MEMS Reference Shelf

MEMS Reference Shelf

Series Editors:

For other titles in this series, go to:
www.springer.com/series/7724

Jeffrey H. Lang
Editor

Multi-Wafer Rotating MEMS Machines

Turbines, Generators, and Engines

Springer

Editor
Jeffrey H. Lang
Department of Electrical Engineering &
Computer Science
Massachusetts Institute of Technology
77 Massachusetts Ave.
Cambridge MA 02139-4307
USA
lang@mit.edu

ISSN 1936-4407
ISBN 978-0-387-77746-7 e-ISBN 978-0-387-77747-4
DOI 10.1007/978-0-387-77747-4
Springer New York Dordrecht Heidelberg London

Library of Congress Control Number: 2009933947

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

This book is an outgrowth of the MIT Micro Engine Project. This project began at the Massachusetts Institute of Technology in the Fall of 1995, and later expanded through collaborations with the Georgia Institute of Technology, the Clark Atlanta University, and the University of Maryland at College Park. By the time the project ended in the Summer of 2008, almost 13 years later, it had supported over one hundred people including faculty, staff, post doctoral researchers, and many students.

The overall objective of the Micro Engine Project was to develop a small but power-dense gas turbine generator based on MEMS fabrication technologies. Thus, the project sought to develop a fuel-burning jet engine that would drive an electric generator to produce electric power for general purpose use. Along the way, the project would advance the science and engineering of many disciplines from the MEMS perspective. The purpose of this book is to pull together the results of that study in a compact, and hopefully integrated, manner.

The Micro Engine Project was by its very nature a highly multi-disciplinary project pursuing advances in materials, structures, fabrication, combustion, heat transfer, turbomachinery, bearings and electromechanics, all at the MEMS scale. Most of these critical disciplines are discussed in this book. To begin, Chapters 1 and 2 lay the foundation for the project, both in terms of its practical objectives, and its scientific and engineering rationale. Chapter 3 then discusses materials, structures, and packaging. Chapters 4 and 5 focus on MEMS fabrication, with an emphasis on technologies specifically required to make a device as complex as a micro-engine. Chapter 4 in particular focuses on silicon-related fabrication, while Chapter 5 focuses on electroplating magnetic components, such as windings and cores, into a silicon superstructure. Chapter 6 presents our development of very-high-speed air bearings. Chapter 7 presents our work on thermofluidics and turbomachinery. Chapter 8 studies electromechanics as required to develop an MEMS electric generator. Finally, Chapter 9 focuses on combustion at the MEMS scale.

It has been my great pleasure to work with the contributors to this book for the last 13 years and beyond, and the many other faculty, staff, postdocs, and students involved in the project over those years. I am grateful for their enthusias-

tic hard work, from the beginning of the project through the completion of this book. Without that effort this book and the work described herein would never have materialized.

Cambridge, MA
March 2009

Jeffrey H. Lang

Contents

Contributors

Mark G. Allen School of Electrical and Computer Engineering, Georgia Institute of Technology, 791 Atlantic Dr., Atlanta, GA 30332-0269, USA

David P. Arnold Department of Electrical and Computer Engineering, University of Florida, 229 Benton Hall, Gainesville, FL 32611-6200, USA

Sauparna Das Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Bldg 10-050, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Alan H. Epstein Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Bldg 31-265, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Stuart A. Jacobson Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Bldg 31-269, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Jeffrey H. Lang Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Bldg 10-176, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Hanqing Li Microsystems Technology Laboratories, Massachusetts Institute of Technology, Bldg 31-261E, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Martin Schmidt Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Bldg 3-240, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Zoltán S. Spakovszky Gas Turbine Laboratory, Massachusetts Institute of Technology, Bldg 31-265, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

C.M. Spadaccini Center for Micro and Nano Technology, Engineering Technologies Division, 7000 East Avenue, Livermore, CA 94550, USA

S. Mark Spearing School of Engineering Sciences, University of Southampton, University Road, Southampton SO17 1BJ, UK

I.A. Waitz Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Bldg 33-207, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Chapter 1
Introduction to PowerMEMS

Alan H. Epstein

The term "PowerMEMS" was first suggested by Epstein and Senturia [1] in 1996 to describe microsystems which generated power or pumped heat. Their primary interest was micro-electro-mechanical systems (MEMS) heat engines, specifically Brayton cycles (such as gas turbines) 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 PowerMEMS system has evolved into a broader concept which includes other conventional thermodynamic cycles, new heat engine concepts which may only be attractive at microscale, energy harvesting schemes, and micro-fuel cells – all based on MEMS approaches.

Thermodynamic cycles and their heat engine embodiments – Rankine, Brayton, Otto, Diesel, etc. – were at the heart of the industrial revolution. Such engines can convert chemical energy into heat and then into mechanical work. This mechanical energy may be used directly for applications such as vehicle propulsion or fluid pumping or converted into electric power. Propulsion is one goal of MEMS jet engines and rocket engines, while MEMS gas turbine, steam, and internal combustion engines are being developed to power electric generators for electric power production. With electrical, mechanical or thermal power input, micro heat engines can also pump heat as in familiar conventional heat-pumps, chillers, and refrigerators. PowerMEMS also encompasses heat engines which convert chemical energy directly to electrical energy, often 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. PowerMEMS also encompasses devices which convert mechanical energy directly into electric power such as self-charging electric watches and heel strike power generators.

