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

Praveen K. Cheekatamarla*, Caine M. Finnerty, Charles R. Robinson, Stanley M. Andrews, Jonathan A. Brodie, Y. Lu, Paul G. DeWald

NanoDynamics Energy Inc., 901 Fuhrmann Blvd, Buffalo, NY 14203, United States

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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.

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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* Corresponding author. Tel.: +1 303 949 1629; fax: +1 716 853 8996.
E-mail address: praveen_chemi@yahoo.com (P.K. Cheekatamarla).

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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 reformate 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 reformate contained ~45.6% of electrochemically oxidizable species (hydrogen, H_2 and carbonmonoxide, CO) and <0.1% break through of hydrocarbons (>C2).

The molar O_2/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 H_2/CO present in the POX reformate, and is relatively higher compared to that generated from gaseous POX reformate (e.g. propane) and a lower overall concentration of H_2 + CO (~45.5%) in the reformate 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 H_2 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 loses (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.

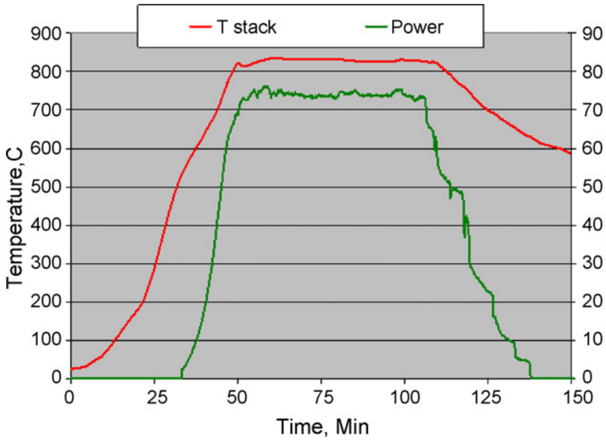

Fig. 1. Power output and SOFC stack's temperature as a function of time during the startup and steady state operation of the integrated reformer-SOFC package.

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 reformate 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 selfsustaining 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 reformate stream that provides a reducing atmosphere inside the fuel cells. These conditions were identified for maintaining an appropriate reformate 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 reformate stream is maintained within the operational limits of the stack, thus enabling the

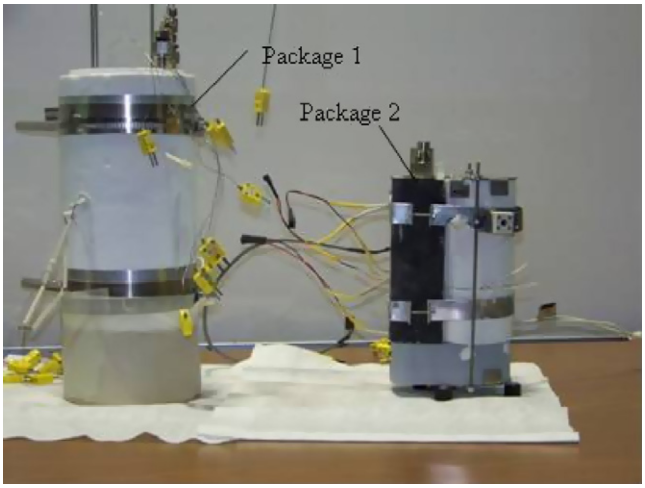

Fig. 2. Comparison of the integrated stack–reformer thermal package after optimizing different subcomponents.

stack to cool down without oxidizing and damaging the electrode structure.

2.2. Integration of stack with the POX reformer

Details regarding the SOFC technology utilized for these stacks are provided elsewhere [10]. The stack configuration was optimized for size and performance contributing to a smaller thermally integrated insulation package, improved operation characteristics, and optimum power required for the portable system. To achieve this, five main subsystems: the SOFC stack, the JP8 reformer, fuel vaporization subassembly, combustor subassembly, and the insulation package, were optimized for performance, size, and packaging. The optimized SOFC stack/JP8 reformer package size was reduced to <2 L, a 55% reduction from the previous test unit [8]. Fig. 2 shows a side by side comparison between the two integrated stacks.

