serves as a journal bearing. This unit is a rotor dynamics test piece. With the addition of a generator on the back surface of the disk, it becomes an 80 watt turbine generator. Also, using only known process steps, a "strawman" process simulation yields wafers of completed engines, including a freely turning rotor, without additional assembly. It is a complex and aggressive process requiring 7 aligned wafer bonds, 20 lithography steps, and the deposition of 9 thin film layers.

Turbomachinery and Fluid Mechanics

Considerations of engine thermodynamic efficiency, combustor performance, and turbine viscous losses suggest that compressor pressure ratio should be relatively high. Since both the pressure ratio and the centrifugal stress in the rotor scale with the square of the peripheral Mach number, the pressure ratio per stage of compression is set by the allowable material stress. Material property values in the literature are consistent with a 500 m/s rotor tip speed which was therefore adopted as a baseline. A 4:1 pressure ratio compressor has been designed to operate at this speed. Current fabrication technology largely restricts complex curvatures to in-plane which inhibits the use of the high degree of three-dimensionality typically employed in centrifugal turbomachinery to improve efficiency and reduce material stresses. However, the usable material strength is higher at microscale. Also, this flow regime is unusual in that it is supersonic (Mach 1.4) but laminar (Reynolds number 20,000). Three-dimensional fluid calculations suggest that this machine should achieve an adiabatic efficiency of about 70%. To facilitate detailed measurement of the turbomachinery fluid mechanics, a 75:1 geometrically scaled-up test rig has been built. It operates at the same Mach and Reynolds numbers as the microturbomachinery.

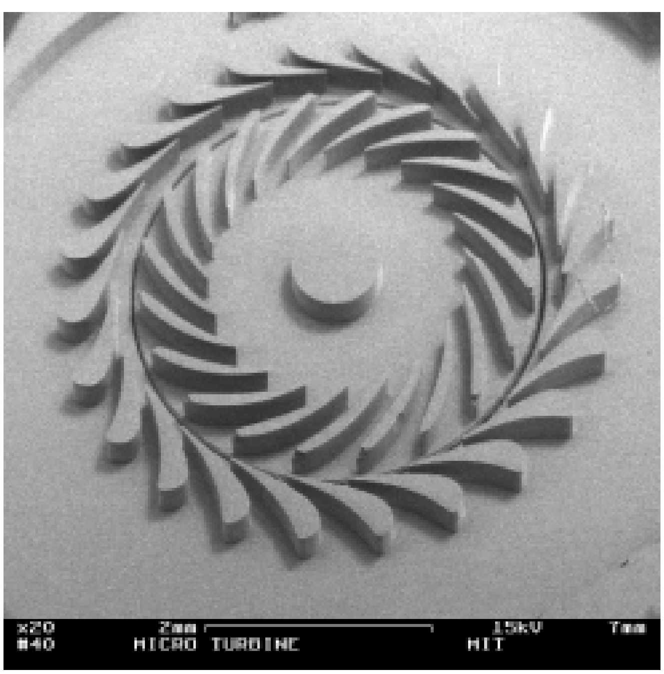

Figure 2: 80 watt microturbine.

Combustion

Airbreathing combustion requires fuel injection (and evaporation if a liquid), fuel-air mixing, and chemical reaction of the mixed reactants. The time required for these processes (the combustor residence time) sets the combustor volume. In large engines, the residence time is typically 5-10 ms. Most of this is for fuel mixing; chemical reaction times are a few hundred microseconds or less. In order to expedite the engine development process, hydrogen was selected as the baseline engine's fuel. Hydrogen offers rapid mixing and chemical reaction times, and flammability over a wide range of fuel-to-air ratios. By operating at a low fuel-to-air ratio, the peak combustor temperature can be reduced to levels compatible with uncooled SiC construction (1600 K), eliminating the requirement for the complicated cooling geometries needed on large engines.

A combustor with the geometry of Figure 1 has been built and tested. It has demonstrated the predicted levels of performance over a wide range of temperatures and mixture ratios. The data agree with numerical simulations that suggest that complete combustion can still be achieved with a factor of two reduction in combustor volume [2]. Work is now beginning on a hydrocarbon fueled catalytic combustor.

Bearings and Rotor Dynamics

Low friction bearings are required to support the rotor against fluid and electrical forces, rotor dynamics, and externally applied accelerations while operating at speeds of over two million rpm. Gas film, electrical, and hybrid gas-electrical bearing concepts were examined. Gas bearings were selected for the baseline engine based on superior load bearing capability and relative ease of fabrication. A journal bearing supports the radial loads and thrust plates support the axial loads. The physical regime that the micro-gas bearings operate in is unusual in several regards: the peripheral speed of the bearing is transonic so compressibility effects are important; the ratio of inertial to viscous forces (Reynolds number) is high; the surface area of the bearing is very large compared to the mass of the rotor; and the journal length-to-diameter ratio is quite low. The net effect of these influences is a journal bearing well outside existing theory and empirical design practice. The scaling is such that the design rotor speed is two orders of magnitude higher than the critical frequency (spring-mass-damper equivalent) of the rotating system. Subcritical operation would require submicron operating clearances which are difficult to fabricate and incur viscous losses greater than the engine power output.

The design adopted uses a ten micron journal gap to reduce losses to a few watts but is linearly unstable at some speeds. Numerical simulations indicated, however, that this design will operate satisfactorily in a nonlinear limit cycle. Turbine-driven rotor dynamic test rigs have been constructed both at 1:1 microscale (Figure 2) and at 26:1 macroscale (to facilitate detailed instrumentation). Preliminary data confirm that the rotor does operate in a stable limit cycle. As a precaution, an electric damper is being designed to augment the bearing stability should it prove desirable.

Electrical Machinery

A motor-generator starts the gas turbine and produces the electrical power output. Integrating the motor-generator within the engine offers the advantages of mechanical simplicity since no additional bearings or structure are required over that needed for the engine and cooling air is available. Either electric or magnetic machines could be used. Here, an electric machine was chosen due to considerations of power density, ease of microfabrication, and high-temperature and high-speed operation. The baseline design is a 180 pole planar electric induction machine mounted on the shroud of the compressor rotor. Simulations suggest that such a machine can produce on the order of 20-40 watts with an electrical efficiency in excess of 80%. The major source of loss in the machine is viscous drag in the rotor-stator gap. A superscale version of the machine has been constructed as an aide to the development of the power and control electronics.

CONCLUDING REMARKS

The design of the micro-gas turbine generator presents a considerable challenge to all the disciplines involved. However, progress to date has been quite encouraging. The ability to manufacture MEMS-based high speed rotating machinery opens up a host of possibilities including various thermodynamic machines. MIT is also working on a motor-driven microcompressor and a micro-high pressure liquid rocket motor employing turbopumps. The concept of MEMS-based, high power density heat engines appears extremely attractive and physically realizable.

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