The proliferation of small, portable electronics – computers, digital assistants, cell phones, GPS receivers, etc. – requires compact energy supplies. Increasingly,

A.H. Epstein (✉)
Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Bldg 31-265, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

J.H. Lang (ed.), *Multi-Wafer Rotating MEMS Machines*, MEMS Reference Shelf, DOI 10.1007/978-0-387-77747-4_1, © Springer Science+Business Media, LLC 2009

these electronics demand energy supplies whose energy and power density exceed that of the best batteries available today. The lack of adequate energy sources has motivated considerable effort on energy efficient approaches to electronics design. Also, the continuing advance in microelectronics permits the shrinking of electronic subsystems of mobile devices such as small animal-sized ground robots and air vehicles. These small, and in some cases very small, mobile systems require increasingly compact power and propulsion. Thus, the interest in PowerMEMS results from both an applications pull and a technology push. The primary motivations for the work described in this book were that of (1) portable electric power and (2) propulsion for very small aerial vehicles, but the approaches and technologies apply well to other applications discussed above.

1.1 Compact Portable Power Considerations

Energy supplies for portable electronics must satisfy many requirements. These are often in conflict for a specific technology so that design compromise is usual. Energy can be stored in a variety of manners – chemical, mechanical (e.g., springs), fluid (pressurized gas), potential (e.g., a liquid in a gravity field), or nuclear. This discussion will focus on chemical energy since at this time chemical energy density greatly exceeds that of other known non-nuclear sources. Such requirements included the following considerations.

Energy Density – A primary metric is the mass and volume required to hold the needed energy. This includes the primary energy source (the chemistry), the structure needed to contain it (fuel tank, pressure vessel, etc.), and the power converter (engine, fuel cell, etc.). The relative size of the energy chemistry versus that of the power converter varies greatly depending upon the peak power needed, total energy required (average power times the duration), and the energy source. An energy harvester is all power converter, a battery could be considered all chemistry (although practical batteries are now closer to 60–80%).

Power Density – Equally important is the mass and volume needed to generate the power (energy per unit time) the power system is required to deliver. Peak power required may size the power conversion system. For example, batteries designed for very long lives but very low power applications (such as for watches) now have twice the energy density of high peak power batteries (such as for power tools). Similarly for mechanical generators, given a fixed total system weight budget (generator plus fuel), a larger output power generator will weigh more with this weight displacing that of fuel. Again, the system designer must trade power density against energy density.

Efficiency – The fraction of the chemical energy consumed converted to electrical energy delivered to the reduces the gross energy density. Clearly, the size of the primary energy supply needed scales inversely with the efficiency. Energy not delivered to the user ends up as heat that must be rejected from the package. For some devices, rejection of this heat is a primary design driver, influencing energy system size, weight, and complexity.

Safety – It is important to consider safety since an apple-sized battery contains more chemical energy than a hand grenade. In addition to explosion and fire, concerns of toxicity, thermal injury, and environmental impact are important. For example, batteries for unmanned aeronautical and munitions applications can be formulated with more than twice the energy density considered safe for industrial or retail use.

Environment – Consideration of the storage and operating environment may drive the energy/power system design. Ambient temperature requirements from –40°C to +50°C are typical for outdoor applications. This is a large temperature range for common battery chemistries. At the high temperature end, safety requirements reduce energy density. At low temperatures, most batteries do not deliver much power. Indeed, experienced hikers and soldiers often sleep with their batteries in their sleeping bags to keep the batteries warm in cold climates. Systems which use liquid water, such as some fuel cells, must include special provisions for storage, startup, and operation in sub-freezing conditions. Heat engines produce less power as the temperature rises both due to a drop in the mass of air flowing through the engine and due to a reduction in efficiency. For both engines and many fuel cells, altitude of operation is an important consideration since these air-breathing systems depend on the atmosphere for their oxygen. Oxygen density drops off rapidly with increasing altitude – down by about 30% at 3,000 m. Unless turbocharging or a similar approach is used, power output will drop concomitantly. Clearly, air-breathing devices will not work underwater. Contamination from the ingestion of dust, aerosols (a problem in marine environments), and rain or snow can be a concern. Environmental challenges also include mechanical considerations such as orientation (right side up – upside down), vibration (jogging, vehicle motion), and shock (dropping a device on a hard floor from 2 m can result in loads of 5,000 g).

The point of the above discussion is that while energy and power density are obvious requirements for portable energy supplies, there are many other considerations that influence the performance and utility of a particular technology. Many of these considerations are application specific, implying that the optimal solution may be as well.

