Design and Integration of Portable SOFC Generators

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Introduction

Although the majority of development on solid oxide fuel cells has been directed towards stationary multi-kilowatt systems, recent advances in high power density stacks and system integration have made it possible to build portable SOFC generators with power ratings under 500 W. Portable SOFC generators in this class could be competitive with PEM and direct methanol systems, particularly in light of their ability to operate with hydrocarbon fuels. Capable of operating on fuels ranging from methane and propane through gasoline and kerosene, these generators can operate over wide environmental temperature ranges, can be more efficient than internal combustion engines, and can achieve high power and energy densities.

Over the past six years, Mesoscopic Devices, LLC and its partners have been developing the core technologies required to build compact, efficient portable SOFC generators in sizes under 500 W. In this paper, we report on the design and testing of the MesoGen™-75 and MesoGen-250 portable SOFC generators having output powers of 75 and 250 W, respectively. Intended for military and industrial uses, these prototypes (shown in Figure 1) demonstrate the practicality of solid oxide fuel cell generators under 500 W. Applications include field battery charging, remote power, and low level auxiliary power where long-term power generation cannot be practically served by batteries or noisy internal combustion generators.

Figure 1. The 250 W MesoGen™-250 (left) and the 75 W MesoGen-75 (right) SOFC generators.

The MesoGen-75 is a man-portable generator approximately 130x180x250 mm, with a dry mass of 3 kg and a fuel consumption of ~0.55 kg/day. Two versions of the system have been developed, one operating on propane, and one on low-sulfur kerosene. Future models will use kerosene (jet fuel or military JP-8) processed through a separate liquid-phase desulfurizer also under development at Mesoscopic Devices. The generator includes an internal hybrid battery, and can provide peak power of up to 150 W. Both 12 V DC and 24 V DC output are available from the same system. The MesoGen-250 is 178x203x356 mm, with a dry mass of 6.3 kg, and a projected fuel consumption of ~1.8 kg/day. This system is intended to run on liquid fuels and perform as a battery charger for multi-day field operations.

SOFC System Integration

Portable SOFC generators are made possible by careful integration of optimized balance-of-plant (BOP) components. Considering that the stack occupies less than 1/3 of the total volume in a well designed generator, attention to system integration is vital to achieving small size. Furthermore, the BOP parasitic power demand can severely limit generator efficiency without optimization of the tradeoffs between stack and BOP performance characteristics. Off-the-shelf BOP components are generally not available for the specific requirements of optimized portable systems, and custom components must be manufactured. Tying these elements together into a practical system requires particular attention to integration, thermal management, and balancing component level performance tradeoffs to optimize overall system level performance. Furthermore, design optimization must be constrained by practical considerations including reliability and manufacturing costs.

Figure 2 shows a flow diagram of the MesoGen SOFC generator. The generator is separated into two zones: a *hot zone* containing the CPOX reactor, tail gas combustor, recuperator, stack, and insulation; and a *cold zone* comprising the air and fuel feed equipment, control electronics, battery, and case. A feed system meters fuel and air into a catalytic partial oxidation (CPOX) reactor generating a hydrogen and carbon monoxide rich gas that can easily be consumed by the SOFC without carbon formation. The stack is also fed air that is preheated in a recuperator using energy from the stack exhaust. Typical stack utilization is about 75%, and the remaining fuel in the anode exhaust is combined with the cathode exhaust and burned in a tail gas combustor.

