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Miniaturization Technologies for Advanced Energy Conversion and Transfer Systems

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Microfabrication technologies have made possible the development of meso-scale energy conversion and chemical processing systems with microscale features. Scaling effects, such as the linear increase in surface-area-to-volume ratio that affects surface processes such as convection heat transfer, adsorption, and catalytic chemical conversion processes, provide some of the motivation for the miniaturization efforts. Other mechanical, thermal, and fluid scaling effects are presented. Fabrication and material limitations, as well as scaling effects, must be considered in the design process and may result in miniaturized systems that are considerably different than their full-scale prototypes. System and component development efforts at Battelle Pacific Northwest National Laboratories are highlighted. A fuel atomizer for gas turbine engines and a multicomponent fuel processor for the production of on-demand hydrogen are microscale components that show potential for improving current large-scale systems. Complete miniaturized systems such as a gas turbine, a vapor-absorption heat pump, and a Joule–Thompson cryocooler could be used for mobile power production and cooling of electronics and individuals. Components for miniaturized systems include microbatteries with multiple definable voltage levels and a high degree of integratability and a combustor/evaporator for methane combustion with low levels of harmful emissions.

Introduction

TECHNOLOGIES for microfabrication have undergone some dramatic improvements since their inception in the early 1980s as extensions of processes for creating electronic circuits. These technologies include photolithographic techniques, such as the German lithographie, galvanoformung, abformung (LIGA) process; bulk and surface silicon micromachining; and the complementary processes such as energy beam machining (focused ion beam and laser), microdrilling, micromilling, microelectrical discharge machining, and microdiamond cutting and sawing. A wide variety of products with microscale features, such as sensors and actuators and inkjet printer heads, have been developed and commercialized as a result of these enabling technologies. Many more components and systems have been demonstrated over the last 10 years. These include optical devices such as switches and micro mirrors, biomedical devices such as micromachined pipette arrays for drug delivery, and acoustic devices such as immersion transducers and systems for distance measurement. A large number of microfluidic systems have also been proposed and demonstrated. Examples include liquid dosing systems, micropumps, microvalves, liquid micromotors, particle filters, injectors, microcombustors, evaporators, condensors, and heat exchangers. A natural extension is to combine subsystems and components to form complete systems for biological and chemical processing or for energy conversion. Miniaturized energy systems may be used for purposes as diverse as mobile power sources, propulsion, and cooling of electronics and individuals.

Simply having the ability to construct miniaturized versions of large-scale systems is not enough motivation to spend the time and resources to do so. However, significant motivation for their development is evident when scaling issues associated with the downsizing of components and systems are considered. This paper will introduce scaling effects related to the miniaturization of energy systems and will also present ongoing projects from Battelle Pacific Northwest National Laboratories (PNNL) and others that seek to take advantage of small scale. The energy-related projects include miniaturized systems such as a gas turbine, a vapor absorption heat pump, a fuel processor, and a Joule–Thompson cryocooler. In addition, efforts to develop components such as microbatteries and a combustor/evaporator are introduced.

Scaling Effects

One of the earliest reports of a miniaturized energy system was that of Nakajima et al.[1] in which they describe the development of a meso-scale Stirling engine. The engine has an overall length, width, and height of, at most, several centimeters, weighs approximately 10 g, and has a piston swept volume of 0.5 cm^3. The engine output power is approximately 10 mW at 10 Hz with a power-to-weight ratio of 100 W/kg. A scale analysis was conducted to assess the influence of various physical phenomena that may change with the scale reduction. It was assumed that physical characteristics such as thermal conductivity, modulus of elasticity, friction factor, density, and viscosity are fixed. In addition, the working gas pressure, temperature, and engine speed are also assumed to be constant. The scale analysis results for the mechanical parameters have been updated and are presented in Table 1. The scale factor d represents a linear dimension, and the scale factor per unit volume was obtained by dividing the scale factor by the volume scale factor d^3. The scale factor per unit volume is of interest here because the trend of all parameters may be considered on a per engine output power basis (also scales as d^3).