1.2 Chemical Energy Sources

Table 1.1 compares several chemical energy source in terms of both the gross gravimetric energy in the chemistry and an estimate of the net energy output including assumptions about the efficiency of current and near term conversion processes. Lithium battery chemistry has about the same theoretical energy density as TNT. Two current practical implementations of lithium battery chemistries are shown,

Table 1.1 Chemical energy sources

Energy source	Potential[a] W h/kg	Practical W h/kg[b] based on conversion device efficiency
Lithium battery	1,400	175 ($LiSO_2$) 300 ($LiSOCl_2$)
TNT	1,400	NA
Sugar	4,700	NA
Methanol	6,200	1,500–3,100
Diesel fuel	13,200	1,320–5,000
Hydrogen	33,000	1,150–23,000

[a] *Based on enthalpy* (after R. Paur).
[b] (*System conversion efficiency*) × (*Energy available in fuel*).

lithium sulfur dioxide ($LiSO_2$) and lithium thionyl chloride ($LiSOCL_2$). While $LiSOCL_2$ batteries can have twice or more than the energy density of $LiSO_2$, current implementations are not considered safe enough for commercial applications or even military or aerospace ones that put people at risk. Both are onetime use primary batteries. Rechargeable batteries formulations have 30–50% less energy density. Batteries are important because they widely available and inexpensive, so they represent a baseline to which all portable power source PowerMEMS concepts must compare favorably to be of value.

The energy density of both lithium batteries and explosives is low compared to other chemical energy sources, one reason being that they contain both fuel and oxidizer while the other chemistries use atmospheric oxygen as the oxidizer which therefore need not be carried by the power source (unless used underwater or in space).

Hydrogen has the highest chemical energy density but since it is a gas at standard conditions it must be contained. For current approaches, the containment mass considerably outweighs the hydrogen it holds. Storage methods available include: as a metal hydride, as a high pressure gas, and as a liquid. In all three cases, the net energy density accounting for containment is considerably less than that of liquid hydrocarbons fuels such as diesel or methanol. Sugar, a biological "fuel," has an energy density about a third of that of diesel.

Fuel energy density information is plotted in Fig. 1.1 in terms of gravimetric energy density versus volumetric energy density. It can be seen in the left graph that all three forms of contained hydrogen have an energy density about equivalent to that of the potential of lithium battery chemistry, and all are about an order of magnitude below that of diesel fuel, which has about the highest density of any known liquid fuel.

The right plot of Fig. 1.1 shows the same data but now accounts for the assumed efficiency of the power converters (but not their mass or volume). Current lithium primary batteries deliver about an order of magnitude less power than their theoretical potential. Proton-exchange-membrane (PEM) fuels cells run on hydrogen and operate at about 50% net efficiency. Current direct methanol fuel cells (DMFC) are

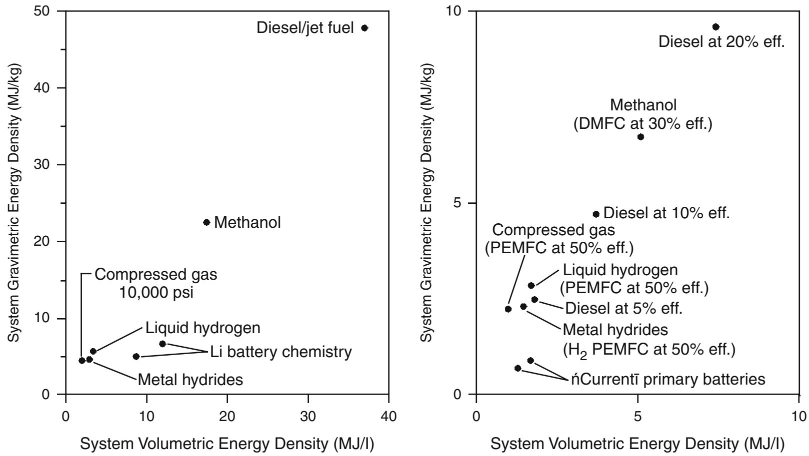

Fig. 1.1 *Left*: Energy density of common portable power fuels. *Right*: Net energy density accounting for converter efficiency but not converter mass and volume

about 30% efficient. Portable diesel generators below 10 kW are 20–30% efficient with efficiency increasing with size.

Figure 1.2 is the data of Fig. 1.1 replotted on a larger scale along with the efficiencies of large scale energy conversion systems in production. Large gas turbines are now 45–55% efficient. Modern, large (100+MW) combined cycle, gas turbine-steam power plants are the most efficient at 60%. Large diesels are in the 40–50% range, while automotive engines are closer to 30%. The best fuel cell systems

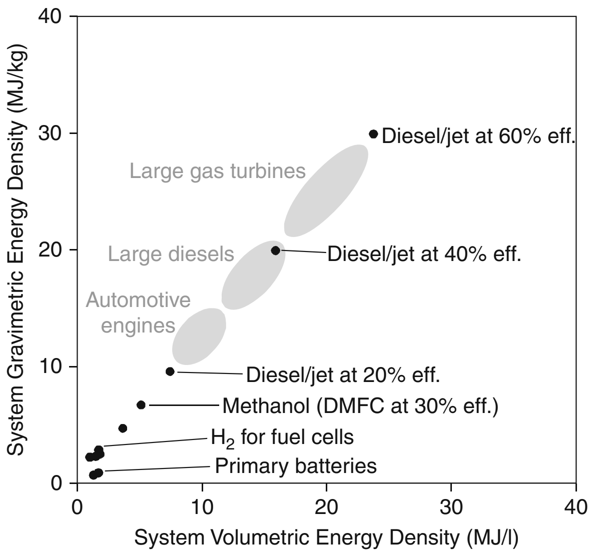

Fig. 1.2 Net fuel energy densities including conversion efficiency and efficiency of current conventional-sized devices

today are about 50% efficient. In all cases, the effective system efficiency can be improved if the waste heat is captured and used for other purposes such as heating or cooling.