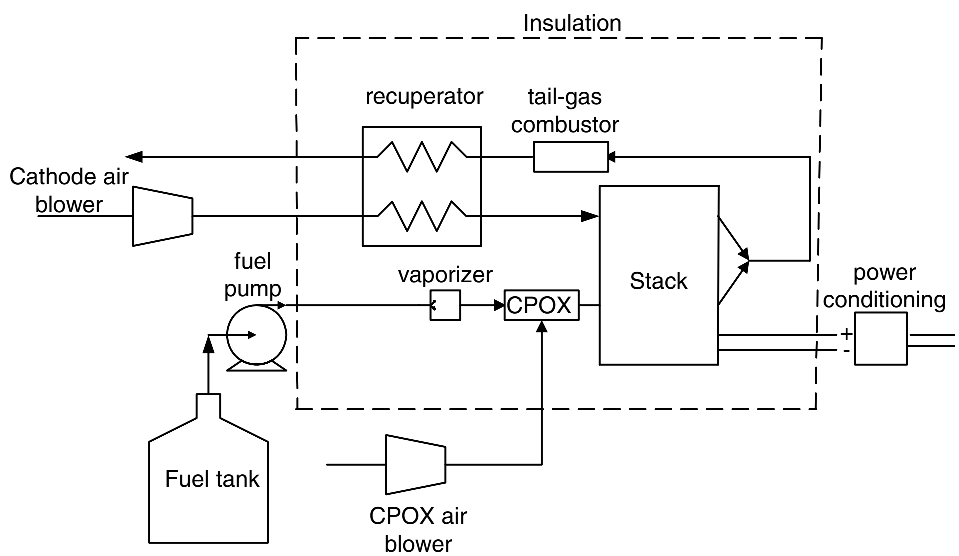


Figure 2. SOFC generator flow diagram.

Fuel processing

A major advantage of SOFCs is the ability to operate on CPOX reformate that is easily generated in a compact reactor. While not as efficient as steam reforming or autothermal reforming reactors, the absence of water in the CPOX feed greatly simplifies the feed equipment and overall balance-of-plant. A fuel processing approach that requires water would also require the either an internal water recovery system or that the user carry water in addition to fuel. Both approaches carry a significant size and weight penalty that is impractical in portable systems.

Implementing a CPOX reactor requires steady fuel feed, good air and fuel mixing, and preheat of the feed mixture. Figure 3 shows a CPOX reactor and feed system for a 75 W SOFC generator. The CPOX catalyst is highly active with residence times of several milliseconds and occupies less than 2 cm^3 in this fuel processor. This reactor includes a feed tube in which fuel vapor and air are mixed and preheated prior to the CPOX catalyst. Steady fuel vapor flow is provided by a vaporizer that operates on electrical heat during startup and stack heat under normal operating conditions. The CPOX reactor also includes an electrical igniter for cold start operation. Owing to its small size and the strong exothermicity of the CPOX reaction, reactor ignition in less than 10 seconds is possible.

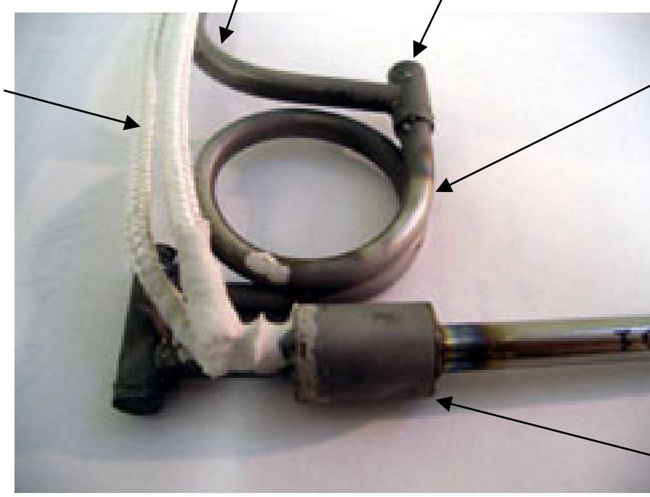


Figure 3. CPOX reactor with mixing and preheat section and electrical igniter

While not as susceptible to sulfur poisoning as PEM fuel cells, typical SOFC performance is degraded by a few ppm of sulfur. We have built systems with small onboard desulfurizers for propane driven systems that can operate for 1000 hours before requiring replacement. Liquid phase desulfurization is more challenging, especially for military fuels that can contain as much as 3000 ppm sulfur. The need for portability in small systems strongly favors performing liquid phase desulfurization in off-board equipment. A stand-alone desulfurizer can produce sulfur-free fuel for multiple portable generators, and we are pursuing this approach for our military 250 W battery charger. We are also developing on-board liquid phase desulfurizers for military systems ranging from 5 kW to over 500 kW.