The scale analysis may be used to decide if a large-scale part is to be simply downsized or if complete redesign is required to

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Table 1 Geometric scaling of some mechanical parameters

Parameter	Equation	Scale factor	Scale factor per unit volume	Nomenclature
Mass	$m = \rho V$	d^3	1	ρ = density, V = volume
Force due to pressure	$f_p = pA$	d^2	d^{-1}	p = pressure, A = area
Force due to gravity	$f_g = mg$	d^3	1	g = acceleration due to gravity
Force due to inertia	$f_i = m\,\mathrm{d}^2 x/\mathrm{d}t^2$	d^4	d	x = displacement, t = time
Force due to thermal expansion	$f_t = CA$	d^2	d^{-1}	C = const
Friction force due to pressure	$f_{fp} = \mu f_p$	d^2	d^{-1}	μ = coefficient of friction
Friction force due to gravity	$f_{fg} = \mu f_g$	d^3	1	——
Friction force due to inertia	$f_{fi} = \mu f_i$	d^4	d	——
Friction force due to thermal expansion	$f_{ft} = \mu f_t$	d^2	d^{-1}	——
Stress due to pressure	$\sigma_p = f_p/A$	d^2	——	——
Stress due to gravity	$\sigma_g = f_g/A$	1	——	——
Stress due to inertia	$\sigma_i = f_i/A$	d	——	——
Stress due to thermal expansion	$\sigma_t = f_t/A$	d^2	——	——
Linear spring constant	$k = 2UV/\delta^2$	d	d^{-2}	U = strain energy per unit volume, δ = displacement
Natural frequency	$f = C(k/m)^{1/2}$	d^{-1}	d^{-4}	
Moment of inertia	$I = Cmr^2$	d^5	d^2	r = radius of rotating body

accomplish the same end function. Based on the scale analysis, Nakajima et al.[1] came to the following conclusions:

1) The piston sliding motion in the cylinder is not desirable because the gas-pressure-induced friction force per output power increases as the engine size is reduced. It was suggested that a bellows mechanism be used instead.

2) A traditional crank-flywheel mechanism is undesirable because the flywheel capacity per output power is reduced significantly with size.

3) A free-piston mechanism that uses the resonance of a gas spring is often used as a replacement to a flywheel; however, it is not suitable in a microengine because the resonance frequency increases significantly as engine size is reduced. These three design decisions are examples of scale analysis application.

The scaling of thermal fluid phenomena is more complex than that of the mechanical parameters. Barron[2] has presented scale factors for some of the important heat transfer phenomena. Conduction would appear to scale with d from Fourier's law, given as $q_{\mathrm{cond}} = -kA\,\mathrm{d}T/\mathrm{d}x$, where q_{cond} is the rate of conduction heat transfer, k is thermal conductivity, and T is temperature. However, when the thickness of the conduction layer becomes smaller than about 7 times the phonon mean free path, microscale effects become evident because the value of k will decrease from that of the bulk material due to boundary effects. The transient response of a material to a sudden change in a boundary condition scales with d^2 indicating that the time response is generally quite rapid on the microscale. Internal convection scaling depends on the nature of the flow. For laminar fully developed flow (most microtube flow is laminar), the heat rate q_{conv} scales with d whereas the heat flux q''_{conv} scales with d^{-1}. The pressure drop for constant mass flow rate in laminar internal flow scales as $\Delta p \sim d^{-4}$. Thus, the heat transfer is much less sensitive to scale than the pressure drop. The scale effects for external convection, radiation, and phase change processes are more complicated and are not presented here.

Another scaling effect is the cube-square law, so named because volume (and mass) scale with the cube and surface area with the square of a linear dimension. Surface phenomena, such as convection heat transfer and adsorption, increase linearly as a device is scaled down linearly. Thus, devices such as heat exchangers and vapor-absorption refrigeration systems benefit from the cube-square law. Power-producing energy conversion systems, such as the microscale turbine under development at Massachusetts Institute of Technology (MIT),[3] also benefit greatly from the cube-square law. If the power per unit of airflow is constant, then the power-to-weight ratio will increase linearly as the engine size is reduced. The surface-area-to-weight ratio of a rotating component such as a turbine or compressor rotor also benefits from the cube-square law, which allows the relatively large loads to be supported by miniature air bearings.[3] Chemical reaction times are invariant with scale; however, small sizes result in reduced flow residence time. Mixing of chemical components, such as a fuel and its oxidant, is a major portion of the total combustion time, and mixing times are scalable.