One implication of Figs. 1.1 and 1.2 is that hydrocarbon fuels burned in air have 20–30 times the energy density of the best current lithium chemistry-based batteries, so that fuelled systems need only be modestly efficient to compete well with batteries. Another is that the very low net density of hydrogen (hydrogen plus container) renders it unattractive as a portable fuel for many applications. Thus, portable converters that must operate on hydrogen, such as PEM fuel cells, will likely manufacture hydrogen in situ from denser hydrocarbons, a process which greatly increases device complexity and drops the overall efficiency. This means that heat engines or solid oxide fuel cells which directly burn hydrocarbon fuel are attractive alternatives, if they can be realized in the needed sizes and efficiencies.

1.3 Power System Considerations

Since the size and efficiency of power converters vary greatly depending upon the technology, and the energy density of the fuels are so different, the optimal approach is quite application specific. If the power requirements are large but energy requirements are modest, then the power converter dominates the overall system mass. In this case, a compact power converter is favored even if it is relatively inefficient and uses a fuel with relatively low energy density. Conversely, when the total energy requirements are large, a more efficient power converter using high energy density fuel is favored, even if the converter is relatively large.

An example of the trade between power density and energy density is illustrated in Fig. 1.3. Here the total energy supply mass is plotted against the total energy; it can supply for three technologies – $LiSO_2$ primary batteries, a DMFC operating at 20% over all efficiency, and a notional MEMS heat engine. All three approaches are sized to deliver 50 W. A BA5590 battery weighs about a kilogram and can output 170 W-h (about twice the energy of a large laptop computer battery). If more energy than 170 W-h is needed, then a second battery must be added, etc. This discreteness results in the staircase appearance of the battery curve in Fig. 1.3. At an equivalent 20% conversion efficiency, methanol has a higher energy density than a battery, so the DMFC line has shallower slope than that of the battery. (The fuel energy density shown on the plot reflects the combined effect of the system efficiency and methanol concentration.) The fuel cell has a zero fuel mass of 2 kg, so for these assumptions, a battery is a lighter solution if less than 170 W-h is needed. As the energy required increases, the fuel cell looks increasingly attractive. The mass of a 50 g notional micro heat engine power system running on diesel fuel is shown for two overall efficiencies, 5 and 10%. Because of the very high power density of a micro heat engine, it is always better than a battery. At 5% efficiency it is superior to the fuel cell if the energy requirement is less than about 2,000 W-h. At 10%

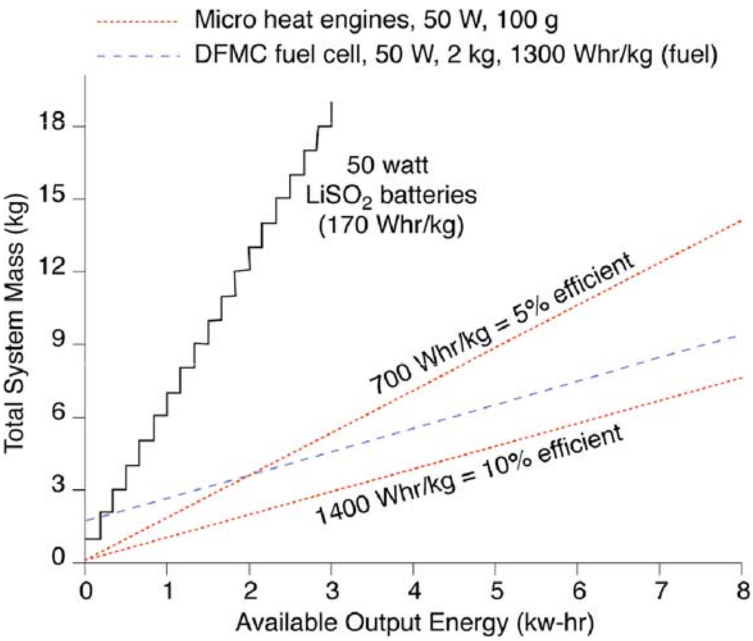

Fig. 1.3 Total mass for a 50 W power system as a function of total energy required for batteries, a direct methanol fuel cell (DMFC), and a notional micro heat engine using diesel fuel

efficiency, the micro heat engine is always better than the DMFC because the energy density advantage of the diesel fuel over methanol more than offsets the difference in efficiency.

The above example is for illustrative purposes only since the performance of a field ready DMFC or micro heat engine is projection only. However, several points can be made. First, the efficiency of a micro heat engine can be modest compared to that of the current conventional size variants shown in Fig. 1.2 for a micro solution to be a very attractive alternative to a battery in terms of size and mass. Second, the ability to use a liquid hydrocarbon, diesel in particular, is a powerful advantage compared to an approach requiring hydrogen. Third, the high power density of the micro heat engine compared to a fuel cell is an advantage when the total energy required is modest.