Air feed

Fuel cells are air breathing generators, and feeding air to these systems represents the single largest parasitic power draw and source of noise in the generator. Minimizing air feed power demand and equipment size and noise requires minimization of downstream pressure drop in the stack, tail gas combustor, and both sides of the recuperator. Lower pressure drops in these components generally results from increased flow passage dimensions and larger hardware. Furthermore, poor flow distribution and decreased power density within the stack results when flow channel spacing is made too large in an attempt to reduce pressure drop.

Using comprehensive system level analysis, we have optimized the tradeoffs between blower demand and component flow characteristics on the cathode air side of the generator. This optimization, which considers system efficiency, size, and weight, leads to a typical target of 10-15% parasitic power loss for the air blower in our generators. Blower designs that have been considered include vane, scroll, diaphragm, and others with tradeoffs in efficiency, noise, and lifetime. Figure 4 shows an advanced blower designed at Mesoscopic Devices that generates as little as 50 dBA at 1 m. These blowers allow the fuel cells to be inaudible at distances more than 20 m, nearly twenty times quieter than competing engine-driven generators.

Figure 4. Custom high-speed air blower for portable fuel cells.

Thermal management

Recovering thermal energy from the system exhaust is vital in small SOFC generators in order to maintain stack operating temperatures that may be as high at 800 °C. While the CPOX reactor, tail gas combustor, and stack all generate heat, heat is lost from the hot zone through the insulation and the hot exhaust gas. Maintaining hot zone temperature can be a challenge as system power is reduced since heat loss through the hot zone insulation increases relative to the generator power as the surface area to volume ratio increases. More heat can be produced within the hot zone by operating a lower utilization and burning the excess fuel in the tail gas combustor, but this approach reduces efficiency and is not preferred. Effective thermal recuperation from the exhaust gas and high performance insulation are necessary to achieve desired hot zone temperatures in small generators.

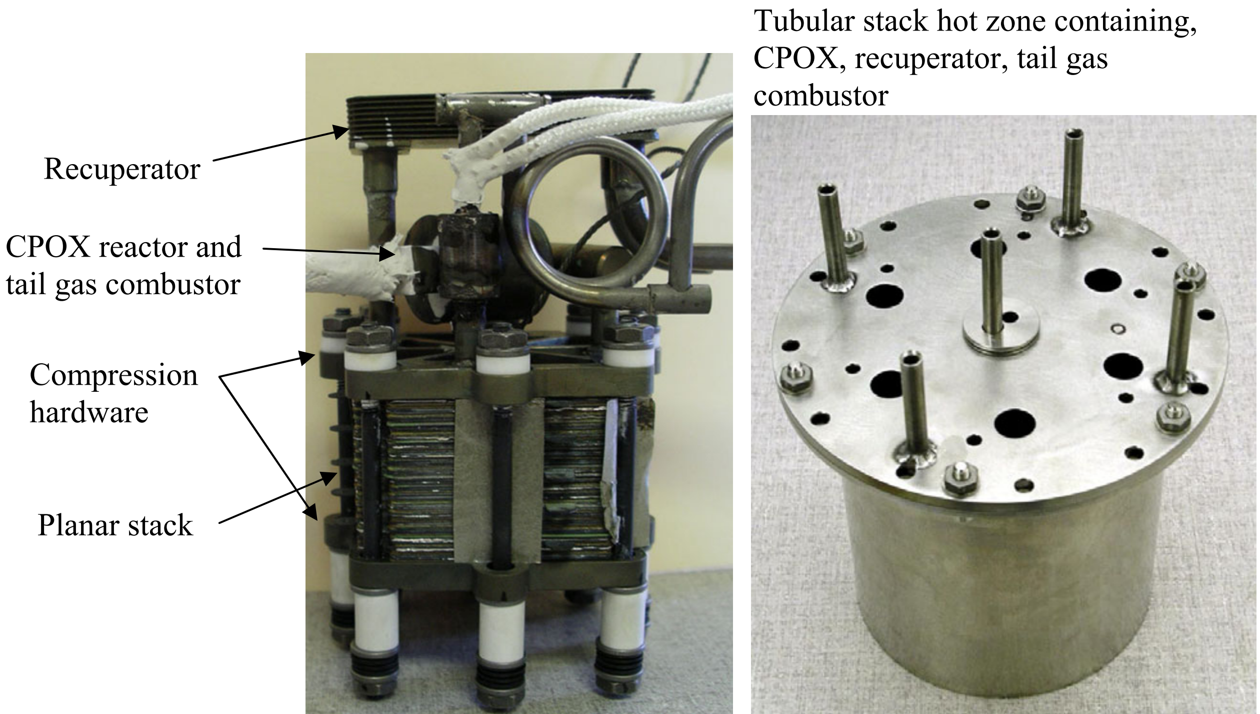
Our MesoGen generators use very high performance recuperators and insulation. By using a high effectiveness recuperator, the systems require less than 10 mm of insulation thickness, which is critical for minimizing system mass. Recuperators for our 75 W systems using planar stacks weigh as little as 60 g with an effectiveness of 75% and a single side pressure drop of only 500 Pa. These recuperators can operate for long periods with gas feed temperatures in excess of 850 °C.