Micromachining technologies are limited in most cases to two-dimensional planar geometries, thus limiting device dimensions. For example, the upper limit in silicon micromachining is set by the etching-depth capability (currently a few hundred micrometers). The lower limit is set by feature resolution and aspect ratio capabilities of the microfabrication process. A wide variety of materials may be used for microscale parts; however, silicon is the material of preference in many cases. The strength of brittle materials is scale-dependent due to the reduced probability of flaws. Therefore, microfabricated parts that are made of materials that are defect free will be stronger than their macroscale counterparts.

Complicating the scaling analysis are microscale phenomena that have been shown to cause deviation of convection heat transfer and fluid dynamic behavior from the macroscale correlations and theory. A number of studies[4] have considered single-phase internal flow in tubes and conduits that have characteristic dimensions from one to several hundred micrometers. These studies have primarily concentrated on the flow rate (or the Reynolds number) effect on pressure drop (or the nondimensional friction factor). Unfortunately, the currently available experimental data in microchannels is inconclusive. There is an apparent microscale effect that causes deviation from the macroscale predictions at dynamically similar conditions; however, the actual effect may be due to a number of factors such as viscosity variation near the surfaces, slip flow at the boundaries, compressibility, and microcontinuum effects.[5] A limited number of experimental studies have attempted to determine the effect of Reynolds number on the heat transfer coefficient (or Nusselt number).[6] Nusselt number data in the laminar regime have shown an unexpected Reynolds number dependence, whereas in the apparent turbulent regime the Nusselt number is increased by as much as a factor of 2 over the macroscale prediction from accepted correlations at dynamically similar conditions. These results indicate that the Reynolds analogy may be invalid at the microscale. The limited amount of available data as well as the inconclusive nature of the fluid studies suggest that considerable more work will be required to quantify the apparent microscale effects.

Design tradeoffs related to issues of heat transfer, fluid mechanics, electric performance, structural design, and fabrication methods must be made in the design of a miniaturized energy system, just as they must be made at the macroscale. The physics and mechanics of scale, as mentioned, affect these design decisions and may result in a miniaturized system quite different than its macroscale prototype. Examples of ongoing efforts that utilize the scaling benefits to develop miniaturized energy conversion systems and chemical processing systems are given in the following section.

Examples

In the field of advanced energy conversion and transfer systems, micromachining technologies are used in two ways. One approach is to microfabricate individual components of a large-scale system to improve the system. Another method is to design and build a completely new microscale device with functionality comparable to a macroscale system. Examples of both of these approaches are presented.

A. Component Development for Macrosystems

Researchers at Case Western Reserve University have recently presented their ongoing efforts in fabricating fuel atomizers for gas turbine engines.[7] The fuel atomizers are micromachined in nickel and silicon carbide and are a continuation of the earlier research on silicon atomizers that suffered significant wear under corrosive operational conditions. The nickel atomizers are fabricated using LIGA micromolds and nickel electrodeposition. Because the thickness of the nickel structures is 200 μm, the atomizer is constructed from two halves. The silicon carbide atomizers are fabricated using deep reactive ion etching of silicon for micromold formation, followed by chemical vapor deposition of silicon carbide. The silicon micromold depth, and thus the silicon carbide structure thickness, is 400 μm.

Both silicon carbide and nickel atomizers perform well at pressures above 2500 kPa with silicon carbide devices exhibiting superior erosive wear resistance. Performance tests show average flow rates of approximately 4 and 3.2 kg/h, for silicon carbide and nickel, respectively, for devices at 600 kPa, compared to 4.6 kg/h for the Si atomizers.

