Micro-Power Generation Using Combustion: Issues and Approaches

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ABSTRACT

The push toward the miniaturization of electro-mechanical devices and the resulting need for micro-power generation (milli-watts to watts) with low-weight, long-life devices has led to the recent development of the field of micro-scale combustion. The concept behind this new field is that since batteries have low specific energy, and liquid hydrocarbon fuels have a very high specific energy, a miniaturized power generating device, even with a relatively inefficient conversion of hydrocarbon fuels to power would result in increased lifetime and/or reduced weight of an electronic or mechanical system that currently requires batteries for power. In addition to the interest in miniaturization, the field is also driven by the potential fabrication of the devices using Micro Electro Mechanical Systems (MEMS) or rapid prototyping techniques, with their favorable characteristics for mass production and low cost. The micro-power generation field is very young, and still is in most cases in the feasibility stage. However, considering that it is a new frontier of technological development, and that only a few projects have been funded, it can be said that significant progress has been made to date. Currently there is consensus, at least among those working in the field, that combustion in the micro-scale is possible with proper thermal and chemical management. Several meso-scale and micro-scale combustors have been developed that appear to operate with good combustion efficiency. Some of these combustors have been applied to energize thermoelectric systems to produce electrical power, although with low overall efficiency. Several turbines/engines have also been, or are being, developed, some of them currently producing positive power, also with low efficiency to date. Micro-rockets using solid or liquid fuels have been built and shown to produce thrust. Hydrogen-based micro size fuel cells have been successfully developed, and there is a need to develop reliable reformers (or direct-conversion fuel cells) for liquid hydrocarbons so that the fuel cells become competitive with batteries. In this work, some of the technological issues related to meso and micro-scale combustion and the operation of thermochemical devices for power generation will be discussed. Some of the systems currently being developed will be presented and described.

INTRODUCTION

The last few years have experienced a growing trend in the miniaturization of mechanical and electro-mechanical engineering devices, which follows that initiated by the areas of microelectronics, biomechanics, and molecular biology, and that is in large part the result of the progress made in micro-fabrication techniques. High precision fabrication of devices in the centimeter scale range are being made using micro-fabrication techniques such as electro-discharge machining (EDM), laser beam machining (LBM) or focused ion beam machining (FIBM) [1,2]. Devices in the millimeter scale range are being fabricated using Micro-Electro-Mechanical Systems (MEMS), rapid prototyping and batch-manufacturing techniques [3,4], and materials that are similar to those used in the integrated circuit /microchip industry. Although initially the micro-devices produced using EDM, LBM or FIBM were primarily related to biomedicine, and those fabricated using MEMS were sensors and actuators, recently other more complex mechanical devices such as pumps, motors, micro-rovers, and micro-airplanes are being developed. The interest in producing miniaturized mechanical devices opens exciting new opportunities for combustion, especially in the field of micro-power generation, because of the need for power supply devices with high specific energy (small-size, low weight, long duration).

Typical portable consumer electronics suffer from short operation cycles between charges or replacement, and their overall weight consists largely of battery weight. Similarly, other more advanced MEMS based devices depend on battery systems that occupy significant fractions of both mass and volume of the entire device. A typical example of this problem is depicted in Fig. 1 that shows a MEMS sensing /communication network device of a few mm^3 volume powered by one of the smallest batteries currently available [5]. Miniature mechanical devices such as micro-rovers, micro-robots, and micro-airplanes are also limited by the weight of the available power systems. The need to reduce system weight, increase operational lifetimes, and reduce unit cost has engendered the field of micro-power generation [6-9], high-specific-energy micro-electro-mechanical power systems.

The concept behind this new field is to utilize the high specific energy of liquid hydrocarbon fuels in combustion driven micro-devices to generate power. The potential advantage of using liquid hydrocarbon combustion to produce power is shown graphically in Fig. 2. Liquid hydrocarbons have an extremely high specific energy, (typically 45 MJ/kg), are easily transportable and are quite safe [10]. Top batteries currently available (Lithium) have an energy density of 1.2 MJ/kg (0.6 MJ/kg for an Alkaline battery). Thus, a miniature combustion device with a mere 3% system efficiency would compete with top batteries simply from the fact that the fuel is easily replaceable. Although higher efficiencies are needed for combustion systems to displace batteries, the high efficiencies obtained in large-scale power systems encourage the development of miniaturized power generation devices using combustion, with the expectation that devices with competitive efficiencies can be developed. Furthermore, there are specific applications were mechanical power, or simply heat, is desired (rovers, airplanes, Stirling engine, etc) and were a combustion based device will have the added advantage of providing this power directly. In addition to the interest in miniaturization, the field is also driven by the potential fabrication of the devices using MEMS or rapid prototyping techniques, with their mass production and low cost characteristics. There is of course the added issue of environmental considerations related to the use of combustion. Given the small size of the devices being considered, however, their CO_2 and H_2O emissions and heat release would be comparable to that of the human being for the meso-scale size, and significant less for the micro-scale ones [11]. Since it is likely that the micro-devices will have combustion efficiencies smaller than those of the larger devices, it is expected that the fractional production of unburned hydrocarbons and CO, will be comparatively larger. On the other hand, batteries have their own environmental issues, and their production and disposal present an environmental hazard.

The power-generation devices addressed in the present review are those that aim to generate power in the range of a few watts to milliwatts. This is in contrast with the so-called micro-turbines, which generate power of the order of kilowatts and are not "micro" in the present sense but rather in the sense of being smaller than their larger counterparts. Power generation in the watts range has multiple applications, such as electronic devices (laptops, phones, etc), and miniaturized mechanical systems (small robots, rovers, airplanes, etc.). The corresponding combustion devices are of the order of one centimeter in size (meso-scale), and their micro-fabrication techniques are relatively conventional (EDM), in some cases with some MEMS components. Power generation in the milliwatt range (micro-scale) has its application primarily in micro-electronic components (sensors, transmitters, etc), with the ultimate goal of incorporating the power-generation device into the micro-electronic component. These power generation devices are constructed using primarily MEMS. The ultimate goal is to have "power generation in a chip". The system would then incorporate in the same unit the power device, the microprocessor to control the overall system, and some sort of sensor/emitter or actuator.

The micro-power generation field is young (4 to 6 years) because its interest has resulted from the recent development of fabrication techniques to miniaturize mechanical devices, and still is in most cases in the feasibility stage. However, considering that it is a new frontier of technological development, and that only a few projects have been funded to date (primarily by government agencies that fund advanced conceptual projects, such as DARPA [8,9]), it can be said that significant and encouraging progress has been made. Several micro-combustors have been fabricated that appear to operate with good combustion efficiency [12-14]. Some of these combustors have been applied to energize thermoelectric systems to produce power. The system efficiency is currently too low, but the limitation appears to be in the thermoelectric component and not in the combustion process itself. Several turbines/engines have also been or are being developed, some of them currently producing positive power, although again with low efficiency [6,15,16]. Here the problem appears to be in fabrication and thermal management that either limit the tolerances in moving parts (leakage, low compression ratio), or cause reduced efficiency of individual components (compressor, combustion chamber). Fuel cells are also being developed [17], and although not a combustion device, they have issues that are of interest to the combustion community. Although hydrogen-based micro-fuel cells have been successfully developed [17], there is a need to produce reliable reformers (or direct conversion fuel cells) so that they can be used with liquid hydrocarbons, and can become competitive with the batteries. Still not looked at is the potential complementarity of the different systems (cogeneration), such as using the exhaust heat from engines to run thermoelectric generators, fuel cell reformers, or Stirling engines. The combined systems could result in improved overall conversion efficiencies. Also worth mentioning is that small-scale combustion has other useful applications than power generation and heat production for use in power cycles. Positioning of localized heat is an example of its potential applications. Another interesting example is the use of arrays of meso-scale burners to produce distributed combustion in large scale gas turbine combustors, which has the potential for inter-turbine reheat, and for premix or highly vitiated combustion, to reduce NOx [18].

Some of the technological issues related to micro-scale combustion and thermo-chemical devices for power generation are discussed below. Many of the systems currently being developed are also presented and briefly discussed.

THERMOPHYSICAL ISSUES

The characteristic length of the micro-combustors being developed to date, even in MEMS size systems, is sufficiently larger than the molecular mean-free path of the air and other gases flowing through the systems that the physical-chemical behavior of the fluids is fundamentally the same as their macro-scale counterparts. For example, the Knudsen number for air flowing through a 0.1 mm wide channel is of the order of 10^{-3}, which is much smaller than that for free-molecule flow (Kn >1). Consequently, the standard hypotheses of thermo-fluid such as the no-slip condition and the continuum medium will still apply. However, the small size of the micro-devices or their components causes particular characteristics of the fluid mechanics, heat transfer and combustion involved in the device operation.