The stack used in this system is an optimized configuration of the earlier integrated stack, where the orientation of vaporizer/mixer was improved to allow for a better control of transients during operation and also minimize the package volume. In order to optimize for size and packaging, the fuel vaporizer, mixer, and reformer had to be optimized to work more efficiently in smaller zones, respectively, and re-oriented to allow for integration into a portable enclosure (Fig. 3).

Exhaust gases passing through the afterburner (4) downstream of the SOFC stack/JP8 POX reformer are ducted over the mixer and vaporizer. The size of the mixer (2) dictated the location of the vaporizer (1) (a larger mixer positioned the vaporizer further away from the heat source and meant more heat input was needed from the stack exhaust to achieve the vaporization temperature and vice-versa). A heat exchanger (3) on the bend closer to the tail-gas burner was required since the exhaust temperature required to achieve the vaporization temperature exceeded the temperature of ignition in this region. Highly efficient microporous insulation was used for the integrated thermal package. To provide the heat needed to vaporize the fuel, a section of insulation was added to funnel the exhaust gasses from the afterburner region of the stack where waste heat is recovered (see Fig. 3). Microporous insulation provides an order of magnitude lower thermal conductivity as compared to conventional alumina/silica based insulation materials. Incorporating this into the design added more challenges since it decreased the space available for locating other components (vaporizer, combustor, etc.) while maintaining proper thermal balances. The thermal balances between the different subassemblies within the package became much more sensitive to one another and shortened the lags in thermal response times. These effects were considered during the re-orientation and optimization of the vaporizer, mixer, etc. discussed above.

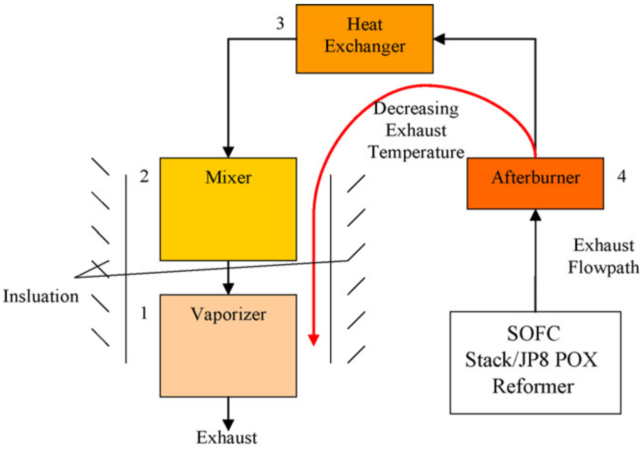

Fig. 3. Optimized integrated reformer design.

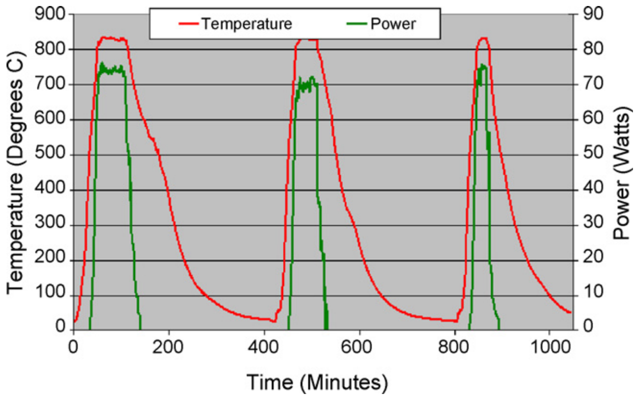

Fig. 4. Integrated system performance showing stack temperature and power output during three different startup and shutdown cycles.

Several tests were then conducted on the final integrated system design. Fig. 4 shows the system performance during the startup using BoP components containing valves and pumps, breadboard control discussed later in Section 2.4. It can be noticed that the system generates >50 W of electric power with in 40 min from an ambient startup. The actual startup time is ~50 min for peak power generation from the stack. This stack achieved 75 $\mathrm{W_e}$ at steady state conditions and was later shutdown on liquid fuel according to the shutdown process identified.

A system test for the integrated process chain was then performed by combining all the subcomponents that were evaluated individually (discussed above). The integrated package was brought up to required temperature and demonstrated good performance producing 75 $\mathrm{W_e}$, as shown in Fig. 4 (1st thermal cycle). Operating parameters such as oxygen-to-fuel ratio, fuel flow rate, air flow rate, stack load voltage, and reformer temperature were adjusted to thermally balance the system before a relatively stable power output was observed.