1.4 Conclusion

This chapter has outlined a motivation for powerMEMS, especially micro-heat engines. If their potential can be realized, they represent a very attractive alternative for many applications, compact power in particular. The engineering requirements for a MEMS gas turbine are discussed in Chapter 2. Subsequent chapters discuss the micro component technologies needed including structures and materials, bearings and rotor dynamics, fluid mechanics, combustion, electro-mechanics, and micro-fabrication. These chapters include theory, engineering design, fabrication, and test results.

Reference

1. Epstein, A.H., and Senturia, S.D., 1997, "Macro Power from Micro Machinery", *Science*, **276**, p. 1211

Chapter 2
System Design Considerations and Device Overview

Alan H. Epstein

2.1 Introduction

The primary objective of the engineering describe in this book is the realization of an MEMS gas turbine driven electric generator producing tens of watts of electric power. The same device with reduced electrical power extraction could produce tens a grams of thrust to propel very small air vehicles massing a few hundred grams. As a part of this effort, several MEMS engine subsystems were engineered and tested as stand alone devices, including: air-turbine driven generators, a motor driven gas compressor, combustion chambers, and turbochargers. Although challenging, useful, and complete in themselves, these devices and the requisite microfabrication technologies were engineered as part of the gas turbine engine's research and development program. The device design space, materials, and fabrication approaches were thus constrained to be consistent with the requirements of the gas turbine and within the bounds of realizable fabrication techniques. In this chapter, we describe the overall system design of the gas turbine and its subsidiary devices, presenting an overview of the MEMS devices and technologies which underlie them. The point of view presented in this chapter is that of a device designer rather than those described in greater detail in subsequent chapters. We start by reviewing the thermodynamics of a gas turbine, briefly describe the relevant mechanics considerations – including materials, fluids, and dynamics – which shape the design space, and then consider individual MEMS devices.

2.2 Thermodynamic and Scaling 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.

A.H. Epstein (✉)
Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Bldg 31-265, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

J.H. Lang (ed.), *Multi-Wafer Rotating MEMS Machines*, MEMS Reference Shelf,
DOI 10.1007/978-0-387-77747-4_2,

A conventional, macroscopic gas turbine generator consists of a compressor, a combustion chamber, and a turbine driven by the combustion exhaust to power the compressor. The residual enthalpy in the exhaust stream provides thrust or can power a turbine to drive an electric generator. A macroscale gas turbine with a meter-diameter air intake area 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 air flow is maintained. When based on rotating machinery, such power density requires combustor exit temperatures of 1,200–1,600 K; rotor peripheral speeds of 300–600 m/s and thus rotating structures centrifugally stressed to several hundred MPa because the power density of both turbomachinery and electrical machines increase with the square of the speed, as does the rotor material centrifugal stress; low-friction bearings; and tight geometric tolerances and clearances between rotating and static parts to inhibit fluid leakage, the clearances in large engines are maintained at about one part in 2,000 of the diameter; and thermal isolation of the hot and cold sections.

These thermodynamic considerations are no different at micro- than at macroscale. But the physics and mechanics influencing the design of the components do change with scale, so that the optimal detailed designs can be quite different. Examples of these differences include the viscous forces in the fluid (larger at microscale), usable strength of materials (larger at microscale), surface area-to-volume ratios (larger at microscale), realizable electric field strength (higher at microscale), and manufacturing constraints (limited mainly to 2-D, planar geometries given current microfabrication technology). Chemical reaction times are invariant with size but most of the fluid residence time in gas turbine combustors is set by mixing considerations which do scale with size.

There are many thermodynamic and architectural design choices in a device as complex as a gas turbine engine. These involve tradeoffs among fabrication difficulty, structural design, heat transfer, and fluid mechanics. Given a primary goal of demonstrating that a high-power density MEMS heat engine is physically realizable, a simple-as-possible design philosophy is attractive, with performance traded for simplicity. For example, a recuperated cycle, which requires the addition of a heat exchanger transferring heat from the turbine exhaust to the compressor discharge fluid, offers many benefits including reduced fuel consumption and relaxed turbomachinery performance requirements, but introduces additional design and fabrication complexity.

How large should a “micro” engine be? A micron, a millimeter, a centimeter? Determination of the optimal size for such a device involves considerations of application requirements, fluid mechanics and combustion, manufacturing constraints, and economics. The requirements for many power production applications favor a larger engine size, 50–100 W. Viscous effects in the fluid and combustor residence time requirements also favor larger engine size. Current MEMS manufacturing technology places both upper and lower limits on engine size. The upper size limit is set mainly by precision etching depth capability, hundreds microns at this time. The lower limit is set by feature resolution and aspect ratio. Economic concerns include manufacturing yield and cost. A wafer of fixed size (say 200 mm diameter) would yield many more low-power engines than high-power engines at essentially the same manufacturing cost per wafer. (Note that the sum of the power produced by all of the engines on the wafer would remain about constant at 1–10 kW.) When commercialized, applications and market forces may establish a strong preference here. For the first demonstrations of a concept, a minimum technical risk approach is attractive. Analysis suggested that fluid mechanics are more difficult at smaller scales, so the largest size near the edge of then current microfabrication technology, 1–2 cm rotor diameter was selected.