Some of the scaling issues involved in micro-combustors can be understood by normalizing the conservation equations of momentum, energy, and species in terms of the characteristic length and parameters of the device, and analyzing their terms as the length scale is reduced. The normalized 1-D form of the governing equations for the gas and solid phase and their relevant boundary conditions can be written as (symbols are defined in the nomenclature)

$$\frac{l_c}{t_c u_c}\frac{\partial \overline{u}}{\partial \overline{t}} + \overline{u}\frac{\partial \overline{u}}{\partial \overline{x}} = -\frac{p_c}{\rho_c u_c^2}\frac{1}{\overline{\rho}}\frac{\partial \overline{p}}{\partial \overline{x}} + \frac{1}{\mathrm{Re}}\overline{\nu}\frac{\partial^2 \overline{u}}{\partial \overline{x}^2} + \frac{g l_c}{u_c^2} \qquad (1)$$

$$\frac{l_c}{t_c u_c}\frac{\partial \overline{T}}{\partial \overline{t}} + \overline{u}\frac{\partial \overline{T}}{\partial \overline{x}} = \frac{1}{\mathrm{Pe}}\overline{\alpha}\frac{\partial^2 \overline{T}}{\partial \overline{x}^2} + \mathrm{Da}\frac{Q}{\overline{C}_p T_c}\overline{\dot{w}''} \qquad (2)$$

$$\frac{l_c}{t_c u_c}\frac{\partial \overline{y}_i}{\partial \overline{t}} + \overline{u}\frac{\partial \overline{y}_i}{\partial \overline{x}} = \frac{1}{LePe}\overline{D}\frac{\partial^2 \overline{y}_i}{\partial \overline{x}^2} + Da\frac{1}{y_{ic}}\overline{\dot{w}''} \qquad (3)$$

$$\frac{\partial \overline{T}_s}{\partial \overline{t}} = Fo\overline{\alpha}_s\frac{\partial^2 \overline{T}_s}{\partial \overline{x}^2} \qquad (4)$$

The relevant normalized boundary conditions for these equations are:

$$\overline{u} = 0 \qquad \overline{\tau} = \frac{\mu_c u_c}{\tau_c l_c}\overline{\mu}\frac{\partial \overline{u}}{\partial \overline{y}}$$

$$\overline{T} = \overline{T}_w \qquad \lambda_s\frac{\partial \overline{T}_s}{\partial \overline{x}} = \lambda\frac{\partial \overline{T}}{\partial \overline{x}} \qquad \frac{\partial \overline{T}_s}{\partial \overline{x}} = Bi\left(\overline{T}_s - 1\right)$$

$$\overline{y}_i = 0 \qquad \frac{\partial \overline{y}_i}{\partial \overline{x}} = \left(LePe\right)\overline{y}_i$$

The characteristic length of the components of large power systems is large and generally the Reynolds and Peclet numbers are also large. Thus the fluid flows are mostly turbulent, and as seen from Eqs. (1) –(3) the viscous and diffusive effects are small compared to the convective effects. It is also deduced that the characteristic time in these convective dominated flows is $t_c = l_c / u_c$, which is normally referred to as residence time. The boundary conditions provide information about wall effects that usually have a small influence on the overall system.

As the size of the devices is reduced, the character of the governing equations and the importance of the different terms in the equations change. As the characteristic length of the device is reduced, the Reynolds and Peclet numbers decrease and fluid flow tends to be less turbulent, so the viscous effects and the diffusive transport of mass and heat become increasingly important. From the point of view of combustion, an important issue is the magnitude of the residence time, because it decreases as the length of the combustor decreases, and it has to be larger than the chemical time, $t_c = \rho_c / \dot{w}''$, for complete combustion to occur.

For micro-devices (MEMS scale) with very small characteristic lengths and consequently small Reynolds and Peclet numbers, the flow is primarily laminar. Also as can be seen from Eqs. (1)-(3), the viscous and diffusive terms can become dominant, and the convective and buoyant effects become negligible. In this case the characteristic time becomes $t_c = l_c/u_c \, Pe = l_c^2/\alpha_c$ (for unity Prandtl and Lewis numbers), normally referred to as the diffusion time. Since turbulent mixing is small, species mixing will be primarily by diffusion. In this regard the diffusion time is important since it has to be smaller than the residence time for complete mixing to occur.

Concerning combustion, the source term of Eq. (2) becomes factored by Pe, which gives rise to a Damkohler number based on a diffusion time, i.e., $Da = l_c^2 \dot{w}''/\rho_c \alpha_c$. The value of the Damkohler number (ether based on residence or diffusion time) is important to determine whether combustion will be completed in the combustion chamber of the micro-device since it is necessary that the chemical time be smaller than the physical time.

Turning to the solid phase, the Fourier number increases as the length scale is decreased, which results in a quasi-steady behavior of the solid temperature. The characteristic time of heat conduction through the solid is $t_{sc} = l_c^2/\alpha_{sc}$. Since the thermal diffusivity of the micro-devices' materials (Si, SiC) is of the same order of magnitude as that of air, the gas and solid diffusion times will be similar, which has implications in the heat transfer characteristics from the gas to, or from, the solid, particularly if there are periodic heat fluxes at their boundary with characteristic times much different than the diffusion time.

From the relevant boundary conditions of the gas phase conservation equations, it is deduced that as the length scale is reduced while keeping the wall and flow variables fixed, the velocity gradients and wall frictional effects increase, as do the gas temperature and species gradients at the wall. Because of the high gradients, however, it will be difficult to keep the difference between the wall and the bulk flow variables fixed since the resulting increase in head loss and heat and mass transfer will tend to reduce it. This implies that in micro-devices it will be difficult to keep flow velocities, and temperature and mass concentration differences, of the same magnitude as in their large counterparts. In the solid, on other hand, since the Biot number will tend to decrease (factored by the corresponding increase in the heat transfer coefficient), the solid temperature gradient will also tend to decrease as indicated by the wall boundary condition. It is expected therefore that micro-devices will have nearly uniform solid phase temperatures, unless the boundary heat transfer coefficient is large enough for $Bi > 0.1$, which is unlikely. Thus, the wall effects will be very important from the point of view of combustion in micro-combustors. The tendency will be for the presence of small Damkohler numbers (weak combustion) due to heat losses through the combustor walls that reduce the reaction rate and consequently increase the chemical time, while the small dimensions reduce the physical time.

The implications of these trends on the operation of small-scale combustion devices are discussed with some detail below.

Fluids

The small diameter of the channels for the reactant intake, the product exhaust, and the actual combustion chamber constrain the flows in micro-devices to relatively small Reynolds number. For example, for a 100 W meso-scale device using a stoichiometric mixture of octane/air and with a system efficiency of 10%, the volumetric flow rate of gaseous mixture will be approximately 0.4 l/s. Assuming a 5 mm diameter intake tube, the Reynolds number will be of the order of 5000 or below, depending on the gas temperature. Similarly, for a 100 mW micro-scale device with a 0.5 mm diameter intake, the Reynolds number will be around 50. Thus, the flow will be primarily laminar for the small devices and consequently mixing of different species will be primarily by diffusion. Also as stated above, viscous effects will be important, which together with the large aspect ratios in the micro-channels, implies that frictional losses will be high and that increased pumping will be required. On the other hand, viscous forces help in some of the problems characteristic of these devices, such as leakage of gases through joints or through moving surfaces. This could be important in IC, engines since their efficiency is strongly dependent on the compression ratio, which will be affected by the leakage at the piston (rotor)/housing surfaces.

Unexpected behavior may result in those cases with extremely small length scales (~μm), such as in some MEMS devices or their components. The most obvious effect is that the flow in these cases operates in the near-Stokesian regime where the Reynolds number is often less than one. Small changes in temperature, for example, can significantly change the volumetric flow rate as can fluid-wall interactions that are normally ignored in macroscopic flows. Also the small length scales of the channels result in high velocity gradients in the fluid. As seen from the aforementioned boundary conditions, this results in high wall frictional losses, and high convective heat transfer coefficients. These in turn can result in large pressure losses, high heat transfer to or from the fluid to the wall, and enhanced diffusive mixing.

As in their large-scale counterparts, the micro-combustors must use the ambient air as the source of oxygen to both reduce volume and to maintain their performance edge in energy density. This implies that the liquid hydrocarbon must be evaporated and mixed with the air prior to entering the combustion chamber in premixed systems, or injected directly in the combustion chamber in non-premixed systems. The small length scales have a large impact on the dynamics and energy requirements associated with phase change and two-phase flows. It has been observed, for example, that the phase change from liquid to vapor in MEMS size channels occurs abruptly and in an unstable fashion [19], quite differently from the transition observed in large tubes [20]. This is partially due to the large surface area to volume ratio in micro-channels that enhances the nucleation and wetting effects at the wall, and to the behavior of bubbles that is strongly affected by the small length scales and significantly differs from macroscopic behavior.

To increase fuel evaporation or to inject the fuel into the combustion chamber, it may be convenient to atomize the liquid. As the devices become smaller, the atomization device and the droplets must also be reduced in size. Since the surface energy of a droplet is inversely proportional to the radius of curvature, a decrease in the system's dimensions will increase the pressure and energy requirements for atomization. Although some MEMS-based simple atomizers (plain orifice type) have been developed [21], it appears that more elaborate devices or techniques to produce micron size droplets that will evaporate and mix with the air in the available micro-scale residence time will be needed. MEMS-based micro-electrospray atomizers [22,23] appear to be good potential candidates for micro-combustors [24,25].

The low Reynolds number coupled with the planar nature of MEMS devices makes mixing of the reactants a potential problem in micro-systems. Although the small diameter of the channels helps their diffusive mixing, the residence time of the fluids in the channels is also small, and may be insufficient to ensure complete mixing. For example, for a gaseous fuel/air mixture flowing through a 0.5 mm channel, the diffusion time will be of the order of 0.02 sec, and if flow velocity is of the order of 1 m/s, the channel length would have to be 25 mm to ensure diffusive mixing. This channel length may be too long for the device, or result in significant pressure losses. Thus, in some cases where mixing of species may need to be enhanced, different dynamic mixing approaches (flow instabilities, ultrasound, etc) may have to be implemented, even though they will introduce fabrication complexities and will consume valuable energy. To date, several approaches have been used to increase mixing rates, primarily of liquids [26-28]. The main problems with these approaches are fabrication complexity, system size, and increased pressure drops. Although these works are geared to mix liquids, similar concepts could be applied to mixing gases.