Additional tests were also conducted to identify the system performance when subjected to thermal cycling. Fig. 4 shows the power output as a function of stack temperature during startup on three different occasions. The stack delivered consistent power after three startup and shutdown cycles. Fig. 5 shows the power output as a function of time while the system was started up from ambient conditions and operated at steady state for 20 min and shutdown on the same fuel according to the shutdown process identified. The

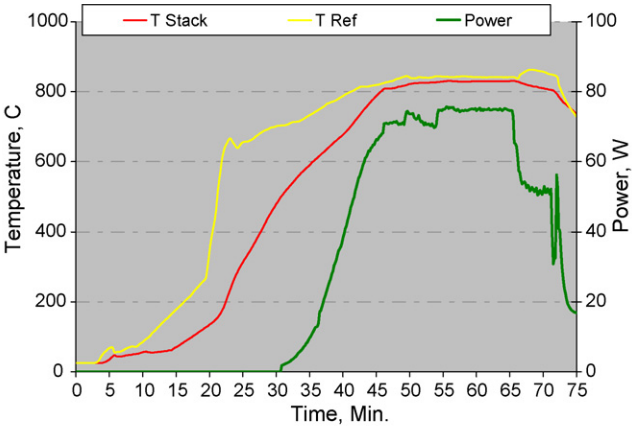

Fig. 5. Power vs. time on the integrated system after shutting down on the JP8 fuel.

system was restarted again and it showed no signs of degradation (Fig. 6). Fig. 6 shows the test results from the same integrated system that was used in the tests described above. It can be noticed that the system generated same power after four thermal cycles. It was also an objective of this test to minimize the BoP power consumption during the shut down cycle, for this reason lower flow rates of the fuel were utilized during the shutdown process and the stack was maintained in a reducing environment by switching over to head space vapor of the fuel at a safe temperature, leading to an overall energy savings of 3–4 Wh and a faster cool down. The safe shutdown temperature (300–400 °C) was reached in 85 min from the steady state operation (Fig. 6). Based on all these observations, logic for the state-machine document was established which was later translated in to a software code with corresponding control parameters.

2.3. BoP design

The balance of plant for this technology demonstrator was based of the design used in the Revolution®50, an internally developed product [11]. Standard order components available in industry viz. sensors, pumps, fans, valves, etc. to be optimized for size, performance, and power consumption were used. Component operational requirements (i.e. flowrate, pressure, accuracies) were confirmed through testing of the SOFC stack and JP8 reformer on laboratory scale test equipment. Cycle and life tests were also conducted on individual components to confirm stable and repeatable performance. Through previous testing of components for internally developed products at NanoDynamics Energy, Inc., the air pumps have been determined to be the limiting component beyond 1000 h of operation, with the exception of the liquid fuel pump, which has only been tested for 100 h, of which it tested successfully.

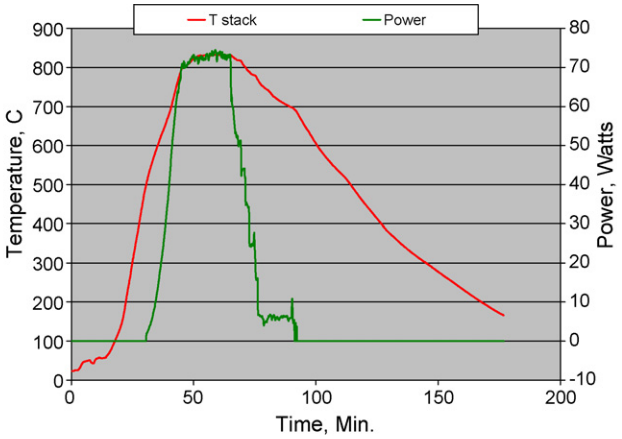

Fig. 6. Integrated system performance during startup and shutdown of the stack using JP8 fuel and vapor head space.

