Review on progress and challenges of the power generation systems at micro-scales

Junjie Chen*, Deguang Xu

School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo, Henan, China

*E-mail address: comcjj@163.com, comcjj@yahoo.com

ABSTRACT

The miniaturization of electro-mechanical devices, and the resulting need for micro-power generation (milliwatts to watts) with low weight, long life devices, has led to the recent development of the field of micro-scale combustion and power generation. The primary objective of this new field is to leverage the high energy density of fuels, specifically liquid hydrocarbon fuels relative to batteries and all other energy storage devices other than nuclear fission, fusion or decay. Some brief scaling arguments are given in this work, and more detailed efforts are referred. A brief introduction to several of the fabrication techniques is presented in this work. Hydrogen-based and some preliminary specialty fuel micro-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 the batteries. In this work, the technological issues related to micro-scale combustion and the development of thermoelectric devices for power generation will be discussed. Some of the systems currently being developed will be presented, ongoing critical study issues under investigation, and other potential areas of development discussed. Comments regarding the opportunities and limitations of each of the techniques are also presented where applicable.

Keywords: Micro-combustor; Power generation; Micro-engine; Micro-rocket; Fuel cell; Micro-fabrication; Environmental effect; Micro-power generation

1. INTRODUCTION

Despite the fact that the micro-power generation field is young, significant and encouraging progress has been made, especially when one considers that only a few projects have been funded to date. Several micro-combustors have been fabricated that appear to operate with good combustion efficiency. Some of these combustors have been applied to energize thermoelectric systems to produce power. The system efficiency is currently too low, but the limitation often 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 [1]. Here the problem appears to be in fabrication and thermal management, which both limit the tolerances in moving parts (leakage, low compression ratio), and cause reduced efficiency of individual components (compressor, combustion chamber). Fuel cells are also being developed, and although not a combustion device, these chemical reaction systems have issues that are of interest to the combustion community [2]. Although hydrogen-based micro-

fuel cells have been successfully developed and some liquid fuel (methanol/formic acid) based micro-fuel cells have been demonstrated, there is a need to produce reliable reformers (or further refinement of direct conversion fuel cells) so that they can be used with liquid hydrocarbons, and can become competitive with batteries.

It should also be mentioned that small-scale combustion has other useful applications than power generation and heat production for use in power cycles [3]. As an example, the positioning of localized combustion and meso-scale burner arrays to produce distributed combustion in large-scale gas turbine combustors, increasing the potential for inter-turbine reheat, and for premix or highly vitiated combustion, to reduce NO_x [4]. Micro-scale combustion can also have application in the area of flame ionization detectors and potentially in applications that require rapid temporal or periodic pressure or temperature profiles.

Some of the technological issues related to micro-scale combustion and their chemical devices for power generation are discussed below. A brief introduction to many of the fabrication technologies being employed follows. An introduction to solid oxide fuel cells (SOFCs), which can convert hydrocarbons directly at moderate temperatures into useful electrical power, is given to follow as well. Lastly, a description of many of the systems currently in development are also presented and briefly discussed.

2. FUNDAMENTAL ISSUES

2.1. Thermal and heat transfer

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 enhanced heat transfer to the incoming gas in the intake manifold of the combustor is of particular concern in devices using pre-mixed 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 [5]. Thus, measures must be taken to control the amount of heat that will be transferred to the incoming fuel/air mixture (reduced volumetric efficiency). Furthermore, heating of the reactants in the intake manifold will also 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 [6]. 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.

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 [7]. However, thermal management is not only restricted to spatial temperature gradients, but also to transient heat transport. Very different characteristic times in the gas or the solid, or in the periodic heat fluxes from intermittent combustion may result in quasi-insulating conditions at the boundary [8]. 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 would be reduced because the lack of time to transfer the energy to the walls.