Thermal

At the length scales of micro-combustion devices, heat transfer by natural convection becomes small because the induced buoyant flow is small (Eq. (1)). However, heat transfer by conduction through the gas to the surrounding surfaces and by forced convection in the intake and exhaust channels and in the combustion chamber is significant because of the temperature gradients are higher as the characteristic length is decreased. Heat transfer by radiation also increases as the characteristic length decreases because of the large view factor. In addition, as the scale of the device is reduced, the surface-to-volume ratio increases, which combined with the enhanced heat flux, results in heat transfer effects becoming very important at the surface or boundary of the device. This has advantages in components that use heat transfer in their operation, such as evaporators or heat exchangers, since it enhances their heat exchanging characteristics. It may become problematic however in devices where surface heat losses may deter their performance as may occur with combustion chambers due to wall quenching.

It should be noted that the small buoyancy and the low thermal conductivity of air ($\lambda_a \sim 0.03$ W/mK) render the heat losses from a combustor relatively small when compared to its total heat generation. The order of magnitude of the heat losses from a combustor to the surrounding air can be obtained with a simple 1-D, steady state calculation. The heat flux from a flowing hot gas in the combustion chamber, through the combustor housing, to the still ambient air surrounding the combustor can be approximately calculated by

$$\frac{q}{A} = \frac{T_g - T_a}{\frac{1}{h_g} + \frac{l_c}{\lambda_s} + \frac{1}{\frac{\lambda_a}{l_c} + h_{ra}}} \quad (5)$$

Where the subscript g represents the hot gases in the combustion chamber and the subscript a represents the air surrounding the combustor. Considering, for example, a meso-size combustor with a characteristic length of l_c=20 mm capable of providing around 50W power [15], a combustion gas and ambient air temperatures of T_g =1,000 C and T_a=20 C respectively, a heat transfer coefficient of the gases flowing through the combustion chamber of h_g=100 W/m^{2}K, (convection and radiation), a SiC combustor housing (λ_s = 500 W/mK), and a linearized radiative heat transfer coefficient from the housing to the ambient air h_{ra}=130 W/m^{2}K , Eq.(5) gives for the heat flux 0.05 W/mm^2. Assuming that the combustor's combustion chamber has a 25 mm^2 area, the heat loss from the combustion gases would be around 1.3 W, i.e., ~3% of the combustor output. Several observations can also be deduced from Eq. (5). One is that because of the large thermal conductivity of the housing (SiC , steel, etc), the solid conduction term is negligible at these small scales, and that heat conduction through air is also small compared with radiation. Thus in order to reduce the heat losses from the combustion chamber it is important to reduce radiative heat loss from the combustor housing to the ambient air. For this purpose a material like silica aero-gel would be good to insulate the combustor since it has excellent insulating properties both for conduction and radiation.

If instead of still air, there is a forced flow as in an intake manifold or in a gas turbine compressor, the heat transfer from the combustion chamber to the incoming air would be considerably larger than the one calculated above (λ_a / l_c in Eq. (5) would be replaced by a heat transfer coefficient, h_a >100 W/m^{2}K) The enhanced heat transfer to the incoming gas in the intake manifold of the combustor is of particular concern in devices using premixed reactants for combustion. While pre-heating the reactants will aid in sustaining combustion to scales smaller than the quenching distance, it may result in the auto-ignition of the mixture in the inlet port. Thus, insulating measures must be taken to control the amount of heat that will be transferred to the incoming fuel/air mixture. Furthermore, heating of the reactants in the intake manifold will result in a smaller mass charge in the combustion chamber due to the reduced density, thus reducing the potential net power output of the device. The lower density will also result in higher compression work per unit mass, and consequently lower overall system efficiencies. This is particularly critical in gas turbines since the power requirements of the compressor determine their overall efficiency. In these cases thermal management becomes essential in order to reduce heat losses and increase the performance of the devices.

As noted earlier, most micro-devices tend to operate at a relatively uniform temperature because of their small size. For example, the Biot number for a steel or a silicon device with a length scale of 10 mm, and subjected to moderate convection and radiation (combined convection and radiation heat transfer coefficient of 100 W/m^2 K), will be of the order of 0.002, which is considerably smaller than that normally considered sufficient for a lumped heat transfer analysis (Bi<0.1). Thus a uniform temperature could approximately describe the device's internal temperature (boundary condition for Eq. (2)). Reduced thermal gradients will reduce thermal expansion stresses and subsequent misalignments in moving parts. However, it introduces potential problems whenever large thermal gradients are needed for high performance of the device such as in thermoelectric generators. This is also a problem for gas-cycle type devices (heat engines) because their efficiency depends on the ratio of the high and low temperature reservoirs, and it may be difficult to attain or maintain a large temperature ratio. The solution of these problems again requires complex thermal management.

Regarding thermal management, complex structures with highly insulating materials, vacuum gaps and/or complex thermal coatings may be needed to insulate and reduce heat transfer from high to low temperature regions. However, thermal management is not only restricted to spatial temperature gradients, but also to transient heat transport. Very different characteristic time in the gas or the solid, or in the periodic heat input from intermittent combustion may result in quasi-insulating conditions at the boundary. For example, if the combustion time in a compression ignition engine is much shorter than heat transfer time through the engine housing, heat losses from the combustion reaction to the wall could be negligible because the lack of time to transfer the heat.

Combustion

Combustion in micro-scale systems presents problems related to the time available for the combustion reaction to occur, and to the possible quenching of the combustion reaction by the wall. Near-wall chemical kinetics, i.e. potential low wall temperature and radical depletion characterize the combustion reaction. Once again, the basic requirement for micro-combustion to occur is that the physical time available for combustion (residence time) must be larger than the time required for the chemical reaction to occur (combustion time). For gas-phase combustion in flow systems such as in a gas turbine combustor, the residence time is determined by the size of the combustion chamber and the flow rate of the reactant stream through the chamber. For closed systems such as in internal combustion engines, in addition to the size of the chamber, the rpm of the engine also determines the residence time. For catalytic combustion the diffusion of species to the wall and species absorption/desorption at the wall also determine the residence time. Since in general the residence time will be small in micro-combustors, it is important to have small chemical times to ensure completion of the combustion process within the combustor. In general, small chemical times are obtained by ensuring high combustion temperatures, which in turn can be achieved by reducing the heat losses in the combustion chamber, preventing radical depletion at the wall, increasing the reactants' temperature, using stoichiometric mixtures, and using highly energetic fuels.

As engine size or combustion volume decreases, the surface-to-volume ratio increases, resulting in increased combustor surface heat losses and increased potential destruction of radical species at the wall. These mechanisms will increase the chemical time and possibly prevent the onset of the gas-phase combustion reaction, or lead to quenching of an ongoing reaction. Thermo-chemical management techniques that can be used to overcome quenching are, among others, the use of excess enthalpy combustors, generating adiabatic walls by stacking planar devices in a symmetrical fashion (insulated temperature boundary condition), establishing high temperature ceramic walls, and using surface coatings. The earliest work on excess enthalpy, recirculating, burners, was conducted by Weinberg and co-workers [10, 29, 30]. In these works, the combustion reaction was optimized by using the enthalpy of the products to preheat the fuel air mixtures, in what is known as "Swiss roll" combustor shown in Fig. 3. As a result of the enthalpy exchange obtained by recirculating the exhaust, steady combustion has been obtained with mixtures well below the normal flammability limits. Stable combustion, (described as "flameless" by the authors of Ref. [31]) has also been observed at temperatures below the expected homogeneous combustion temperatures of the fuels tested but above their normal catalytic temperatures [31]. The concept of recirculating the exhaust to reduce the heat losses from the combustion region and to pre-heat the incoming reactants has been further implemented to attain combustion in thin tubes [32, 33] with diameters smaller than the quenching distances that are reported in the literature. It has also been used to develop micro-combustors such as that shown in Fig. 4 [33]. Concerning the quenching distance, it is worth mentioning that the magnitude reported in the literature is considered often as the limiting scale for micro-scale combustion. This is a conceptual error, because the quenching distance depends on the reaction rate, and thus on the temperature, species and radical concentration (it is related to heat and radicals losses to the wall). The problem of wall quenching can be reduced or prevented by increasing the wall temperature (the quenching distance is approximately inversely proportional to the square root of the temperature), or equivalently preventing the heat losses to the wall (adiabatic wall).

Elevated operating temperatures of the combustor walls not only help preventing quenching, but also by reducing the chemical time also help counter the adverse effect of the small physical time inherent in micro-combustors. The physical time of the combustor will be given by the above indicated residence time, diffusion time, or the rpm if an engine. An order of magnitude of this time is from 1 to 10 ms (a 10 mm gas turbine combustor with 1 to 10 m/s flow velocity, or a rotary IC engine at 4,000 to 40,000 rpm). Thus chemical times of 1 ms or less are necessary for the operation of the combustors, which requires elevated, but not too high, temperatures. Ceramic materials, such as SiO_2, SiC, and Si_3N_4, can withstand temperatures of around 1700K, which are high enough to ensure short chemical times, and thus are good candidates for micro-combustors. The small scale of the devices and their uniform temperature operation reduce the problems of fracture inherent in the use of ceramic materials in large-scale combustors. Coating the combustor walls with inert materials can also reduce radical recombination and chemical quenching at relatively low temperatures [34].

