



Design, integration and demonstration of a 50 W JP8/kerosene fueled portable SOFC power generator

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ABSTRACT

A man-portable solid oxide fuel cell (SOFC) system integrated with desulfurized JP8 partial oxidation (POX) reformer was demonstrated to supply a continuous power output of 50 W. This paper discusses some of the design paths chosen and challenges faced during the thermal integration of the stack and reformer in aiding the system startup and shutdown along with balance of plant and power management solutions. The package design, system capabilities, and test results of the prototype unit are presented.

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1. Introduction

There is an urgent need for tactical power systems both for direct power applications and battery charging. These power sources need to be capable of operating on existing military fuels in order to meet logistics requirements. The power sources may also be operated close to the front battle lines, where low acoustic signature is critical. As a result, these power systems must be small, light-weight, energy-dense, and operate with low acoustic signature. A major challenge for the introduction of fuel cells within the military is developing a means to deliver an acceptable anode feed stream. The technology described in this paper responds to this requirement by targeting existing logistics fuels as the fuel cell feedstock.

Solid oxide fuel cells (SOFCs) are one of several technologies that are suitable for these power needs. The application of SOFC technology for power generation and supply to military equipment is desired using the JP8 fuel due to its energy density, safety, and logistics.

Thermodynamic and economic assessment of SOFC hybrid systems fed by liquid fuels for stationary power generation in isolated areas has been well assessed [1]. Catalytic reformer development and operation characteristics particularly designed for SOFC applications is a well studied subject [2–6]. However, there have been

very few efforts in the development of complete power generators using SOFCs fueled by JP8 fuel [7] in the kilowatt range and none in the sub-100 W range. As far as the authors know the prototype unit described in this paper is the first ever demonstrated portable system generating 50 W of electric power using an integrated catalytic partial oxidation reformer and a SOFC stack powered by JP8/kerosene fuel.

The 50 W prototype demonstrator described here was developed by the design and optimization of various subcomponents including stack optimization, reformer optimization, balance of plant (BoP) design and testing, manifold design and testing, power management, and system package design and testing. Details of all the subcomponents including the catalytic components, cell electrode materials, vaporizer, reformer operation, stack operation, etc. were discussed in detail in our previous publications. The main focus of this article is pointed towards the challenges faced during integration of various working subcomponents and how they were resolved. This paper discusses some of the design paths chosen and challenges faced during the thermal integration of the stack and reformer in aiding the system startup and shutdown along with BoP and power management solutions.

2. Results and discussion

Our earlier work clearly established the inherent advantages provided by catalytic partial oxidation (POX) vs. other reforming technologies, particularly for the portable system powered by the

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complex JP8 fuel [8]. This technology was adapted to serve as both the heat and fuel source for the current system. Tests reported henceforth both on a lab scale reformer and in an integrated stack/system are all based on POX technology.

2.1. POX reformer

The fuel utilized for all the tests was obtained from commercial vendor (AlfaAesar) and it is certified 0% sulfur in kerosene. Typical composition of kerosene is: n-alkanes and branched alkanes = 79%; alkyl-monoaromatics = 13%; di-aromatics, naphthalenes, and polynuclear aromatics = 8%. The catalyst was tested under POX conditions and the composition of the reformat was determined using a gas chromatograph (GC). Detailed description of the reformer characteristics including operating conditions, fuel vaporization, and the test setup/procedure is discussed elsewhere [8,9]. The dry reformat contained ~45.6% of electrochemically oxidizable species (hydrogen, H₂ and carbonmonoxide, CO) and <0.1% break through of hydrocarbons (>C2).

The molar O₂/C ratio was ~0.65, which is relatively higher compared to that used in POX based gaseous hydrocarbon reformers (e.g. methane, propane, etc.) and are typically close to stoichiometric values (0.5). One of the reasons for using higher oxygen to carbon ratios is the presence of higher amounts of carbon in the fuel. C/H ratio of a light hydrocarbon such as propane is 0.375, however it is in the range of 0.52–0.54 for kerosene based aviation fuels and even higher for heavier petroleum distillates such as diesel fuel. POX based reforming hence requires relatively higher amounts of oxidant (air) to operate in a coke free environment which effectively results in a higher ratio and lower overall reforming efficiency due to higher amounts of heat generated during the exothermic process. The measured reformer efficiency for the catalytic POX reformer utilized for this system was in the range of 73–75% at the optimal operating conditions. Another significant outcome from using these higher ratios is the amount of CO or H₂/CO present in the POX reformat, and is relatively higher compared to that generated from gaseous POX reformat (e.g. propane) and a lower overall concentration of H₂ + CO (~45.5%) in the reformat due to the presence of higher amounts of nitrogen as a diluent. All of these factors in turn also affect the SOFC stack efficiency as H₂ is more favorable for electrochemical oxidation compared to CO.