2.2. Fluid dynamics

The critical parameter that dictates fluid flow in power MEMS systems is the Reynolds number since the scale of the device and the fluidic throughput dictates the power level of the device. 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 and hence, the majority of small-scale power systems are laminar and issues related to viscous drag and mixing of multiple streams become critical for system designers. Much work in fluidic handling has been carried out in regards to lab-on-a-chip or micro total analysis systems (μ TAS) in this size range. For many of the power generating concepts, especially those described below, 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 [9]. The small channels also result in high velocity gradients in the fluid, which as the aforementioned boundary conditions indicate, lead to high wall frictional losses, and high convective heat transfer coefficients. This in turn can result in large pressure losses, high heat transfer to or from the fluid to the wall, as well as enhanced diffusive mixing [10]. This next section will attempt to address issues related channels where the flow is laminar ($1 < Re < 2300$), including pressure drops in channels, fluidic mixing, issues with the introduction of liquid fuels, micro-scale mass exchange and some microfluidic applications.

2.3. 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, the potential low wall temperature and radical depletion characterize the gas-phase combustion reaction [11]. 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, engine speed also determines the residence time. For catalytic combustion the diffusion of species to the wall and species absorption/desorption at the wall can 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 [12]. 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 [13]. 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. Thermochemical 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 combustion reaction was optimized by using the enthalpy of the products to pre-heat the fuel air mixtures, in what is known as “Swiss-roll” combustor [14]. 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 has been observed at temperatures below the expected homogeneous combustion temperatures of the fuels tested but above their normal catalytic temperatures. 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 with diameters smaller than the quenching distances that are reported in the literature. This has also been used to develop micro-combustors [15]. 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) [16]. 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), preventing heat losses to the wall (adiabatic wall), or through catalytic activity on the wall.

3. FABRICATION

MEMS fabrication techniques will briefly be summarized here inasmuch as to give the reader a good feel for each of the techniques. Working with silicon based MEMS is advantageous as it allows the existing knowledge and foundries to be leveraged and most importantly it allows for the coupling to traditional CMOS (Complementary Metal Oxide Semiconductor) IC (Integrated Circuitry) [17]. It is this coupling that allows for nearly instantaneous sensing, control and actuation. Rapid feedback sense and control is vital to the growth of the mechatronic devices and systems due to the inherent disadvantages of scale and inertia [18]. Traditional surface and bulk micromachining material removal (etching) and addition (deposition) techniques, as well as relevant, less traditional techniques that have promise in the future growth of the Power MEMS field will also be covered.

Silicon fabrication has its beginnings in the CMOS IC industry and only recently has the field of MEMS in which mechanical elements are constructed of semiconductor materials using similar deposition and etching methods grown [19]. Silicon is the most common structural material due to its well characterized properties and fabrication tooling. MEMS fabrication occurs by first patterning the substrate by lithography and then depositing or removing material. Many of these steps are repeated to create ‘features’ on the wafer. Two types of micromachining have been identified, surface and bulk, and they are defined by the whether material is deposited onto the wafer (substrate) surface or three-dimensional features are etched into the bulk of the wafer [20]. Many modern MEMS features incorporate both surface and bulk micromachining into their processing. That being said, surface

micromachining is more applicable for static and thermoelectric systems whereas bulk micromachining techniques are more applicable for thermo-mechanical systems.

Very often, the feasibility, design and fabrication of devices and systems become the primary focus of MEMS study and very little time or thought is given to assembly. Micro-assembly and micro-joining are critical to the production of systems as there is currently no good way to integrate several of the aforementioned techniques to create the system.

One of the major concerns with the emerging field of combustion power MEMS is the harsh environment to which materials are exposed. Thermal gradients and transients, corrosive fuels, elevated temperatures and pressures, oxidation, and combustion product reactivity all can have significant influence on the semiconductor materials that comprise most systems [21]. This section will attempt to address many of these issues and their implications toward the extended operation of these devices. Many arguments have been given toward the low unit cost of MEMS devices and that these devices will not be operated for extended periods of time [22]. However, when individual components (pressure sensors for example) are implemented into a larger device (such as a gas turbine) in order to effectively leverage the capability of mass fabrication and associated sensing and actuation elements, the ramifications of long-term exposure must be understood.

Many power MEMS concepts are low Biot number systems, which serves to minimize thermal gradients within the solid structures [23]. However, many of the systems utilize thin solid films as tribological elements, for electrical insulation or for chemical etch protection [24]. These thin films, not unlike bimetallic strips or thermostats, can generate very large thermal stresses in the materials due to atomic lattice and coefficient of thermal expansion (CTE) mismatch.