If the reactants are not pre-mixed and the fuel is liquid, additional time and volume will be required for fuel evaporation and mixing. The time can be significant when compared to the gaseous premixed residence time, because the liquid evaporation, and the mixing at the low Reynolds numbers expected in these systems, are generally slow. As such, alternatives to spray combustion in liquid-fueled micro-combustors are currently being explored. Particularly interesting is the concept of burning the liquid fuel while forming a liquid film along the wall of the combustion chamber [35]. The advantage of this approach is that the wall film reduces heat losses from the combustor since it keeps the combustor walls cooled (at the liquid boiling point). It also inhibits wall quenching because the gas phase combustion occurs away from the wall, while maintaining sufficiently large vaporization rates because of the large surface to volume ratio of the micro-combustors. The researchers have proven the concept in a miniaturized cylindrical continuous combustor that induces a swirling air flow that keeps the film of liquid fuel on the wall. The device is projected to deliver power levels varying from 10 watts to kilowatts [35].

One important aspect of micro-scale combustion that should be kept in mind is that although the increase of the surface-to-volume ratio of the combustor presents a problem for gas-phase combustion, it favors catalytic combustion. Although the catalytic reaction is generally slower than the gas-phase reaction, and surface heat loss is a problem that also affects the catalytic reaction, the relative increase of surface area and the lower temperatures of the catalytic reaction suggest that micro-scale combustors using catalytic reaction may be easier to implement than those using gas-phase reactions. For example, it was noted in the above referred Swiss roll combustor that hydrogen-air mixtures could be ignited at room temperature and other fuels (butane and propane) at less than 200 C if a catalyst were deposited on the surfaces of the combustion volume [31]. The role of catalytically active surfaces within micro-channels is under investigation to stabilize the flame structure, determine extinction limits, optimize combustion efficiencies and reduce emissions [14,31,36-38]. The device being developed in [37] is a single pass counterflow heat exchanger that is designed with an incorporated catalytic surface. The small scale greatly enhances both thermal and mass transfer, which can result in volumetric heat generation rates of up to 10 W/mm^3, and therefore confirms the potential of micro-technology-based energy conversion and chemical systems.

Although the potential solutions to the low temperatures and short residence times seemingly inherent in micro-scale combustors could result in competitive operating devices, further understanding of low temperature chemical kinetics (homogeneous and catalytic), and the development of highly reactive energetic fuels is likely to be necessary to achieve this goal. Also needed are accurate theoretical models of the physico-chemical process involved in the combustion chamber.

APPROACHES TO MICRO-POWER GENERATION USING COMBUSTION

Although the field of micro-scale power generation using combustion is very new, there are currently several ongoing projects to develop micro-scale combustors and power generators that are relatively well advanced. The ultimate objective of most of these projects is to develop a portable, autonomous power generation system using combustion with improvement in energy density over batteries. A brief description of some of these projects is presented here. There are a few other projects that have been recently initiated but that have not been referenced here for lack of sufficient information about them. The projects have been grouped into three categories:

micro-combustors, heat engines, and rockets. Although combustors and rockets are not power generators by themselves, they can be used in conjunction with other devices (thermoelectric, piezoelectric, inert fluid cycles, etc) to produce electrical power, and are therefore included here because of their combustion component. Furthermore, direct mechanical power generation is also of interest, and as mentioned above it is another of the assets of using combustion for power production.

Micro-combustors/reactors.

Several micro-combustors and chemical reactors are currently being developed, either to use in conjunction with piezoelectric and thermoelectric materials to produce power, or to use as fuel reformers in fuel cells. The obvious advantage of these devices is that they don't have moving parts, but the problem generally lies in the low efficiency of the complete system. Although there are some thermoelectric materials that have attractive efficiencies, they suffer from the difficulty of maintaining a large temperature drop across the thermoelectric material, because of the small scale of the devices, and because good thermal conducting materials generally are also good electrical conductors. Thus good thermal management, or the possibility of decoupling the thermal and the electrical conductivities, is key for the success of these devices.

The Swiss roll approach has been used to develop thermoelectric power generation devices using micro-scale combustion [12,14]. The referenced researchers have demonstrated that their device can produce power, although to date with low efficiency. New designs of this type of power generation devices have been recently proposed based on thermodynamic analysis that promise to provide better efficiencies [39]. The specific proposed design consists of a section where heat is transferred to the incoming reactants followed by another section that discards unconverted heat to the cold surroundings.

The goal of the University of Southern California project [12, 31] is to develop a highly miniaturized, integrated, monolithically and batch-fabricated power generator with no moving parts, capable of powering devices down to MEMS scales. With its 3-D Swiss roll characteristics, the reactor shown in Fig. 5 appears to be well suited for MEMS size devices because the heat losses are greatly reduced. Complication presently appears in the implementation of the thermolectric unit. To date macro-scale and meso-scale combustors have been fabricated and tested. Low temperature, self-sustained combustion has been demonstrated in these larger reactors [31, 36].

The chemical energy conversion and power generation device at the MEMS scale developed at Princeton University [14] consists of a recirculating catalytic, 12.5mmx12.5 mmx5.0mm micro-reactor (2-D Swiss roll) made of alumina ceramic and platinum as catalyst and a thermopile unit, as shown in Fig. 6. A prototype device has been operated with hydrogen and with butane. Continuous operation with hydrogen has been demonstrated over a wide range of fuel-air mixtures and chemical energy inputs from 2 to 12 watts, at an operation temperature of 300 C. The device generated electrical power sufficient to power a 100 mW light bulb. Plans to increase the efficiency of the electrical generator by stacking several devices to reduce heat losses are currently underway. These researchers expect that stacking two dimensional combustors may be as efficient a method to reduce heat losses as a three-dimensional configuration

A thermoelectric power generator based on catalytic combustion in a micro-machined combustion chamber has been developed at the University of Michigan [40] (Fig. 7). The combustion chamber is 2mmx8mmx0.5mm and is covered by a dielectric diaphragm that integrates polysilicon-Pt thermopiles. Using hydrogen/air mixtures the device has produced power levels of the order of 1μW/thermocouple. The researchers expect to be able to reach power levels of 10 μW/thermocouple with geometrical modifications that will increase the temperature gradients on the diaphragm.

A micro-scale power device that includes a combustion-driven fuel reformer and fuel cell has been developed at Pacific Northwest National Labs [41]. The micro-scale fuel reformer strips hydrogen from a hydrocarbon fuel (such as methanol) and the hydrogen-rich stream is then fed to a fuel cell to generate electrical power. To date a 10 to 500 mW steam reformer system has been assembled and fabricated with a reactor volume of around 0.5 mm^3. In preliminary testing, the fuel reformer, utilizing methanol or butane, was able to provide up to 100 mW of hydrogen at an efficiency of up to 4.8%. The device was able to operate independent of any additional external heating, even during start-up.

At Yale University a meso-scale (~$16x10^3$ mm^3) catalytic combustor operating with a liquid fuel electrosprayed into the combustor chamber has been developed [24]. The combustor is to be coupled with direct energy conversion modules for power generation. Tests have been conducted with n-dodecane and JP8 jet fuel at rates of 10 g/hr and equivalence ratios varying from 0.35 to 0.7. Temperatures in the catalytic surface are reported to be in the range of 650-1000ºC, depending on the equivalence ratio. Combustion efficiencies of the order of 97% have been reported with n-dodecane. The application of electrospraying for liquid fuel combustion in small-scale combustors is an important contribution of this work, since it appears that the technique is potentially applicable in MEMS scale devices.

A chemical fuel processing micro-system for power generation in MEMS applications is being developed at MIT [42, 43]. The micro-system will consist of integrated micro-fabricated catalytic reactors, flow sensors, heaters, micro-valves, micro-pumps and controllers. Several alternative technologies for micro fuel processing are being evaluated, including hydrogen generation for fuel cells, and thermoelectric and thermovoltaic power generation.

Gas Turbines/IC Engines

The MIT Gas Turbine Laboratory is developing a MEMS-based gas turbine power generator with a total volume of approximately 300 mm^3, designed to produce 10-20 W [6,7]. This project can be viewed as the pioneering research in MEMS-based micro-scale power generation, and is for most purposes the most advanced. A schematic of the micro-gas-turbine is shown in Fig. 8, it includes a radial compressor/turbine unit, a combustion chamber and an electrical generator incorporated in the compressor. The compressor and the turbine, 12 mm in diameter and 3 mm thick, are made of traditional CMOS materials, and designed to rotate at more than 1million rpm. Although the gas turbine has not produced positive power yet, the development of the different components is well advanced, with the turbine, compressor and combustor operating independently. Heat transfer from the combustion chamber to the compressor/intake air, together with the difficulty in achieving good fabrication tolerances, appear to be dominant problems keeping the efficiency of the turbine low. Some major accomplishments include the achievement of rotation of the turbine at 1.3 million rpm by using air bearings, and the continuous operation of a silicon based combustor using H_2/air mixtures [44]. More recently a catalytic silicon micro-combustor has been developed and operated with hydrocarbon mixtures [45].