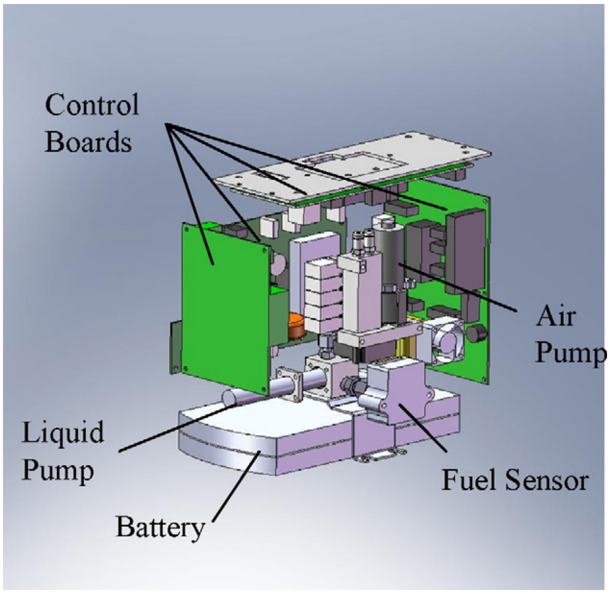

Fig. 7. 3D CAD model configuration of BoP.

The two major challenges in the BoP design were facilitating stand alone startup and shutdown and component layout and manifolding. This BoP design had to incorporate additional control valves and pumps needed for stand alone system startup and shut down capability, however, while keeping power requirements to a minimum and staying within the capabilities of the control and power management subsystem. The solution involved the use of proprietary control techniques which added complexity to the control architecture, but reduced the number of components needed in the design. Further power savings were achieved through the use of ultra low-power consumption control valves.

Appropriate battery technology and capacity was determined based on BoP components and the energy analysis on the additional vaporizer heating mechanism. A lithium polymer battery configuration was chosen which met operation requirements while keeping the demonstrator lightweight, which also easily integrated with the control and power management electronics.

To facilitate the package design and integration process, the entire BoP was modeled using commercial three-dimensional computer aided design (CAD) software. Several BoP layouts were modeled and compared to yield a final design that provided optimal functional, maintenance, size, and weight characteristics. Fig. 7 shows an example configuration.

In order to optimize real-estate in the balance of plant, the components were integrated, where possible through common manifolds. These common manifolds were machined from aluminum stock and served to optimize system flow paths, reduce space constraints, and facilitate package integration. The BoP was integrated in a “breadboard” layout and tested. This test layout (Fig. 8) served to test all functionality of the system during the final stages of development. All control and safety operations were checked for accuracy, repeatability, and stability.

The BoP components were tested against full system operation performance requirements including pressure and temperature conditions. In a similar manner, the electronic controls were integrated with the BoP subassemblies and tested for full functionality to ensure proper control and feedback.

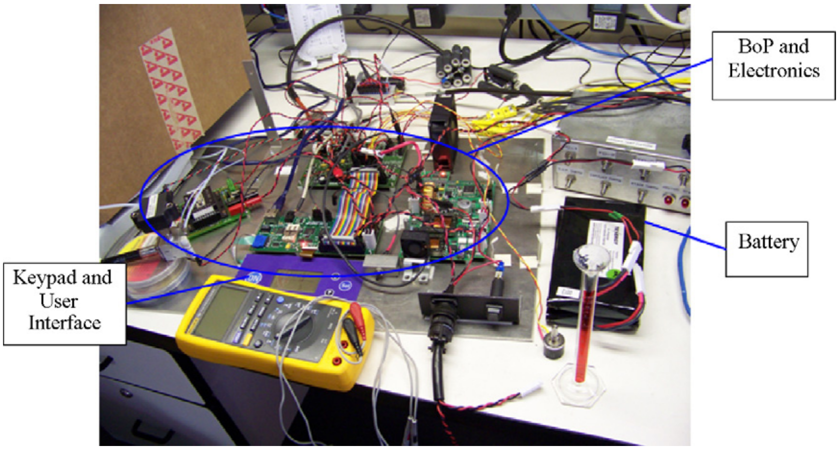

Fig. 8. “Breadboard” test layout.