A fuel processor is a critical component for the development of proton exchange membrane-based fuel cells for both portable and stationary applications. The fuel processor produces hydrogen rich streams from hydrocarbon-based feedstock in a multistep process. The conventional fuel processing technology is based on fixed-bed reactors, which do not scale well with the small modular nature of fuel cells. Microchannel reactor-based fuel processors, however, are small, efficient, modular, lightweight, and potentially inexpensive. The conventional fuel processors that are based on fixed-bed technology are at least an order of magnitude larger than the microchannel reactor fuel processor. Heat transport limitations, which dramatically increase size of the conventional technology, are mitigated using micromachining technologies.

A fuel processor for transportation applications has several components, schematically shown in Fig. 1. The fuel processor contains multiple reactors in series. A primary conversion step produces synthesis gas from either partial oxidation (POx), steam reforming, or autothermal reforming. A second step, the water gas shift (WGS) reactor, converts carbon monoxide (in presence of hydrogen) and water to carbon dioxide and carbon dioxide and hydrogen. An additional gas cleanup reactor preferentially oxidizes (PrOx) the remaining carbon monoxide to carbon dioxide. The final step in the integrated fuel processor system is a vaporizer for liquid hydrocarbon feedstock.

PNNL researchers have recently demonstrated one of the mesoscale components of a fuel processor, the vaporizer.[8] The microchannel vaporizer was demonstrated at both a bench scale and full scale for automotive applications at the 50-kW size. The bench-scale vaporizer, shown schematically in Fig. 2, consists of two stacked plates (reactor and heat exchanger). Each plate is $7.6 \times 10.2 \times 0.64$ cm^3. The reactor plate has four parallel catalyst-covered porous-metal

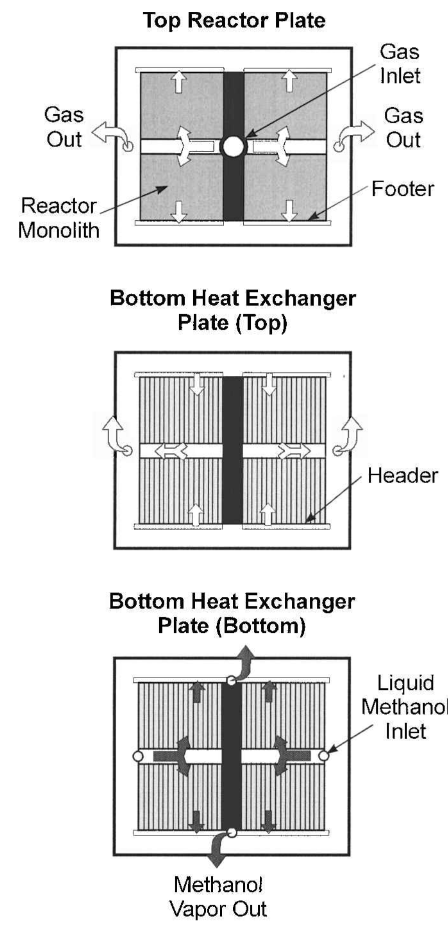

Fig. 2 Full-scale microchannel vaporizer with four reactor and heat exchange cells: gray arrows flow of methanol and white arrows flow of reactant gas.

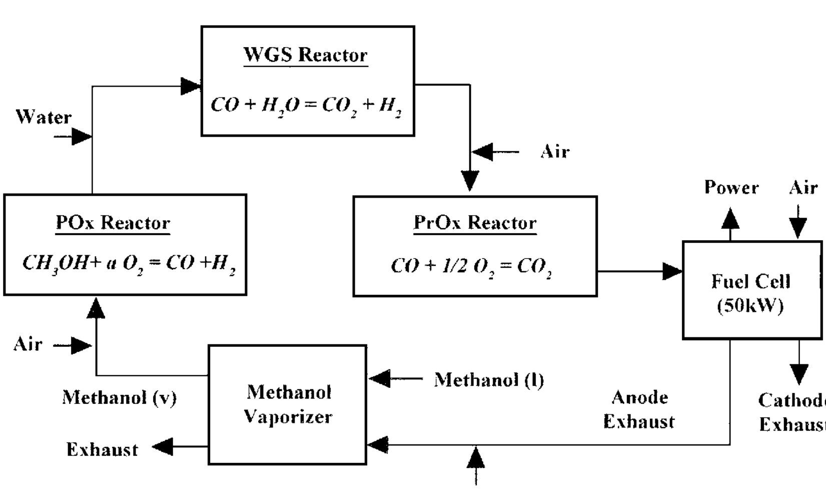

Fig. 1 Fuel processor and fuel cell system for transportation applications.