Thermodynamic performance calculations indicate that the power per unit air flow from the configuration discussed below has the potential to reach 50–150 W/(g/s) of air flow (Fig. 2.1) . For a given rotor radius, the air flow rate is limited primarily by airfoil span as set by stress in the turbine blade roots. Calculations suggest that it might be possible to improve the specific work, fuel consumption, and air flow rate in later designs with recuperators to realize microengines with power outputs of as much as 50–100 W, power specific fuel consumption of 0.3–0.4 g/W-h, and thrust-to-weight ratios of 100:1. This level of specific fuel consumption approaches that of current small gas turbine engines but the thrust-to-weight ratio is 5–10 times better than that of the best aircraft engine. The extremely high thrust-to-weight ratio is simply a result of the so-called "cube–square law." All else being the same as the engine is scaled down linearly, the air flow and thus the power decreases with the intake area (the square of the linear size) while the weight decreases with the volume of the engine (the cube of the linear size), so that the power-to-weight ratio increases linearly as the engine size is reduced. Detailed calculations show that the actual scaling is not so dramatic, since the specific power is lower at the very small sizes [1]. A principal point is that a microheat engine is a different device than more familiar full-sized engines, with different weaknesses and different strengths.

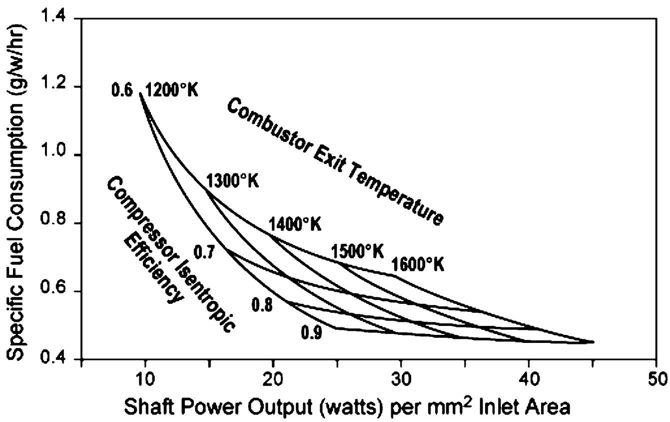

Fig. 2.1 Simple cycle gas turbine performance with H_2 fuel

2.2.1 Mechanics Scaling

While the thermodynamics are invariant down to this scale, the mechanics are not. The fluid mechanics, for example, are scale-dependent [2]. For example, viscous forces are more important at small scale. Turbomachinery pressure ratios of 2:1–4:1 per stage imply turbomachinery tip Mach numbers that are in the high subsonic or supersonic range. Airfoil chords on the order of a millimeter imply that a device with room temperature inflow, such as a compressor, will operate at Reynolds numbers (the ratio of inertial to viscous forces in a fluid) in the tens of thousands. With higher gas temperatures, turbines of similar size will operate at a Reynolds number of a few thousand. These are small values compared to the 10^5–10^6 Reynolds number range of large-scale turbomachinery and viscous losses will be concomitantly larger. But viscous losses make up only about a third of the total fluid loss in a high-speed turbomachine (3-D, tip leakage, and shock wave losses account for most of the rest) so that the decrease in machine efficiency with size is not so dramatic. The increased viscous forces also mean that fluid drag in small gaps and on rotating disks will be relatively higher, and indeed are much larger influences on overall machine performance. Unless gas flow passages are smaller than one micron, the fluid behavior can be represented as continuum flow so that molecular kinetics, Knudsen number considerations, are not important.

Heat transfer is another aspect of fluid mechanics in which microdevices operate in a different design space than large-scale machines. The fluid temperatures and velocities are the same but the viscous forces are larger, so the fluid film heat transfer coefficients are higher, by a factor of about 3. Not only is there more heat transfer to or from the structure, but also thermal conductance within the structure is higher due to the short length scale. Thus, temperature gradients within the structure are reduced. This is helpful in reducing thermal stress but makes thermal isolation challenging.

For structural mechanics, it is the change in material properties with length scale that is most important. Very small length scale influences both material properties and material selection. In a centimeter diameter engine, design features such as blade tips, fillets, orifices, seals, etc. may be only a few microns in size. Here, differences between mechanical design and material properties begin to blur. The scale is not so small (atomic lattice or dislocation core size) that continuum mechanics no longer applies. Thus, elastic, plastic, heat conduction, creep, and oxidation behaviors do not change, but fracture strength can differ. Material selection is influenced both by mechanical requirements and by fabrication constraints. For example, structure ceramics such as silicon carbide (SiC) and silicon nitride (Si_3N_4) have long been recognized as attractive candidates for gas turbine components due to their high strength, low density, and good oxidation resistance. Their use has been limited, however, by the lack of technology to manufacture flaw-free material in sizes large enough for conventional engines and by susceptibility to thermal shock. Shrinking engine size by three orders of magnitude virtually eliminates these problems. Indeed, semiconductor materials such as silicon have usable strength an order of magnitude better than conventional metals. This higher strength can be used to realize lighter structures, higher rotation speeds (and thus higher power densities) at constant geometry, or simplified geometry (and thus manufacturing) at constant peripheral speed.