Reaching operating temperature from a cold start is another challenge in SOFC systems. Fortunately, the CPOX reactor and tail gas combustor are fast starting and can produce the heat required to raise the stack to operating temperature from a cold start. This temperature rise is a strong function of the hot zone thermal mass and the power output of the CPOX reactor and tail gas combustor. While burning more fuel during startup than steady operation can in theory heat the system faster, increasing the amount of air required to achieve this power is not practical. Blower input power scales with air flow to the 3rd power, which would require a blower motor 8 times larger than that required at steady state operation if the system were to be started at twice the operating power. Even if an oversized blower were used to speed startup, the blower would not operate at its maximum efficiency point under normal operating conditions. Minimizing hot zone mass is therefore the critical design criteria for minimizing startup time. Hot zone mass is strongly affected by component integration in the hot zone and by the type of stack used in the system.

Planar and tubular cells

Two main SOFC stack architectures are available: planar stacks, and tubular bundles. Mesoscopic Devices has experience building generators that use both types of SOFC stacks. The more widely perceived practical differences between these two geometries are that planar cells afford greater stack power density but are more difficult to seal into stacks than tubular cells. For portable generators, where system power density is of utmost importance, this cell-level comparison would generally lead to the choice of the planar form over tubes. The system integrator should not be concerned with cell power density or even stack power density, however; hot zone power density is the primary characteristic of interest, regardless of the cell geometry. Cell power density has little relevance at the system level since using that cell in a practical system might require a very large hot zone. When integration of hot zone components is carefully viewed for both cell geometries, hot zones built with tubular cells result in a more compact generator.

Figure 5 shows a comparison between optimized hot zones based on both planar and tubular cells. The planar stack is a conventional stack of cells confined between two end plates that provide the necessary compression force to maintain the seals between cells and accommodate for material expansion throughout thermal cycles. Attached to the top compression plate are the hot zone BOP components. These components represent a volume nearly equal to that of the stack. In the design based on tubular cells, however, the hot zone BOP components are tightly integrated with the stack and impose very little volume penalty. While the planar and tubular cells have similar cell-level power density of about 0.31 W/cm^2, the stack power density for the planar stack is 520 W/cm^3, more than two times that for the tubular stack (200 W/cm^3.) When the entire hot zone power density is taken into account, however, the tube-cell version is almost twice as power dense as that based on planar cells. A significant advantage of tubular cells is therefore the gained by the ability to very tightly integrate hot zone components like the CPOX reactor, tail gas combustor, and recuperator with the stack.



Power density	*Planar cell*	*Tubular cell*
Cell (W/cm^2)	0.32	0.31
Stack (W/liter)	520	200
Hot zone (W/liter)	57	116

Figure 5. Comparison between planar cell and tubular cell based SOFC stacks.

By choosing the most compact hot zone, not only is hot zone volume and mass reduced, but response time and startup time are also reduced, the system battery can consequently be smaller, and efficiency can be improved. In addition to the optimization of system performance, the choices made regarding system integration must also allow for a low cost product. Both materials of construction and assembly labor must be considered. Driving towards simpler system designs also reduces cost while simultaneously increasing reliability. Recent system development at Mesoscopic Devices includes these economic design constraints, and these new generation systems use scalable manufacturing methods.