4. CURRENT TECHNOLOGIES IN MICRO-POWER GENERATION

Although the field of micro-scale power generation using combustion is 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. There are also several approaches for micro air vehicle (MAV) applications, but the majority of concepts are designed for the production of electrical power [25]. The projects have been grouped into four categories: micro-combustors, heat engines, rockets and fuel cells. 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. Fuel cells are not considered traditional combustion device however the oxidation of hydrocarbons in fuel cells and low temperature catalytic combustion are similar in nature [26]. The direct electrochemical conversion results in high efficiencies. The materials of construction and thermal stress issues are also similar for SOFCs and some catalytic designed systems. 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.

4.1. Micro-combustors

Figure 1. 3-D “Swiss-roll” type combustor.

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. The Swiss roll approach has been used to develop thermoelectric power-generation devices using micro-scale combustion. The goal of Monney et al. [27] 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. Power production has been demonstrated, although to date with low efficiency. New designs of these types of power-generation devices have been recently proposed based on thermodynamic analysis that promise to provide better efficiencies. 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. With its 3-D Swiss roll characteristics, the reactor shown in Fig. 1 appears to be well suited to MEMS size devices because the heat losses are greatly reduced. Complication presently appears in the implementation of the thermoelectric unit. To date macro-scale and meso-scale combustors have been fabricated and tested. Low temperature, self-sustained combustion have been demonstrated in these larger reactors. An integrated combustor/SOFC design has also been developed which utilizes the thermal integration of a Swiss roll combustor design as a thermal management technique for SOFC operation.

4.2. P³ micro-engine

Figure 2. Photograph of P³ micro-engine.

Because of the challenges these groups have faced in realizing micro heat engines based on rotating components. Richards et al. [28] have focused on developing a micro heat engine base on flexing components called the P3 Micropower Generator (Fig. 2). The engine, an external combustion engine, consists of a cavity filled with a two-phase fluid bounded by top and bottom thin membranes (Fig. 3). The one membrane acts as an evaporator. The other acts as an expander. A thermal switch controls the timing and duration of the heat addition and heat rejection. Mechanical power is produced as the expander membrane alternately expands and compresses the working fluid. At peak power output from the engine the power required to actuate the switch is a relatively small fraction of the power produced by the engine. Thus, it has been demonstrated net power out from this system consisting of a micro-combustor and micro-engine. A thin film of piezoelectric material is deposited on the expander membrane to obtain mechanical to electrical energy conversion. The engine and components have been integrated to demonstrate net power production when operating from a constant temperature heat source at 60 °C.

Figure 3. Schematic and photographs of MEMS fabricated micro heat engine.

4.3. Micro-rockets

Solid rockets have also been developed and fabricated using traditional MEMS technologies. In fact, many of the designs do not significantly differ from micro-machined airbag generators. Other rocket projects include the development of improved nozzle designs, the development of liquid based micro-thrusters for micro-spacecraft applications, and the use of solid propellants in micro-tubes [29]. Only recently has there been a modeling and simulation effort given to directly address the issues of micro-propulsion. Solid fueled micro-rockets have been developed for both space and terrestrial applications. The space thruster design fabricated at TRW and shown in Fig. 4 is a three-layer thruster developed for orbit and station keeping of picosatellites or micro-spacecraft and consists of a Si_3N_4 burst diaphragm, a glass layer in which the lead styphnate propellants is housed, and a Si base layer with the resistive igniters.

Figure 4. MEMS fabricated array of “Digital-Propulsion” micro-thrusters.

4.4. Fuel cells

Fuel cells are electrochemical conversion devices. They produce electricity from fuel (on the anode side) and an oxidant (on the cathode side), which react in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it [30]. Fuel cells operate virtually continuously as long as the necessary flows are maintained. Fuel cells are different from electrochemical cell batteries in that they consume reactant from an external source, which must be replenished: a thermodynamically open system [31]. By contrast, batteries store electrical energy chemically and hence represent a thermodynamically closed system. Typically, fuel cells need expensive precious materials in order to perform the fuel cells and catalysis would still not be realistic unless the precious materials loading and cost diminished drastically.