reactors. The inlet gas stream enters at the center of the top plate and segregates between the four reactive monoliths where the catalytic reaction process occurs. The split hot gas (>400°C) flows through four parallel slits in the four monolith footers to the parallel headers of the four cells on the top surface of the heat exchange plate below. A cell is defined as a cluster of parallel microchannels that operates in parallel to other cells. After passing through the heat exchanger plate, the cooled gas flows back up through a hole in the reactor plate and out the top of the vaporizer. The cooling fluid (evaporating methanol) enters in two ports in the bottom surface of the heat exchanger plate. Each fluid stream divides and flows countercurrent to the gas stream through four parallel cells. Fluid streams recombine in two exit ports.

The full-scale vaporizer requires two parallel processing units to vaporize the required fuel for an automobile. The vaporizer is capable of processing nearly 1000 l/min of gas at standard temperature and pressure. The total system pressure drop after optimization is expected to be less than several thousand pascal with thermal efficiencies exceeding 90%.

The second meso-scale component of a fuel processor demonstrated by PNNL is a catalytic partial oxidizer, shown schematically in Fig. 3.[9] The oxidizer is based on a microchannel chemical reactor and consists of nine stacked metal sheets. The base metal ($7 \times 3.8 \times 0.4$ cm^3) is stainless steel, and each sheet has 37 parallel channels. Individual channels are 254 μm wide, 1500 μm deep, and 3.5 cm long. The PNNL researchers used the microchannel reactor to demonstrate nonequilibrium chemistry of methane POx. The microchannel reactor architecture has proven to be suitable for POx of methane and is expected to play an instrumental role in the future meso-scale fuel processing units that produce hydrogen on demand.

B. Meso-Scale Energy Conversion and Transport Systems

MIT is developing a meso-scale gas turbine microengine. Such a device will be capable of providing over 10 times the energy and power density of the best batteries available today. In addition to power generation, such microengines could become the enabling technology for micro-air-vehicle control, microrefrigeration, microrocket propulsion, automotive fuel pumps, and mobile power units.[3,10] A feasibility study and preliminary design estimates presented by Epstein et al.[11] show that a device requiring 7 g of jet fuel per hour could produce 10–100 W of electrical power. The detailed calculations indicate that the meso-scale engine would provide a thrust-to-weight ratio of about 100:1, compared with 10:1 for the best modern aircraft engines.

MIT researchers plan to demonstrate manufactureability of all of the meso-scale gas turbine microengine components in silicon first, while silicon carbide microfabrication methods are being developed. MIT researchers have already manufactured a radial inflow turbine wheel from silicon using deep reactive ion etching. The wheel is 4 mm in diameter with a 200-μm blade span and 10-μm bearing gap between the rotor disk and the stator plate. During operation, the wheel will spin at 2.5×10^6 rpm. With minor changes in the airfoil shapes, the same component can function as a centrifugal compressor wheel. The highly integrated design is 12 mm in diameter and 3 mm in height.

A hydrogen–air microcombustor has been fabricated from silicon using deep reactive etching as well.[10] The microcombustor includes a fuel manifold, injector holes, and a combustion chamber measuring less than 0.07 cm^3 in volume and has been demonstrated to sustain premixed and nonpremixed hydrogen combustion providing exit temperatures of up to 1800 K.

In a number of microclimate control applications, individuals must wear protective clothing that significantly reduces heat transfer from the body. Examples include workers exposed to hazardous materials, police wearing body armor, and military personnel exposed to nuclear, biological, or chemical (NBC) warfare agents. The threat from NBC warfare agents on the modem battlefield imposes a substantial burden on U.S. military forces. Present and future individual equipment for military personnel includes a protective suit. Whereas such uniforms provide protection against hazards, they significantly decrease an individual's military effectiveness. Personnel performing labor intensive tasks in a hot environment are susceptible to heat stress, especially when wearing protective clothing. The time that can be spent performing essential tasks before succumbing to heat injury is limited under these conditions. Supplemental cooling will permit tasks to be performed with enhanced efficiency and reduced heat stress when personnel are under hazardous conditions in warm or hot climates. Available cooling systems can be integrated with protective suits, but are too heavy to carry for extended periods. A portable system capable of an 8-h operation, with a cooling capacity of 350 W, weighs more than 10 kg.