At the UC Berkeley Combustion Laboratories, a research project is currently underway to develop a liquid hydrocarbon fueled internal combustion rotary (Wankel-type) engine with sizes that are well below those commercially available [15,46-48]. Two engines are currently being developed, a meso-scale “mini-rotary-engine “ designed to deliver power on the order 30 W, and a micro-scale “micro-rotary-engine” designed to produce power in the mW range. The mini-rotary engine is EDM-fabricated from steel, with an epitrochoidal-shaped housing and a rotor approximately 10 mm in size. The simplest version of one of these mini-engines is shown in Fig. 9. A test bench for the mini-rotary engine has been developed and tests have been conducted with different mini-rotary engine designs to examine the effects of sealing, ignition, design, and thermal management on efficiency. Testing has been performed using hydrogen-air mixtures to facilitate ignition, and a range of spark and catalytic glow plug designs as the ignition source. Net power output of up to 3.7 watts at 9000 rpm have been obtained, although with low efficiency (~0.2%). A major reason for the low efficiency of the engine is its low compression ratio, due to leakage between the rotor apex tip seals and the housing and over the rotor faces. The size of the engine is at the lower scale limit of EDM fabrication, and it is difficult to attain the required tolerances for good sealing, even using apex seals. Work is currently underway to improve sealing and compression ratios by implementing different rotor apex tip and rotor face seal designs [15,46].

As per the "micro-rotary-engine", the project aims at developing an engine with a rotor in the mm range size, using MEMS techniques. The rotary engine is well suited for the MEMS fabrication techniques because of its planar construction, reduced number of parts, and self-valving operation. The fabrication of two MEMS based micro-engines, one made of SiC with a 2.3 mm rotor (Fig. 9) and another of Si with a 1 mm rotor is well advanced (Fig. 10) [47,48]. Initial measurement of the fabricated engine pieces indicates that the fabrication process has produced viable engine parts for an initial investigation into sealing and material characteristics. The housing spur gear and rotor through-holes have been fabricated using a self-masking method to produce structures 150 μm in diameter and 75-100 μm in height. Issues still remain with the fabrication process. Significant lateral etching of the spur gear profile and non-uniform etch rates across the wafer reduces the number of useable parts fabricated during the manufacturing process. Modifications to the fabrication process and STS etch recipe are being implemented to reduce the Si etch uncertainties. A method for obtaining real-time DRIE-etch depths using a Fourier Transform Infrared (FTIR) spectrometer is currently being investigated and installed. The current fabrication process can produce acceptable engine parts, but at the expense of low yield. After fabrication of micro-rotary engine housings and rotors with a 100:1 sidewall straightness, the rotor and housing will be manually assembled. This first generation micro-rotary engine will be tested by compressed air to determine engine leakage and wear characteristics. The Si engine will be tested first, followed by SiC coated Si pieces and then Silicon Nitride (Si_3N_4) coated parts. The objective of these tests is to investigate the long-term wear, lubricity, and toughness of the materials. Initial studies of micro-fluidics, heat transfer and combustion are underway or will soon follow. Thermal management approaches applied, or being considered for application, for these miniaturized rotary engines include: recirculating the exhaust around the combustion section of the housing and packaging the engine in an aero-gel/vacuum container to reduce heat losses, using catalytic surfaces to sustain combustion at low temperatures, and using the exhaust heat to evaporate the liquid fuel.

A free-piston "knock" micro-engine based on homogeneous charge compression ignition (HCCI) of hydrocarbon fuels is being developed at Honeywell [49], with a goal of generating ~10 W of electrical power in a 10^3 mm^3 package volume. In order to achieve reliable autoignition of the fuel and to develop these power densities, the engine must operate at kilohertz frequencies, placing requirements about the allowable ignition delay times. These operating frequencies generate nearly adiabatic compression and expansion since the timescale of the compression and expansion events are much less than the characteristic thermal diffusion time, leading to a higher overall thermal efficiency. To date, compression ignition has been achieved in a piston/cylinder unit 3 mm in diameter operating for several cycles. Sealing problems in the piston/cylinder appear to have limited the efficiency of the engine, and material resistance has limited its life. Attempts to resolve the sealing problem by using a liquid piston are being pursued.

A free piston/cylinder electrical power generator based on a ferromagnetic piston oscillating in a magnetic field is under development at Georgia Tech [16]. The piston is propelled by the alternated combustion of a hydrocarbon fuel/air mixture at each end of the cylinder (Fig. 10). The magnetic field is produced by permanent magnetic MEMS arrays that surround the cylinder assembly. The system also incorporates MEMS igniters. A power generator with a 4.3 cm stroke and 13.4 cm^3 displacement has been developed, and 12 W of electrical power has been extracted to date, although with poor efficiency due in part to sealing problems in the piston cylinder unit.

A rotationally oscillating free-piston engine that forms four distinct combustion chambers from a single base structure (housing) and a swing arm is under development at University of Michigan [50]. The device operates on a four-stroke Otto cycle. The swing arm (piston) is oscillatory, making mechanical torque inefficient but relatively simple for direct electrical power generation. The design goals of this meso-scale device are the production of 20W using a liquid hydrocarbon with a projected system mass of 54 g and a volume of $17x10^3$ mm^3.

Micro-Rockets

Several micro-rocket projects are currently underway, most of them MEMS-fabricated, and designed for space applications such as micro-satellite positioning [51,52]. A solid fueled micro-rockets fabricated at TRW is shown in Fig. 11 [53]. It is designed for orbit and station keeping of pico-satellites or micro-spacecraft. It consists of a three-layer sandwich containing the thrust chambers where a lead styphnate propellant is housed, Si_3N_4 burst diaphragms, and micro-resistors that are used as igniters. When the resistor is energized, the propellant ignites, raising the pressure in the chamber and rupturing the diaphragm. Initial testing has produced 10^{-4} Newton-second of impulse and 100 W of power. A HTPB and Ammonium Perchlorate fueled silicon sounding micro-rocket with a mass of 1 gram has been fabricated at UC Berkeley (Fig. 12) to propel sensors to test the atmosphere [54]. The micro-rocket generated thrust (peak, 4 mN) for an 8 second burn.

At MIT, a high pressure, bipropellant micro-rocket engine has been manufactured and tested. The rocket weights 1.2 g and with a chamber pressure of 12 atm has generated 1 N thrust and delivered 750 W of thrust [55]. A liquid propellant micro-thruster for small spacecraft applications is being developed at The Pennsylvania State University [56]. A prototype microthruster has been successfully tested with gaseous reactants. Propellants being explored include environmental friendly energetic oxidizers, with alcohol as fuel and water as the liquid carrier

CONCLUDING REMARKS

The field of micro-power generation, both electrical and mechanical, is basically in a feasibility stage, and although significant progress has been made in the last few years, there are still a number of technological problems that must be resolved before the field establishes itself. The approach followed to date has been that of miniaturizing currently used large scale devices, which introduces many problems related to fluid flow in micro-channels, heat and mass transport in the micro scale, combustion in small volumes, design, fabrication and diagnostics. The solution of these problems requires a variety of fundamental and applied research and manufacturing development that precedes the development of the micro devices themselves.

The research needs unique to the development of combustion systems at the small scale include: mixing and pumping in low Reynolds number flows, simulation of distributed reactions, low temperature chemical kinetic modeling, investigative diagnostics, materials selection, fabrication of high aspect ratio structures and complex geometries, assembly, testing and characterization. Materials must be able to sustain the high temperature, harsh chemical environment, stress, and wear due to combustion events. Emissions and noise must be reduced to acceptable levels. High precision, high aspect ratio structures are necessary to provide adequate sealing for high compression ratios. A repeatable and simple assembly technique must be developed in order to mass produce these devices and lastly, the devices need to be tested and characterized to optimize their performance.

One can speculate that some of these problems could be avoided if the approach to develop micro-power devices would be based on enlarging small (bio-related) systems rather than miniaturizing large ones. However, it is likely that this approach will also have its own problems. In any case, it is important to keep in mind that, because the specific energy of liquid hydrocarbon fuels is around 100 times larger than that of secondary batteries, there is a lot of room for development of micro devices that use combustion to produce power. Furthermore, given the current need for power (electrical and mechanical) in the small scale the potential pay-off is very large.

NOMENCLATURE

A	surface area
Bi	Biot number, $Bi = l_c (h_{co} + h_r)/\lambda_s$,
D	Diffusion coefficient
Da	Damkohler number, $Da = \dot{w}''_c l_c / \rho_c u_c$
Fo	Fourier number, $Fo = \alpha_{sc} t_c / l_c^2$
g	gravity

h	combined convective and linearized radiation heat transfer coefficient h= $h_{co} + h_r$
h_{co}	convective heat transfer coefficient
h_r	linearized radiation heat transfer coefficient $h_r = \varepsilon\sigma F_{12}(T_s+T_a)(T_s^2+T_a^2)$
Kn	Knudsen number, $Kn = \lambda_f/l_c$
Le	Lewis number $Le = \alpha_c/D_c$
l_c	characteristic length of the device
Pe	Peclet number, $Pe = l_c u_c/\alpha_c$
p	pressure
$\bar{p}$	normalized pressure $\bar{p} = p/p_c$
p_c	characteristic pressure
q	heat rate
Re	Reynolds number, $Re = u_c l_c/\upsilon_c$
t	time
$\bar{t}$	normalized time $\bar{t} = t/t_c$
t_c	characteristic time
T	temperature
$\bar{T}$	normalized temperature $\bar{T} = T/T_c$
T_c	characteristic temperature
u	velocity
$\bar{u}$	normalized velocity $\bar{u} = u/u_c$
u_c	characteristic velocity
$\dot{w}''$	reaction rate
$\overline{\dot{w}}''$	normalized reaction rate $\overline{\dot{w}}'' = \dot{w}''/\dot{w}''_c$
$\dot{w}''_c$	characteristic reaction rate
x	spatial coordinate
$\bar{x}$	normalized spatial coordinate $\bar{x} = x/x_c$
x_c	characteristic spatial coordinate
y_i	mass fraction of specie i
$\bar{y}_i$	normalized mass fraction of specie i $\bar{y}_i = y_i/y_{ic}$
y_{ic}	characteristic mass fraction of specie i