2.3 Overview of an MEMS Gas Turbine Engine Design

The initial designs were directed at demonstrating bench-top operation of an MEMS-based gas turbine. This implies that, for a first demonstration, it would be expedient to trade engine performance for simplicity, especially fabrication simplicity. Most microfabrication technology has been developed for silicon. Since Si rapidly loses strength above 950 K, this becomes an upper limit to the turbine rotor temperature. But 950 K is too low a combustor exit temperature to close the engine cycle (i.e., produce net power) with the component efficiencies anticipated, so cooling is required for Si turbines. The simplest way to cool the turbine in a millimeter-sized machine is to eliminate the shaft, and thus conduct the turbine heat to the compressor, rejecting the heat to the compressor fluid. This has the great advantage of simplicity and the great disadvantage of lowering the pressure ratio of the now non-adiabatic compressor from about 4:1 to 2:1 with a concomitant decrease in cycle power output and efficiency. Hydrogen was chosen as the first fuel to simplify the combustor development. This expedient arrangement was referred to as the H_2 demo engine. It is a turbojet designed with the objective of demonstrating the concept of an MEMS gas turbine. It does not contain electrical machinery or controls.

One fundamental requirement is rotor-bearing technology compatible with microfabrication and capable of stable operation at a million rpm or more. The geometric and mechanical concept upon which the gas turbine was developed is illustrated in Fig. 2.2. This radial inflow air turbine consists of an outer array of nozzle guide vanes which accelerate the flow arranged around a 4 mm diameter

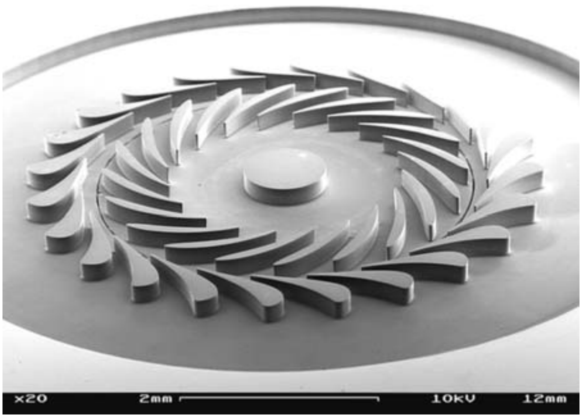

Fig. 2.2 A 4:1 pressure ratio, 4 mm rotor diameter radial inflow turbine stage

rotor which generates about 15 W of mechanical power when spinning at a peripheral speed of 250 m/s (1.2 Mrpm). The rotor is supported on airbearings at the center for axial forces and at the rotor periphery for radial forces. The device was manufactured by deep reactive ion etching (DRIE) the 400 μm tall airfoils and center thrust bearing from one side of a single crystal Si wafer and then freeing the rotor by etching the 12 μm wide journal bearing at the rotor periphery from the rear of a 600 μm thick wafer. Channels etched in capping wafers top and bottom (not shown) duct the air to turbine and the bearings. This turbine concept proved successful early in the research program so the basic arrangement – a thin disk with an air journal bearing on its periphery – was adopted for all of the devices in this program.

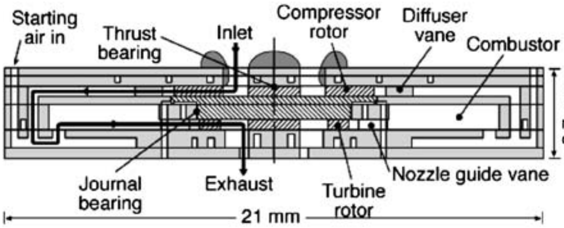

Fig. 2.3 H_2 demo engine with conduction-cooled turbine constructed from six silicon wafers

An elaboration of this geometry form the turbine and compressor of the initial H_2 demo engine design are shown in Fig. 2.3. The centrifugal compressor and radial turbine rotor diameters are 8 and 6 mm, respectively, in this first design (as fabrication capability was improved, later designs increased the component sizes). 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 radial loads are supported on a journal bearing on the periphery of the compressor. 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 pressurization. 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 μm span airfoils, the unit was sized to pump about 0.36 g/s of air to produce 0.1 N of thrust or 17 W of shaft power. A cutaway engine chip is shown in Fig. 2.4 . In this particular engine design iteration, the airfoil span (height) is 225 μm and the disks are 300 μm thick.

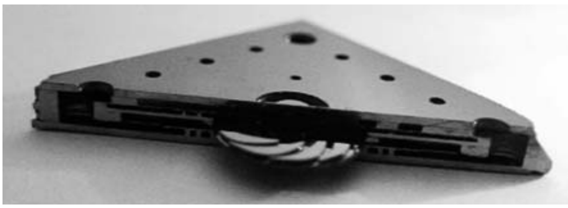

Fig. 2.4 Cutaway H_2 demo gas turbine chip. Compressor blades are evident on the rotor disk

The following sections briefly elaborate on the component technologies of this engine design. It starts with a statement on microfabrication philosophy and then goes on to turbomachinery aerodynamic design, structures and materials, combustion, bearings and rotor dynamics, and controls and accessories. A system integration discussion then expands on the high-level tradeoffs which define the design space of an MEMS gas turbine engine.