One of the key challenges faced and resolved while integrating the catalytic POX reformer with the stack included the introduction of liquid fuel in to the reformer by vaporizing and mixing it with cold air without any premature combustion/ignition to obtain a homogeneous mixture. More details regarding the fuel vaporization process and its introduction in to the reformer are provided in our previous publication [9].

A long-term test (>100 h) was conducted on the integrated SOFC-POX reformer package using an earlier design [8]. The volume of this package was ~4.2 L compared to 5.3 L from an even earlier version. The unit produced over 52 W_e and actually showed a slight increase in power production over the test period (100 h), the unit was thermally stable during the test and demonstrated a relatively stable power output. The system back pressure was reduced to <15 in. of water by re-designing the vaporizer/mixer. This work is crucial in the development of a JP8 reforming technology as the fuel mixing and vaporization poses one of the critical challenges in logistic fuel processors working in autothermal/partial oxidation environments. The new mixer design offered the advantage of a low operational pressure drop thus helping to reduce parasitic losses (an overall savings of 7–8 W_e) in the BoP.

One of the key concerns/issues in developing the integrated system included system startup. In order for the system to be truly portable and suitable for field use, it must be able to start-operate-shutdown on one fuel without the requirement for purge gases.

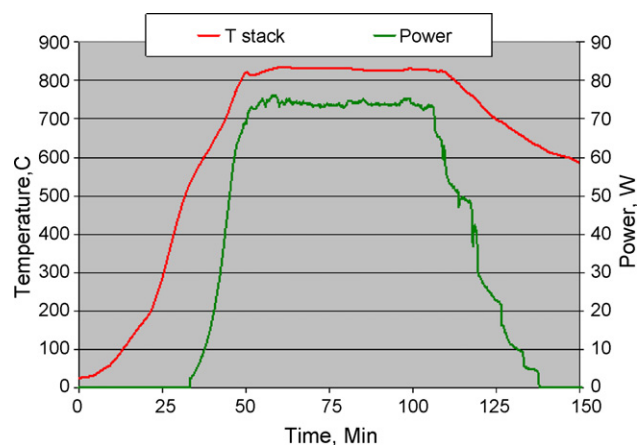


Fig. 1. Power output and SOFC stack's temperature as a function of time during the startup and steady state operation of the integrated reformer-SOFC package.

Based on the experimental observations, a sequence of steps (discussed below) were identified and implemented for starting up the system from room temperature using the liquid fuel. The first stage involves cold start with heating elements providing initial heat to vaporize the incoming cold fuel which evaporates in the vaporizer section. A catalytic burner then combusts the fuel to instantaneously generate combustion products with temperatures in excess of 1000 °C. The second stage involves a simultaneous cold startup stage assisted by the fuel vapor head space. Dry air is bubbled through a gas tight fuel tank which carries the light-ends to the tail-gas burner to generate additional heat. The fuel vapor head space also keeps the stack in a reducing atmosphere due to the presence of fuel as the stack heats up due to the hot gases generated from the first stage heating. This ensures a safe operation of the stack without oxidizing the cells unlike other systems that utilize inert gases such as nitrogen or helium to protect the cells from oxidizing while they get hot. Typical startup times vary from 45 to 55 min as shown in Fig. 1. All the startup techniques are sequenced in such a fashion that the overall power consumption is minimal for system startup (30–35 Wh of total energy consumption for the entire startup until the stack reaches steady state operation).

Once the reforming catalyst temperature reaches a desired value (180–250 °C), the supplied fuel lights-off on the catalyst which in turn starts generating hot reformat streams that aids stack heating. The stack is loaded after reaching an appropriate temperature, while the fuel flow rates are gradually increased to raise the stack temperature by the heat provided from electrochemical reactions and also simultaneously ensures carbon removal from the cell structure via electrochemical oxidation of carbon species. The stack starts generating heat and electricity after being loaded, ensuring a quick startup (typically 30 min as shown in Fig. 1). During this stage, the vaporizer reaches a self-sustaining mode due to the heat provided by the anode exhaust gases and the heat provided by the stack. The overall system reaches a final steady state where the only energy source is the cold liquid fuel entering the system.

Process conditions for a safe shutdown of the system were identified by performing experiments on a lab scale reformer. Fuel at different flow rates (turn-down) was injected in to the system and the air/fuel ratio was adjusted as a function of operating temperature in order to produce a reformat stream that provides a reducing atmosphere inside the fuel cells. These conditions were identified for maintaining an appropriate reformat stream to keep the stack in a reducing atmosphere while cooling down and also generate enough power from the stack to support the BoP load as needed. The ratio of reductants to oxidants in the reformat stream is maintained within the operational limits of the stack, thus enabling the

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