Greek

α thermal diffusivity
λ thermal conductivity
λ_f mean free path
μ dynamic viscosity
ν kinematic viscosity

Subscript
a air
c characteristic value
g gas
i specie i
r radiation
s solid (device housing)

Superscript
\- normalized variable or property with its characteristic value

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References

1. Allen, D., Almond, H. and Logan. P. "Technical Comparison of Micro-electrodischarge Machining, and Copper Vapor Laser Machining for the Fabrication of Ink Jet Nozzles" Proceedings of the SPIE, 4019, 531 (2000)
2. Reyntjens, S. and Puers, R. J. Michromech. Microeng. 11, 287-300 (2001)
3. Madou, M., Fundamentals of Microfabrication, CRC Press, Boca Raton. (1997)
4. Kovacs, G.T.A. Micromachined Transducer Sourcebook, McGraw-Hill, NY (1998)
5. Warneke, B. et al. Computer Magazine, IEEE, Jan.2001, 44-51
6. Epstein, A.H. *et al.* "Micro-Heat Engines, Gas Turbines and Rocket Engines – The MIT Microengine Project", 28th AIAA Fluid Dynamics Conference, 97-1773, (1997)
7. Epstein, A.H. *et al.* "Power MEMS and Microengines." Proc. of the IEEE Transducers '97 Conference, Chicago, IL, June 1997.
8. Pisano, A., Microelectromechanical Systems (MEMS) Program, DARPA/ ETO, BAA 97-43, (1997)
9. Tang, W., DARPA MTO Program, BAA 01-09 "Micro Power Generation (MPG)", (2001)
10. Weinberg, F. Fifteenth Symposium (International) on Combustion, The Combustion Institute, 1 (1975)
11. Introduction to the Human Body 2nd Edition, Tortora, Gerard J., Harper Collins Publishers, 1991, New York
12. Maruta, K., Takeda, K., Sitzki, L., Borer, K., Ronney, P. D., Wussow, S., Deutschmann, O., "Catalytic Combustion in Microchannel for MEMS Power Generation, " Third Asia-Pacific Conference on Combustion, Seoul, Korea, June 24-27, 2001.

13. Jones, E. “Microscale Combustor/Evaporator Development” DARPA/MEMS Project Summaries, August 2001, pp. 16 (2001)

14. Vican, J. Gajdeczko, B.F., Dryer, F.L., Milius, D.L., Aksay, I.A. and Yetter, R.A.”Development of a Microreactor as a Thermal Source for MEMS Power Generation” Proceedings of the Twenty-Ninth International Symposium on Combustion, July 21-26, 2002, Sapporo, Japan (accepted)

15. Fu, K., Knobloch, A., Martinez, F., Walther, D., Fernandez-Pello, A.C., Pisano, A., Liepmann, D., Miyaska K.,and Maruta, K. “Design and Experimental Results of Small-Scale Rotary Engines” Proc. 2001 International Mechanical Engineering Congress and Exposition (IMECE), New York, November 11-16, 2001

16. Allen, M.G. "Ceramic Micromachining Technology," DARPA Workshop on Combustion-based MEMS Power Generation on the Microscale, for the Microscale, Washington, DC, 1998.

17. Savinell, R. “A Micro Hydrogen-Air Fuel Cell” DARPA/MEMS Project Summaries, August 2001, pp. 16 (2001)

18. Lee, S., Nelson, D., Svrcek, M., Edwards, C.F. and Bowman, C.T. ”Mesoscale Burner Arrays for Gas Turbine Reheat Applications” 2002 Spring Meeting, WSS/CI, San Diego, CA March 25,26 (2002)

19. Hetsroni, G., Mosyak, A. and Segal, Z. “Two Phase Flow in Microchannels” Proccedings of the 2001 ASME IMECE, Nov. 11, 2001, New York, NY (2001)

20. Collier, J.C. Convective Boiling and Condensation, McGraw-Hill, (1972)

21. Rajan, N., Mehregany, M., Zorman, C.A., Stefanescu, S., Kicher, T.P. “Fabrication and testing of micromachined silicon carbide and nickel fuel atomizers for gas turbine engines” J. Microelectromechanical Systems, 8, IEEE, Sept. 1999, 251-257 (1999)

22. Chen, G and Gomez, A., Combust. Sci and Tech. 115:177 (1996)

23. Ganan-Calvo, A. M. J. Fluid Mech. **335**, 165-188 (1997).

24. Kyritsis, D.C., Guerrero-Arias, I., Roychoudhury, S. and Gomez, A. “Mesoscale Power Generation by a Catalytic Combustor using Electrosprayed Liquid Hydrocarbons” Proceedings of the Twenty-Ninth International Symposium on Combustion, July 21-26, 2002, Sapporo, Japan (accepted)

25. Chigier, N. et al. “Atomization and Vaporization of Liquid Fuels for Micro-Combustors” to be submitted to the 2003 AIAA Aero-Sci. Conference, Reno, NV,

26. Lowe, H. et al. “Micromixing Technology” IMRET 4: 4th Int. Conf. On Microreaction Technology, AIChE Meeting, Atlanta, GA, 31, (2000)

27. Liu, R.H., Stremler, M.A., Sharp, K.V., Olsen, M.G. Santiago, J.G., Adrian, R.J., and Beebe, D.J., J. Microelectromechanical Systems, 9, 2, 190-197, (2000)

28. Zahn, J.D., Deshmukh, A.A., Papavasiliou, A. P., Pisano, A.P.,and Liepmann, D. ”An Integrated Microfluidic Device for the Continuous Sampling and Analysis of Biological Fluids” Proceedings of the 2001 ASME - IMECE, Nov.11-16, 2001, New York, N.Y.

29. Jones, A.R., Lloyd, S.A., and Weinberg, F.J., Proc. Roy. Soc. (London) *A*, 360, 97-115, (1978).

30. Lloyd, S.A., and Weinberg, F.J., Nature, 251, 47-49, (1974)S

31. Sitzki, L., Borer, K., Wussow, S. Schuster, E., Maruta, K., Ronney, P. and Cohen, A., “Combustion in Microscale Heat-Recirculating Burners”, AIAA-2001-1087, 38th AIAA Space Sciences & Exhibit, Reno, NV. (2001.)

32. Cooley, B, Walther, D. and Fernandez-Pello, A.C.” Exploring the Limits of Microscale Combustion" 1999 Fall Technical Meeting, Western States Section/Combustion Institute, Irvine, CA, October 25, 26, (1999).

33. Peterson R.B. and Hatfield, J.M. “A Catalytically Sustained Microcombustor Burning Propane”, Proc. 2001 International Mechanical Engineering Congress and Exposition (IMECE), New York, November 11-16, 2001

34. Masel R. and Shannon, M. Patent # US06193501 (2001)

35. Sirignano, W.A., Pham, T.K. and Dunn-Rankin “Miniature Scale Liquid Fuel Film Combustor” Proceedings of the Twenty-Ninth International Symposium on Combustion, July 21-26, 2002, Sapporo, Japan (accepted)

36. Sitzki, L, Borer, K., Schuster, E., Ronney, P. D., Wussow, S., "Combustion in Microscale Heat-Recirculating Burners," Proc. 3rd Asia-Pacific Conf. on Combustion, Seoul, Korea, 2001.

37. Peterson, R.B., “Small Packages”, *Mechanical Engineering*, p. 58-61, June 2001

38. Maruta, K., Takeda, K. Ahn, J., Borer, K., Sitzki, L. Ronney, P. D. and Deutschmann, O. “Extinction Limits of Catalytic Combustion in Micro-channels” Proceedings of the Twenty-Ninth International Symposium on Combustion, July 21-26, 2002, Sapporo, Japan (accepted)

39. Weinberg, F.J., Rowe, D.M., Min, G. and Ronney, P. “On Thermoelectric Power Generation from Heat Re-circulating Combustion Systems” Proceedings of the Twenty-

Ninth International Symposium on Combustion, July 21-26, 2002, Sapporo, Japan (accepted)

40. Zhang, C. Najafi, K., Bernal, L.P., Washabaugh, P.D. "An Integrated Combustor-Thermoelectric Micro Power Generator" 11th Int. Conference on Solid State Sensors & Actuators, Munich, Germany, June 10-14, 2001

41. Holladay, J.D., Jones, E.O., Phelps, M., and Hu, J. "High-efficiency microscale power using a fuel processor and fuel cell", SPIE Micromachining & Microfabrication. Paper 4559-20, San Francisco, 21-24 October, 2001.

42. R. Srinivasan, I.-M. Hsing, P.E. Berger, K.F. Jensen, S.L. Firebaugh, M.A. Schmidt, M.P. Harold, J.J. Lerou and J.F. Ryley, , AIChE J., 43, 3059-3069, (1997)

43. Arana, L.R., S.B. Schaevitz, A.J. Franz, K.F. Jensen and M.A. Schmidt, "A Microfabricated Suspended-Tube Chemical Reactor for Fuel Processing", MEMS 2001, Jan 20-25, 2002, Las Vegas NV

44. Mehra, A., and I.A. Waitz, "Development of a hydrogen combustor for a microfabricated gas turbine engine", Solid State Sensor and Actuator Workshop, Hilton Head, GA, (1998).