An assumption underlying the design philosophy of these devices was that they were to be consistent with MEMS batch fabrication, with as few extensions to the state-of-the-art as possible. This constrains shapes to mainly prismatic or "extruded" geometries of constant height. Ongoing research with grayscale lithography suggests that smoothly variable etch depths (and thus airfoils of variable span) may be feasible in the near term [3]. Conceptually, more complex 3-D shapes can be constructed of multiple precision-aligned 2-D layers. But layering is expensive with current technology and 6 is considered a large number of precision-aligned layers for a microdevice. Since 3-D rotating machine geometries are difficult to realize, planar geometries are preferred. While 3-D shapes are difficult to microfabricate, in-plane 2-D geometric complexity is essentially free in manufacture since photolithography and etching processes an entire wafer at one time. These are much different manufacturing constraints than are common in the large-scale world so it is not surprising the optimal machine design may also be different.

2.4 Bearings and Rotor Dynamics

The mechanical design of gas turbine engines is dominated by the bearings and rotor dynamics considerations of high-speed rotating machinery. Micromachines are no different in this regard. As in all high-speed rotating machinery, the basic mechanical architecture of the device must be laid out so as to avoid rotor dynamic problems. The high peripheral speeds required by the fluid and electromechanics lead to rotor-bearing designs which are supercritical (operate above the natural resonant frequency of the rotor system), just as they often are in conventional gas turbines.

Key design requirements imposed by the rotor dynamics are that mechanical critical (resonant) frequencies lie outside the steady-state operating envelope, and that any critical frequencies that must be traversed during acceleration are of sufficiently low amplitude to avoid rotor rubbing or unacceptable vibrations. The bearings play an important role in the rotor dynamics since their location and dynamical properties (stiffness and damping) are a major determinant of the rotor dynamics. The bearings in turn must support the rotor against all radial and axial loads seen in service. In addition to the rotor dynamic forces, the bearing loads under normal operation include all the net pressure and electrical forces acting on the rotor as well as the weight of the rotor times the external accelerations imposed on the device. For aircraft engines, this is usually chosen as 9 g, but a small device dropped on a hard floor from 2 m experiences considerably larger peak accelerations. An additional requirement for portable equipment is that the rotor support be independent of device orientation. The bearing technology chosen must be compatible with the high temperatures in a gas turbine engine (or be protected within cooled compartments) and be compatible with the fabrication processes.

Early MEMS rotating machines were mainly microelectric motors or gear trains turning at significantly lower speeds and for shorter times than are of interest here, so these made do with dry friction bearings operating for limited periods. The higher speeds and longer lives desired for microheat engines require low-friction bearings. The very small size of these devices precludes the incorporation of commercially available rolling contact bearings. A microfabricated bearing solution is needed. Both electromagnetic and air bearings have been considered for this application.

Air bearings support their load on thin layers of pressurized gas. The simplest journal bearing is a cylindrical rotor within a close-fitting circular journal. This plane cylindrical geometry was the first approach adopted since it seemed the easiest to microfabricate. Gas bearings of this type can be categorized into two general classes which have differing load capacities and dynamical characteristics. When the gas pressure is supplied from an external source and the bearing support forces are not a first-order function of speed, the bearing is termed *hydrostatic*. When the bearing support forces are derived from the motion of the rotor, then the design is *hydrodynamic*. Since the MEMS gas turbines include air compressors, both approaches are applicable. Both can readily support the loads of machines in this size range and can be used at very high temperatures. The two types of bearings have differing load and dynamic characteristics. In hydrodynamic bearings, the load capacity increases with the speed since the film pressure supporting the rotor is generated by the rotor motion. This can be true for a hydrostatic bearing as well if the film pressure is increased with increasing rotor speed, for example, if the pressure is derived from an integral compressor as is the case with an engine or motor driven compressor.

The relevant physical parameters determining the bearing behavior are the length-to-diameter ratio (L/D); the journal gap-to-length ratio (g/L); and nondimensional forms of the peripheral Mach number of the rotor (a measure of compressibility), the Reynolds number, and the mass of the rotor. For a bearing supported on a hydrodynamic film, the load bearing capability scales inversely with $(g/D)^5$ which tend to dominate the design considerations [4].

The dynamical behavior of the rotor is of first-order concern because the high rotational speeds needed for high-power density by the turbo and electrical machinery require the rotor to operate at rotational frequencies several times the lowest radial resonant frequency of the bearing/rotor system. This complex issue is discussed in Chapter 6.

A rotor must be supported against axial as well as radial loads and so requires thrust bearings in addition to the radial bearings discussed above. Both hydrostatic and hydrodynamic approaches have been demonstrated. In either approach, the bearing must support the axial loads and remain stable. The devices described in this book have been designed for sub-critical thrust bearing operation so that bearing behavior traversing the critical frequency is not an issue.