Especially, among the many types of fuel cells, solid-oxide fuel cells (SOFCs) have received considerable attention due to their high efficiency and fuel flexibility [32]. SOFCs offer a convenient means of generating electric power from conventional fuels, and given the absence of moving parts, may also be well suited to small-scale applications. Unlike proton exchange membrane (PEM) fuel cells, SOFCs can use hydrocarbon fuels directly and do not require fuel pre-processing to generate H_2 prior to utilization. Rather, H_2 and CO are generated *in situ* either by partial oxidation or, more typically, by steam reforming of the hydrocarbon fuel in the anode chamber of the fuel cell. SOFCs are all-solid electrochemical devices with no liquid electrolyte with its attendant material corrosion and electrolyte management problems. The high operating temperature (typically 500-1000 °C) allows internal reforming, promotes rapid kinetics with nonprecious materials, and yields high quality byproduct heat for cogeneration [33]. The total efficiency of cogeneration system can be 80%-far beyond the conventional power production system.

In general, the SOFC consists of three components: (a) cathode for oxygen reduction; (b) anode for fuel oxidation; (c) electrolyte for oxide ions transportation. The function of the fuel cell with oxides is based on the activity of oxide ions passing from the cathode region to the anode region, where they combine with hydrogen or hydrocarbons; the freed electrons flow through the external circuit.

Figure 5. Schematic of a conventional dual-chamber SOFC.

Conventional SOFCs are operated with a split cell, dual-chamber configuration: the anode chamber supplied with fuel and the cathode chamber with air. The dual-chamber SOFC does not require catalytically selective electrodes, since the electrodes are exposed to separate gas streams (Fig. 5), and is generally considered to be the technology of choice for large scale stationary power generation. However, the dual-chamber configuration is not widely applied due to the high cost (~\$1000/kW) which is mainly from the sealing issues of fuel cells. In addition, it is not considered suitable for the portable application in which frequent and rapid start-up and shut-down are necessary due to large internal stress during the heating and cooling processes resulting from the thermal expansion mismatch between cell components and sealant.

Figure 6. Schematic of a Single-Chamber SOFC.

To address the sealing issues, the concept of a single-chamber solid-oxide fuel cell (SC-SOFC) was proposed by Wang et al. [34]. It is a sealant-free configuration with both electrodes exposed to the same pre-mixed fuel-air mixture in one chamber (Fig. 6). An SC-SOFC may operate either using an oxygen ion conducting electrolyte, or one that conducts protons.

Thus, selection of the electrolyte type requires detailed knowledge of the ability of various anode and cathode materials to catalyze these reactions. Amongst conductors within each category, the criteria for materials selection are (a) high ionic conductivity, (b) low electronic conductivity, (c) good chemical stability, and (d) good processability, particularly in conjunction with electrode materials. Rare-earth doped ceria is one of the best choices amongst oxygen ion conductors; whereas rare-earth doped barium zirconate is the best amongst proton conductors [35]. The performance of the SC-SOFC depends on different

catalytic selectivity of the anode and the cathode toward the fuel-oxidant mixture. By employing perovskite type materials, the SC-SOFC can achieve the comparable performance to the dual-chamber SOFC.

Because direct chemical oxidation of the hydrocarbon does not take place on the SC-SOFC, the fuel and oxidant need not be physically separated and complications due to sealing are entirely eliminated. As a consequence, the SC-SOFC greatly simplifies the system design and results in excellent thermal and mechanical shock resistance. These features furthermore enable rapid start-up (<10 s) and cool down. Unfortunately, however, the mixture of oxidant and fuel brings some safety issues because its susceptibility to explosion [36]. In addition, the SC-SOFC needs the extra heating-system for the ignition of fuel cell, rendering the SC-SOFC system complicated and the overall efficiency very low. Furthermore, SC-SOFC developed up to now can only use gaseous fuels directly, thereby limiting its range of fuel flexibility.

Figure 7. Schematic of flame fuel cell.

To overcome the limitation of conventional dual-chamber SOFC and SC-SOFC, Kronemayer et al. [47] proposed an innovative concept of a direct-flame fuel cell (DFFC) operated without a gas chamber. The operation principle of DFFC is based on the combination of a flame with a SOFC in a simple, “no-chamber” setup. The flame serves as fuel-flexible partial oxidation reformer, while simultaneously providing the heat required for SOFC operation. In the combined system, flame and fuel cell are inherently coupled. For DFFC, with the anode of SOFC faces the flame and the cathode is exposed to the ambient air, the atmosphere difference is produced between cathode and anode (Fig. 7). During the combustion of hydrocarbon fuels, a significant amount of useful gases, such as H_2 , CO and other hydrocarbons, is also produced due to the water gas shift reaction and partial oxidation even without any catalyst.