An ongoing research effort at PNNL focuses on development of the components necessary for a miniature LiBr/H_2O heat pump. All components of the single-effect chemical heat pump have been demonstrated (Fig. 4), including a water-cooled condenser and absorber, an evaporator that chills water, a microchannel combustor with exhaust gas at 250°C, and a desorber that uses the exhaust gas for its heat source. The condenser consists of an array of microchannels with channel widths between 100 and 300 μm and channel depths of up to 1 mm. Heat transfer rates in excess of 30 W/cm^2 were attained with small temperature difference and low pressure loss. The evaporator also consists of an array of microchannels with channel widths between 100 and 300 μm and channel depths of up to 1 mm and produces heat transfer rates of up to 100 W/cm^2. The desorber uses a strong refrigerant solution to form an ultrathin film approximately 100 μm thick, which increases performance by a factor of 10 in comparison with conventional systems.

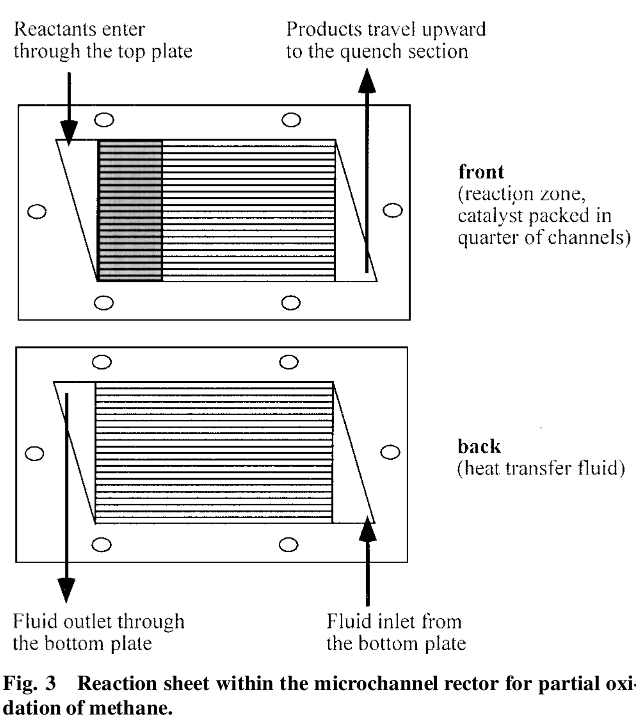

Fig. 3 Reaction sheet within the microchannel rector for partial oxidation of methane.

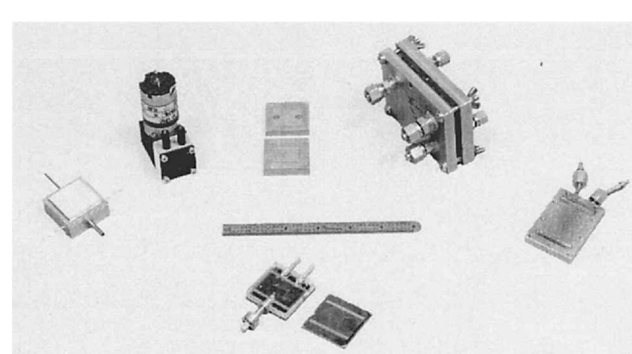

Fig. 4 Single-effect LiBr/H_2O heat pump components.

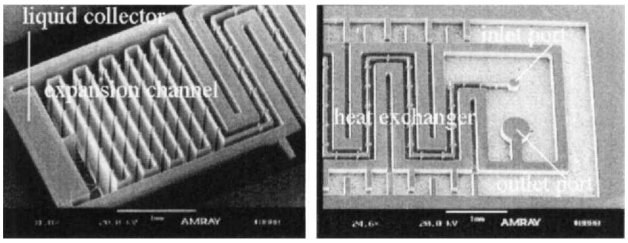

Fig. 5 SEM micrographs showing features of a negative LIGA exposure (by Institute for Micromanufacturing, Louisiana Technical University) of a miniature Joule–Thomson cryocooler (design by iMM, Mainz, Germany) in PMMA.