45. Spadaccini, C.M., Zhang, X., Cadou, C. P., Miki, N., and Waitz, I. A. "Development of a Catalytic Silicon Micro-Combustor for Hydrocarbon-Fueled Power MEMS", MEMS 2001, Jan 20-25, 2002, Las Vegas NV, (2002)

46. Fu, K., Walther, D., Fernandez-Pello, A. C., Liepmann D. and Miyasaka, K. "Preliminary Investigation of a Small-scale Rotary Internal Combustion Engine" 1999 Fall Technical Meeting, Western States Section/Combustion Institute, Irvine, CA, October 25, 26, 1999

47. Fu, K., Knobloch, A., Cooley, B, Walther, D., Liepmann, D., Fernandez-Pello, A.C.and Miyasaka, K." Micro-scale Combustion Research for Applications to MEMS Rotary IC Engines", NHTC2001-11212, Proc. 35th ASME 2001 National Heat Transfer Conf., Anaheim, CA, (2001).

48. Fu, K., Knobloch, A., Martinez, F., Walther, D., Fernandez-Pello, A.C. Pisano, A., and Liepmann D.“Design and Fabrication of a Silicon-Based MEMS Rotary Engine” Proc. 2001ASME International Mechanical Engineering Congress and Exposition (IMECE), New York, November 11-16, (2001)

49. Yang, W. “MEMS Free Piston Knock Engine”, Poster Presentation, 28th International Symposium on Combustion, The Combustion Institute, Edinburgh, UK, July 30-August 4, 2000. Also DARPA MEMS PI Meeting Poster, Broomfield, CO, August 29, 2001.

50. Dahm, W.A., J. Ni, K. Mijit, R. Mayor, G. Qiao, A. Benjamin, Y. Gu, Y. Lei and M. Papke, “Micro Internal Combustion Swing Engine (MICSE) for Portable Power Generation Systems”, AIAA Paper 2002-0722, 40th Aerospace Sciences Meeting, January 14-17, 2002 Reno, NV.

51. Rossi, C. et al.”A New Generation of MEMS Based Microthrusters for Microspacecraft Applications » Proc. MicroNanotechnology for Space Applications, V.1, April 1999

52. Micci, M.M., and Ketsdever, A.D. eds., Progress in Astronautics and Aeronautics, V. 187, AIAA, Reston, VA, 2000

53. Lewis, Jr., D.H. Janson, S.W., Cohen, R.B. and Antonsson, E.K., Sensors and Actuators : Physical, 80(2), 143-154 (2000).

54. Lindsay, W. Teasdale, D. Milanovic, V., Pister K.and Fernandez-Pello, A.C. "Thrust and Electrical Power from Solid Propellant Microrockets", IEEE 14th Int. Conf. on MicroElectroMechanical Systems, Interlaken, Switzerland, p.606-610, Jan. 2001.

55. London, A.P., Ayon, A.A., Epstein, A.H., Spearing, S.M., Harrison, T., Peles, Y. and Kerrebrock, J.L. Sensors and Actuators A 92, 351-357 (2001)

56. Yetter, R.A., Yang, V., Milius, D.L., Aksay, I.A. and Dryer, F.L. "Development of a Liquid Propellant Microthruster for Small Spacecraft", Proc. Eastern States Section, The Combustion Institute, Hilton Head Is., S.C., Dec. 2-5, 2001.

List of Figures

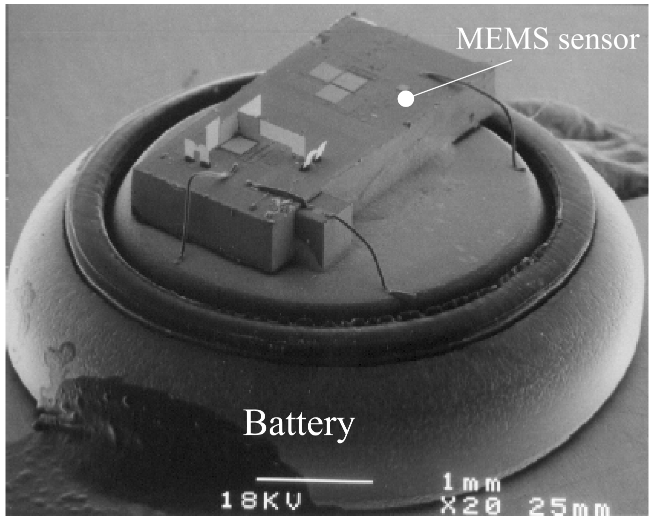


Figure 1

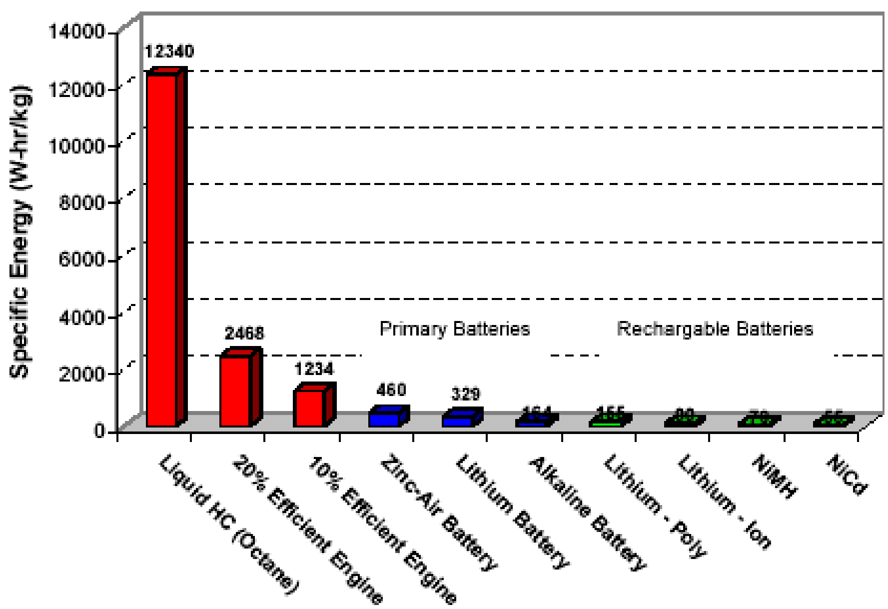
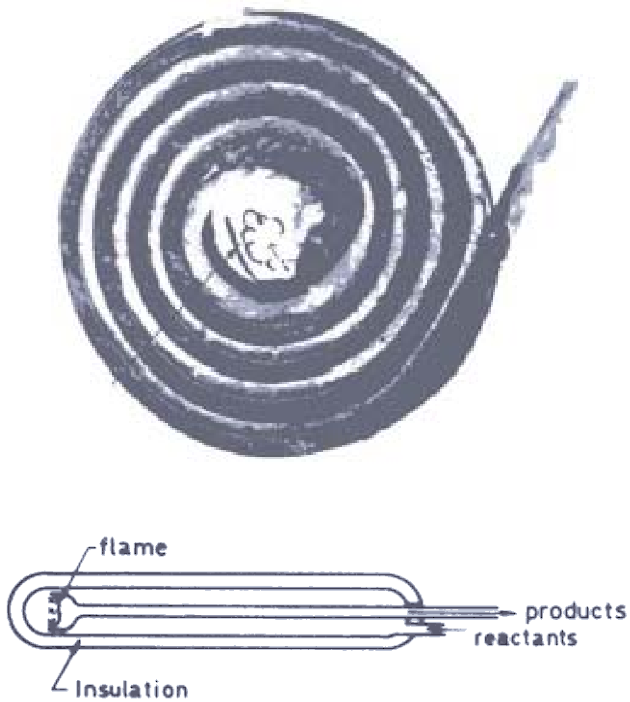


Figure 2



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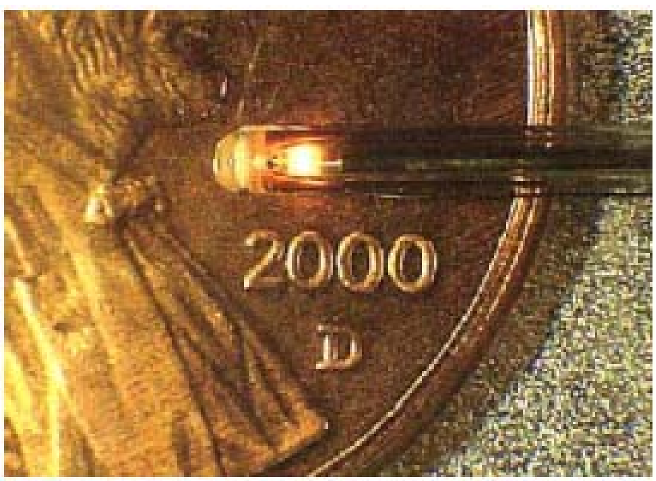
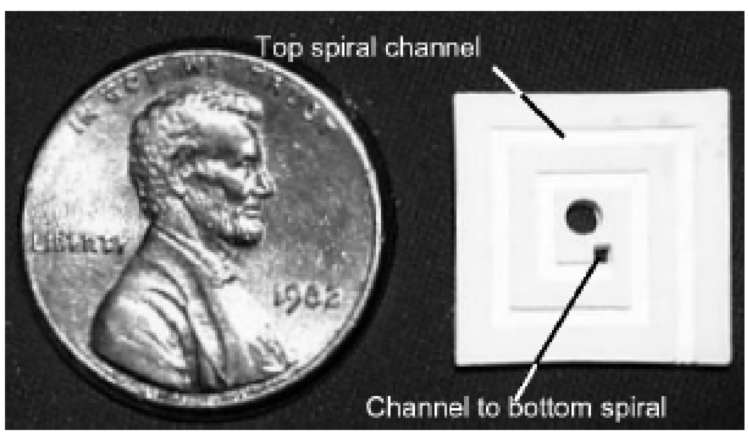