There are a number of advantages in DFFC: (a) Simple setup: the DFFC can be operated in a no-chamber setup, such that the anode is simply held into the exhaust gases of a combustion flame, and the cathode breathes ambient air; (b) Rapid start-up: the flame heat release brings the fuel cell rapidly to its operation temperature; (c) Fuel versatility: since the intermediate species produced by the flame are similar for a wide variety of hydrocarbon fuels, the direct-flame fuel cell is highly flexible in fuel selection included gaseous (e.g. methane, ethane, propane, etc.), liquid (e.g. ethanol, butanol, kerosene, etc.) and solid (e.g. wood, wax, etc.) fuels.

However, on the other hand, the DFFC concept has severe drawbacks: (a) Poor thermal shock resistance: the operating environment of a gaseous flame induces significant thermal stress to the SOFC. In general, the electrolyte layer is easy to crack at the high heating rate generated by the flame (typically 60 °C/s). This may lead to a rapid degradation of fuel cell performance or fractures of the material; (b) Coking: carbon coking is still an issue when the hydrocarbon fuels are employed. Carbon coking will block the gas diffusion inside an anode or even rupture the fuel cell; (c) Low efficiency and poor performance: an inherent property of DFFC is that a part of the fuel's chemical energy is consumed in the flame to sustain the fuel cell temperature [38]. For a typical burner, it is difficult to control the amount of fuel combusted versus the amount utilized for electrical power generation, thus reducing the overall electrical conversion efficiency.

5. CONCLUSION

The field of micro-power generation is basically in a feasibility stage, and although significant progress has been made in the last few years with several important demonstrations, 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 fundamental study as well as manufacturing development that precedes the development of the micro-devices themselves. The study needs unique to the development of combustion systems at the small scale include: mixing and reacting 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. Initial investigations in this area have identified unique oscillatory phenomena which has led to a better understanding of the role of the flow configuration and substrate. Materials must be able to sustain the high temperature, harsh chemical environment, stress, and wear due to combustion events. Emissions must be further investigated and noise must be reduced to acceptable levels. The impact of fouling and coking in micro-combustion structures and catalytic surfaces must be addressed, either through improved designs and/or fuels selection. High-precision, high aspect ratio structures are necessary to provide adequate sealing for high compression ratios and to date, leakage and sealing have limited combustion, and hence, system efficiencies. 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, often termed bottom-up manufacturing. However, it is likely that this approach will also have its own logistical problems. In any case, it is important to keep in mind that, because the specific energy of liquid hydrocarbon fuels is many 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 (both electrical and mechanical) in the small scale the potential pay-off is very large.

As the combustion temperatures decrease in micro-combustors, and the temperature of the electrochemical reactions in fuel cells (SOFCs) increases, it seems that an area of

intermediate temperature oxidation is emerging as the most relevant for small-scale power generation. In this regime, catalysis (either through deposited noble metals or through appropriate membranes) will play a major role over gaseous phase combustion.

In addition to power generation, the lessons learned as part of micro-combustion study can also be applied to components of larger systems such as ignition systems, fire safety applications, diagnostic tools, alternative power system architectures, and improved larger scale power-generation performance. Micro-combustion also has applications in a variety of fields, such as the generation of a large variety of future micro- and nano-materials including fine glass powders and nanoparticles, single walled nanotubes, as well as to deposit oxide, nitride and other materials.

The semiconductor materials used in the manufacture of MEMS devices provide distinct opportunities for the development of micro-combustors due to their elevated operational temperature, thermal and optical properties, however their relatively recent application to the fabrication of mechanical devices implies that a number of new problems must be resolved when used to build micro-power generators.