By taking advantage of the high rates of heat and mass transfer attainable in the microstructural components, PNNL has developed a complete miniature chemical heat pump with a cooling capacity of 350 W that weighs only 0.65 kg (Ref. 12). Compared to a macroscale heat pump, this was achieved with a factor of 60 reduction in volume. A complete manportable cooling system, including the heat pump, an air-cooled heat exchanger, batteries, and fuel, will weigh an estimated 4–5 kg.

Low temperatures provide an excellent operating environment for conventional and superconducting electronics by increasing speed of digital systems and improving signal-to-noise ratio and bandwidth of analog devices. There is a broad range of applications that use cold electronics, including computers, amplifiers, mixers, fast AD/DA converters, and infrared detectors. Whereas a range of cooling techniques is available for cooling such devices, most of these techniques are often largely oversized.

A Joule–Thompson microcooler is under development by the Micromechanical Transducers Group at the University of Twente, The Netherlands. The microcooler uses the Joule–Thompson expansion of high-pressure nitrogen gas that is compressed by a sorption compressor. The microcooler is expected to operate at temperatures of 60–80 K, produce net cooling power of 5–50 mW, and have the total size of less than 250 cm^3.

A similar device is being developed at the University of Utah. Figure 5 shows scanning electron microscope (SEM) micrographs of an LIGA exposure in polymethylmethacrylate (PMMA) of a German design (iMM, Mainz, Germany) for a microscale open-flow Joule–Thompson device. Note that this is a negative; the darker built-up regions define a mold that is electroplated to form three sides of the actual channels. The PMMA is then chemically removed leaving the desired structure. The three-sided metal channels are then sandwiched between two thin external insulation layers to enclose the channels. The inlet channel (hot fluid) is approximately 50 μm wide, whereas the outlet channel (cold fluid) for the heat exchanger is approximately 250 μm wide.

Several problems related to the small size of the Joule–Thompson cryocooler are of current interest. Interconnects with the external N_2 gas supply must be flexible yet robust to withstand the high inlet pressures (on the order of 4 MPa). Adhesion of the two external insulation layers with the central structural layer is also affected by the high gas pressures. Because the outer insulating layers are thin, both fluids in the central heat exchanger portion of the device may be exposed to significant heat transfer with the surroundings. The outcome of this heat addition will be to increase the temperatures of both fluid streams, which results in performance degradation for the Joule–Thompson device. For complete device realization, solutions to these problems, and others not mentioned, must be found.

C. Microscale Components

Thin-film rechargeable batteries with active layers on the order of 1–10 μm have been a topic of interest since the early 1980s. Such microbatteries provide a small, rechargeable, easily integratable power solution. Microbatteries can be fabricated using automated assembly techniques developed for electronic systems, which would sharply decrease the cost. Some of the performance advantages of microbatteries that can be critical to specific system applications include multiple definable voltage levels, high level of integratability, and better power distribution.

Thin-film microbatteries using a metallic lithium electrode layer and solid Li_3PO_4 electrolyte have been described by Bates et al.[13] These batteries have lateral dimensions greater than a centimeter and produce relatively low current densities (8.3 μA/cm^2 at output voltage of ~4 V). Salmon et al.[14] have recently presented microbatteries based on a Ni/Zn electrochemical couple and an aqueous KOH electrolyte. Fabrication of microbatteries involves electrodeposition of the bottom Ni electrode, removal of a sacrificial polyimide layer that defines the electrolyte cavity, thermal evaporation of the top Zn electrode, and sealing of the formed cell. The completed planar microbatteries are 200×200 μm^2 and provide capacities of 200–300 mC/cm^2 at current densities of 10–20 mA/cm^2. Given an operating voltage of approximately 1.5 V, these batteries produce power densities of 15–30 mW/cm^2. Six batteries connected in parallel produce an average current density of 12.2 mA/cm^2 with an adequate cycle life of 265 cycles.