Figure 4

Figure 5



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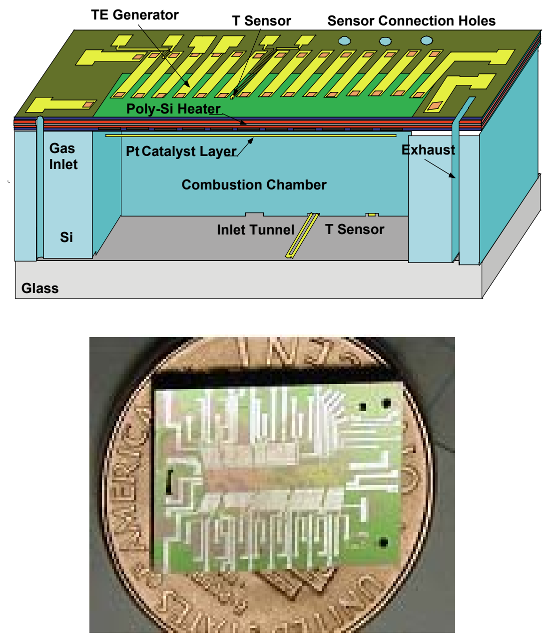

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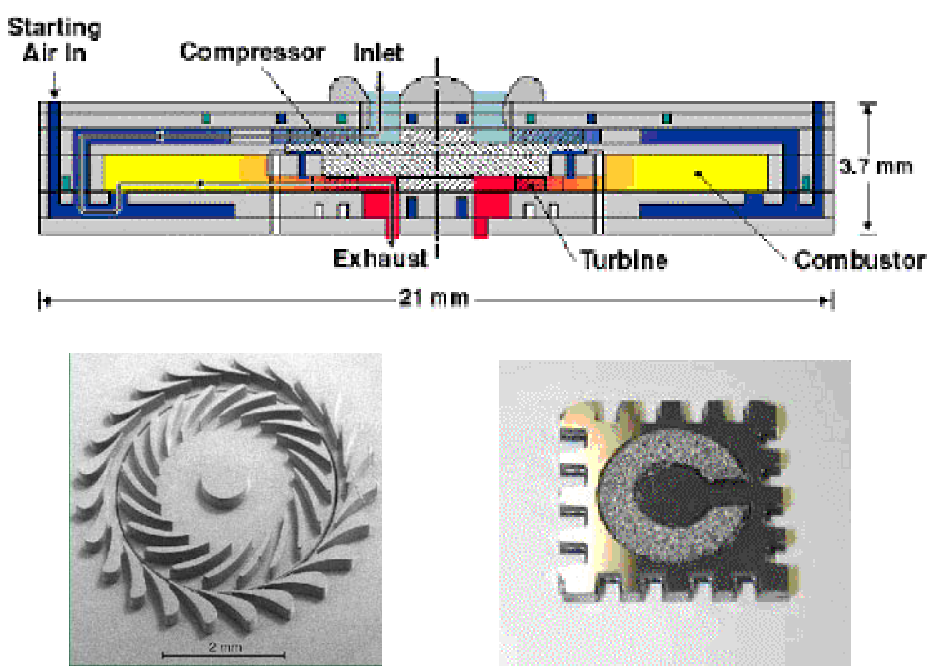
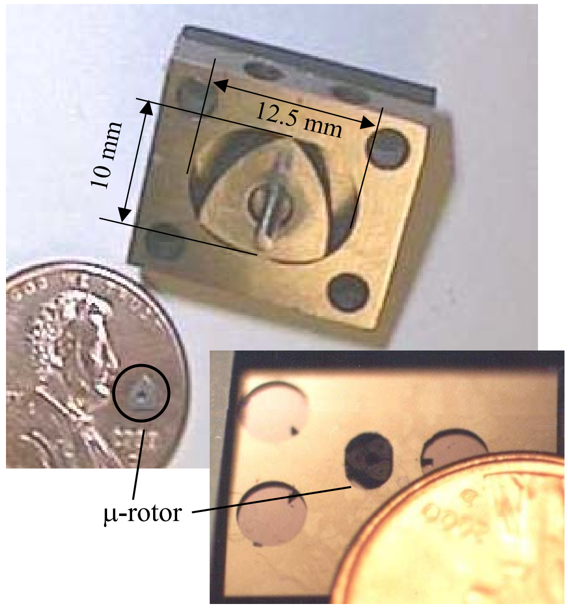


Figure 8.



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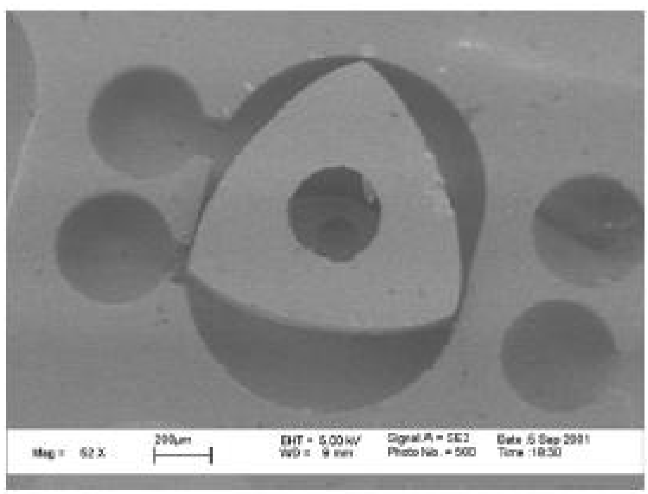
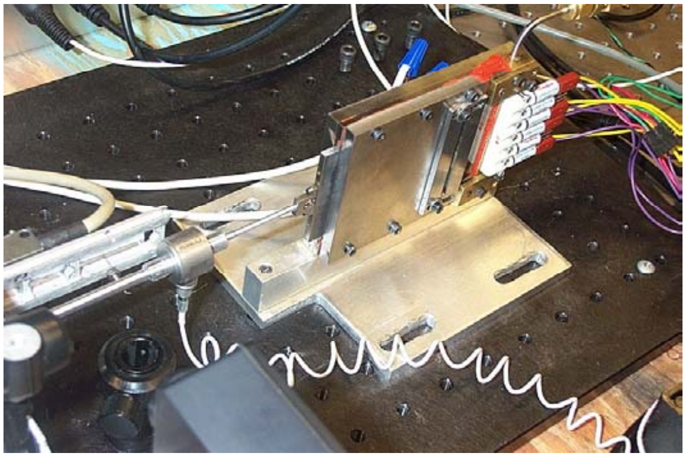


Figure 10



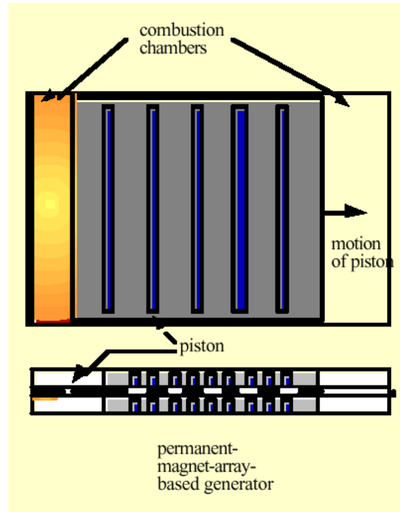


Figure 11

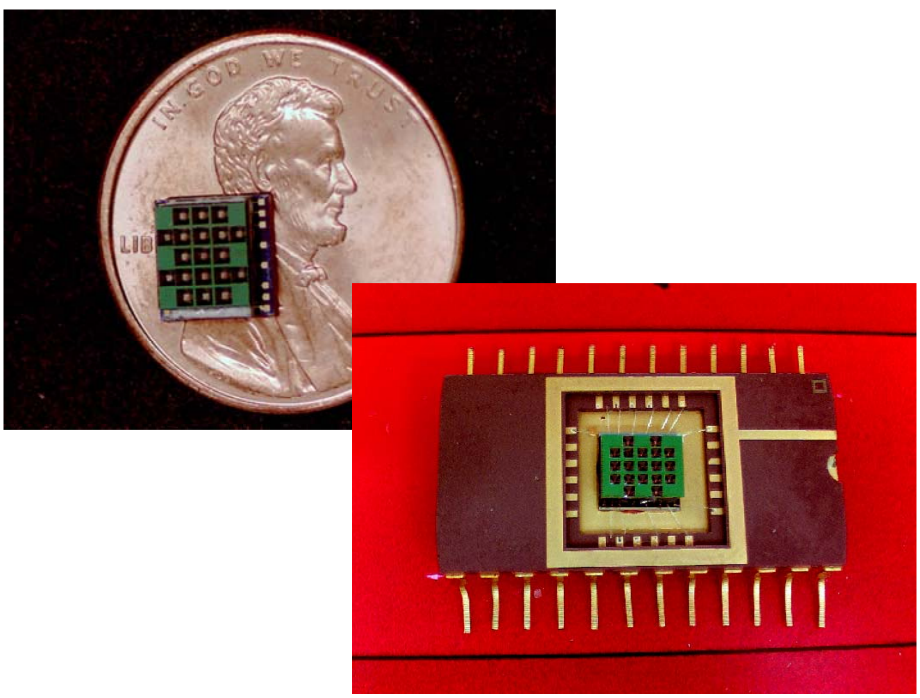


Figure 12

Figure 13