References

- [1] Boyarko G.A., Sung C.-J., Schneider S.J., Catalyzed combustion of hydrogen-oxygen in platinum tubes for micro-propulsion applications. *Proceedings of the Combustion Institute* 30(2) (2005) 2481-2488.
- [2] Zhou J., Wang Y., Yang W., Liu J., Wang Z., Cen K., Combustion of hydrogen-air in catalytic micro-combustors made of different material. *International Journal of Hydrogen Energy* 34(8) (2009) 3535-3545.
- [3] Wang Y., Zhou Z., Yang W., Liu J., Wang Z., Cen K., Combustion of hydrogen-air in micro combustors with catalytic Pt layer. *Energy Conversion and Management* 51(6) (2010) 1127-1133.
- [4] Shih H.-Y., Liu C.-J., A computational study on the combustion of hydrogen/methane blended fuels for a micro gas turbines. *International Journal of Hydrogen Energy* 39(27) (2014) 15103-15115.
- [5] Yuasa S., Oshimi K., Noshima T., Tennichi Y., Concept and combustion characteristics of ultra-micro combustors with premixed flame. *Proceedings of the Combustion Institute* 30(2) (2005) 2455-2462.
- [6] Kikuchi T., Yamamura H., Tezuka T., Hasegawa S., Maruta K., Study on combustion and ignition characteristics of natural gas components in a micro flow reactor with a constant temperature profile. *Combustion and Flame* 161(1) (2014) 37-48.
- [7] Miyata E., Fukushima N., Naka Y., Shimura M., Tanahashi M., Miyauchi T., Direct numerical simulation of micro combustion in a narrow circular channel with a detailed kinetic mechanism. *Proceedings of the Combustion Institute* 35(3) (2015) 3421-3427.
- [8] Liu Y.C., Xu Y., Avedisian C.T., Hicks M.C., The effect of support fibers on micro-convection in droplet combustion experiments. *Proceedings of the Combustion Institute* 35(2) (2015) 1709-1716.
- [9] Li Y.-H., Chen G.-B., Wu F.-H., Cheng T.-S., Chao Y.-C., Effects of catalyst segmentation with cavities on combustion enhancement of blended fuels in a micro channel. *Combustion and Flame* 159(4) (2012) 1644-1651.

- [10] Wan J., Fan A., Maruta K., Yao H., Liu W., Experimental and numerical investigation on combustion characteristics of premixed hydrogen/air flame in a micro-combustor with a bluff body. *International Journal of Hydrogen Energy* 37(24) (2012) 19190-19197.
- [11] Badra J., Masri A.R., Zhou C., Haynes B.S., An experimental and numerical study of surface chemical interactions in the combustion of propylene over platinum. *Combustion and Flame* 160(2) (2013) 473-485.
- [12] Smyth S.A., Kyritsis D.C., Experimental determination of the structure of catalytic micro-combustion flows over small-scale flat plates for methane and propane fuel. *Combustion and Flame* 159(2) (2012) 802-816.
- [13] Kaisare N.S., Vlachos D.G., Extending the region of stable homogeneous micro-combustion through forced unsteady operation. *Proceedings of the Combustion Institute* 31(2) (2007) 3293-3300.
- [14] Sakurai T., Yuasa S., Ono Y., Honda T., Flame stability and emission characteristics of propane-fueled flat-flame miniature combustor for ultra-micro gas turbines. *Combustion and Flame* 160(11) (2013) 2497-2506.
- [15] Sakurai T., Yuasa S., Honda T., Shimotori S., Heat loss reduction of hydrocarbon combustion in ultra-micro combustors for ultra-micro gas turbines. *Proceedings of the Combustion Institute* 32(2) (2009) 3067-3073.
- [16] Ohiwa N., Ishino Y., Yamamoto A., Important role of multiphase process in enhancement mechanism of micro plate-surface particle combustion. *Proceedings of the Combustion Institute* 32(2) (2009) 1994-2000.
- [17] Hosseini S.E., Wahid M.A., Investigation of bluff-body micro-flameless combustion. *Energy Conversion and Management* 88(1) (2014) 120-128.
- [18] Maruta K., Micro and mesoscale combustion. *Proceedings of the Combustion Institute* 33(1) (2011) 125-150.
- [19] Bartrom A.M., Ta J., Nguyen T.Q., Her J., Donovan A., Haan J.L., Optimization of an anode fabrication method for the alkaline Direct Formate Fuel Cell. *Journal of Power Sources* 229(0) (2013) 23-38.
- [20] Azime M., Okuno M., Tsuboi K., Kawahara N., Tomita E., Multidimensional CFD simulation of syngas combustion in a micro-pilot-ignited dual-fuel engine using a constructed chemical kinetics mechanism. *International Journal of Hydrogen Energy* 36(2) (2011) 13793-13807.
- [21] Park J.-S., Park J.-S., Choi S.-H., Cho S.-H., Kim S.-H., Novel micro fuel processor for PEMFCs with heat generation by catalytic combustion. *Chemical Engineering Journal* 113(1) (2005) 47-53.
- [22] Hwang K.-R., Lee C.-B., Lee S.-W., Ryi S.-K., Park J.-S., Novel micro-channel methane reformer assisted combustion reaction for hydrogen production. *International Journal of Hydrogen Energy* 36(1) (2011) 473-481.
- [23] Ganji H.B., Ebrahimi R., Numerical estimation of blowout, flashback, and flame position in MIT micro gas-turbine chamber. *Chemical Engineering Science* 104(0) (2013) 857-867.