The U.S. Department of Defense is investigating ways to improve the soldier system. A soldier of the future may require lightweight and compact sources of electric power and microclimate control similar to the earlier described meso-scale chemical heat pump. If such is the case, thermal energy could drive the electrical generation and provide the energy source for the heating or cooling. Combustion of hydrocarbon fuels produces high-density thermal energy 100 times greater than the most advanced batteries.

PNNL has developed a microchannel combustor/evaporator that heats water using methane combustion through the funding of the Defense Advanced Research Projects Agency.[15] A schematic of the combustor is shown in Fig. 6. The overall dimensions of the unit are $5 \times 5 \times 1.5$ cm^3. The entire unit is constructed of 7000 series aluminum alloy. Premixed air and natural gas are introduced into the combustion chamber, where they are ignited with a spark. The flame holder is a 2-μm sintered metal plate. During operation, the flame sits approximately 2 mm from its surface. After burning, the gases impinge on the top of the combustor wall, separate into two horizontal streams, and enter the heat exchanger microchannels. The combustion products are cooled in an array of approximately 200 microchannels that are 2 mm tall, 15.8 mm long, and 250 μm wide. Whereas the lower side of the top plate has the gas-side microchannels, the upper side of this same plate has cooling water microchannels that extend across both the combustion and microchannel regions. The flowing water cools the gases passing through the microchannels following the combustion.

The combustor was studied over a range of stoichiometries and gas and water flow rates. For these tests, the thermal efficiency

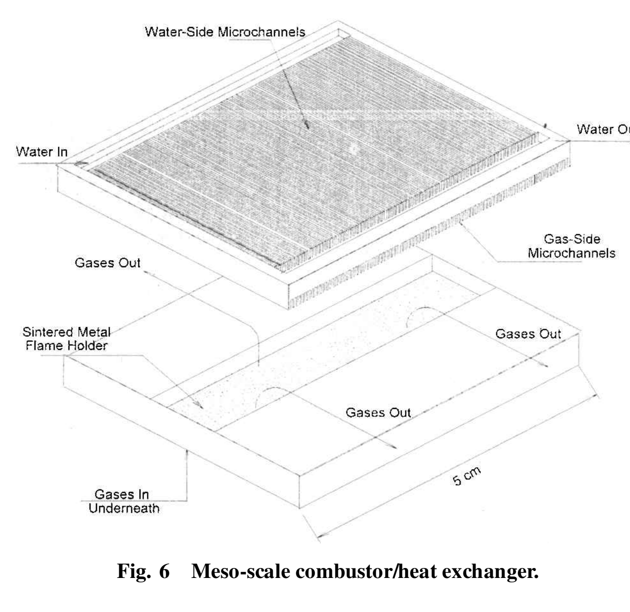

Fig. 6 Meso-scale combustor/heat exchanger.

ranged from 74 to 91%, with the highest efficiencies at low methane flow rates and equivalence ratios. Heat transfer rates of between 8.5 and 21 W/cm^2 were achieved over the range of conditions. The NO_x emission levels were less than 20 ppm, which is below the southern California limit of 30 ppm. Through the use of fuel-lean flame, plasma processing, feed preheating, and combustor insulation, the CO emissions were kept below 1000 ppm. The future work at PNNL will focus on further reducing CO emissions to below the southern California limits of 400 ppm.

Conclusion

Micromachining technologies have been used to develop mesoscale energy conversion and chemical processing systems. Mechanical, thermal, and fluid scaling effects have been reviewed because they are often the motivation behind the miniaturization efforts. Consideration of these scaling effects and the fabrication and material limitations often produces systems that are considerably different from their macroscale counterparts. Some of the microscale components that show potential for improving large-scale systems include a fuel atomizer for gas turbine engines and a multicomponent fuel processor for on-demand production of hydrogen. Several of the miniaturized energy systems include a gas turbine, a vapor-absorption heat pump, and a Joule–Thompson cryocooler. Components for miniaturized systems include microbatteries and a combustor/evaporator for methane combustion. These miniaturized components and systems represent an exciting and promising new direction in the field of advanced energy conversion.

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