- [24] Wan J., Yang W., Fan A., Liu Y., Yao H., Liu W., Du Y., Zhao D., A numerical investigation on combustion characteristics of H₂/air mixture in a micro-combustor with wall cavities. *International Journal of Hydrogen Energy* 39(15) (2014) 8138-8146.
- [25] Jeon S.W., Yoon W.J., Jeong M.W., Kim Y., Optimization of a counter-flow microchannel reactor using hydrogen assisted catalytic combustion for steam reforming of methane. *International Journal of Hydrogen Energy* 39(12) (2014) 6470-6478.
- [26] Moskovskikh D.O., Lin Y.-C., Rogachev A.S., McGinn P.J., Mukasyan A.S., Spark plasma sintering of SiC powders produced by different combustion synthesis routes. *Journal of the European Ceramic Society* 35(2) (2015) 477-486.
- [27] Kuo C.H., Ronney P.D., Numerical modeling of non-adiabatic heat-recirculating combustors. *Proceedings of the Combustion Institute* 31(2) (2007) 3207-3214.
- [28] Cho J.-H., Lin C.S., Richards C.D., Richards R.F., Ahn J., Ronney P.D., Demonstration of an external combustion micro-heat engine. *Proceedings of the Combustion Institute* 32(2) (2009) 3099-3105.
- [29] Lewis Jr D.H., Janson S.W., Cohen R.B., Antonsson E.K., Catalytic micropropulsion. *Sensors and Actuators A: Physical* 80(2) (2000) 143-154.
- [30] Yu X., Manthiram A., Catalyst-selective, scalable membraneless alkaline direct formate fuel cells. *Applied Catalysis B: Environmental* 165(0) (2015) 63-67.
- [31] Wang Y., Shi Y., Yu X., Cai N., Thermal shock resistance and failure probability analysis on solid oxide electrolyte direct flame fuel cell. *Journal of Power Sources* 255(0) (2014) 377-386.
- [32] Giddey S., Badwal S.P.S., Kulkarni A., Munnings C., A comprehensive review of direct carbon fuel cell technology. *Progress in Energy and Combustion Science* 38(3) (2012) 360-399.
- [33] Bartrom A.M., Haan P., Direct methane fuel cell with an alkaline anion exchange membrane. *Journal of Power Sources* 214(0) (2012) 68-74.
- [34] Wang K., Zeng P., Ahn J., High performance direct flame fuel cell using a propane flame. *Proceedings of the Combustion Institute* 33(2) (2011) 3431-3437.
- [35] Vogler M., Horiuchi M., Bessler W.G., Modeling, simulation and optimization of a no-chamber solid oxide fuel cell operated with a flat-flame burner. *Journal of Power Sources* 199(20) (2010) 7067-7077.
- [36] Wang Y., Shi Y., Ni M., Cai N., A micro tri-generation system based on direct flame fuel cell: potential applications. *International Journal of Hydrogen Energy* 39(11) (2014) 5996-6005.
- [37] Kronmayer H., Barzan D., Horiuchi M., Suganuma S., Tokutake Y., Schulz C., Bessler W.G., A direct-flame solid oxide fuel cell (DFFC) operated on methane, propane, and butane. *Journal of Power Sources* 166(1) (2007) 120-126.
- [38] Choi W., Kwon S., Dong Shin H., Combustion characteristics of hydrogen-air premixed gas in a sub-millimeter scale catalytic combustor. *International Journal of Hydrogen Energy* 33(9) (2008) 2400-2408.