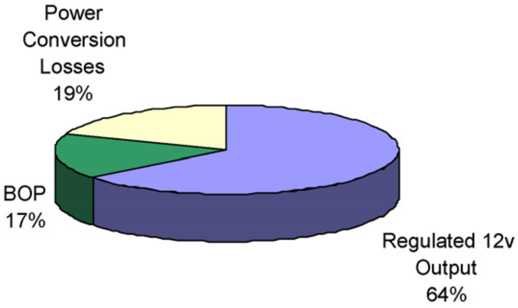

Fig. 9. System’s power balance.

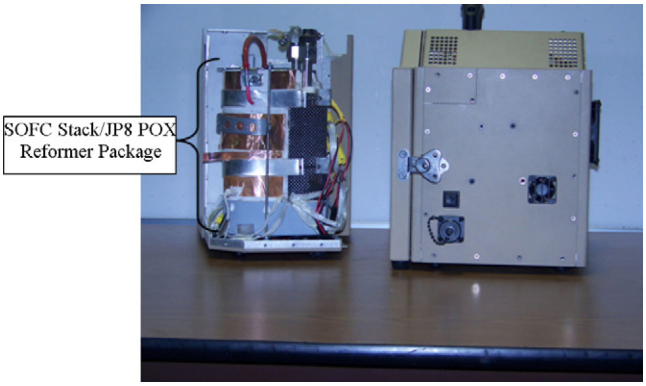

Fig. 11. Optimized SOFC stack/JP8 reformer unit (left) next to portable demonstrator.

The power conversion board efficiencies were also optimized to accommodate the greater power demand of the logistics fuel unit. A complete audit of loads and efficiencies was done and resulted in the implementation of a new modular power converter for the output of the system. The re-design of the board resulted in a 5% gain in overall power conversion efficiency to 80%, enough to meet the following power balance requirements: support the BoP load, support the output load, maintain flexibility in sustaining short duration peak loads. The power management of stack power is given graphically in Fig. 9.

Prior to integrating all system subassemblies into the package, they were tested together in a “breadboard” layout with a SOFC stack/JP8 reformer unit. These results are shown in Figs. 4–6. This provided complete system operation with full capabilities. (Fig. 13).

2.4. System package design and testing

A prototype package was designed to address functionality, portability, and ease of use with a built in single-push “ON” button. To address the possibility of varying operation or “mission” requirements, the fuel storage tank was separated as a modular attachment in the package design. Specifically for this prototype, a

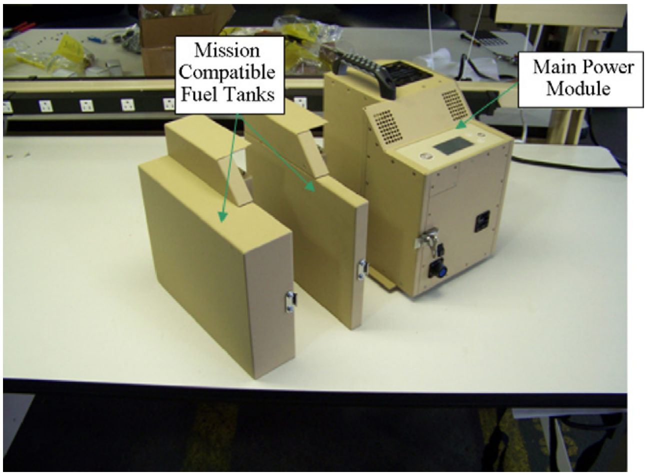

Fig. 10. Main power module with optional fuel tanks.

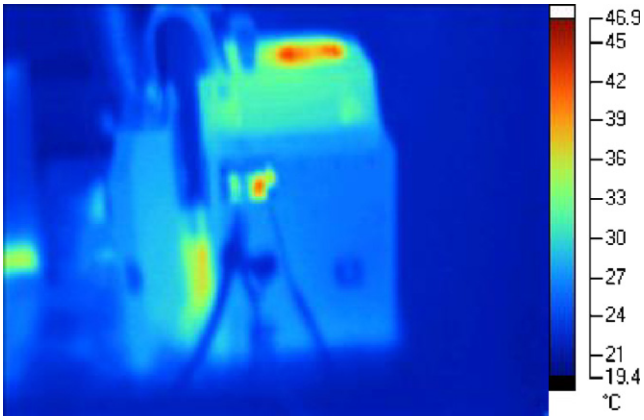

Fig. 12. Front view of SOFC/JP8 portable test unit, thermal image.

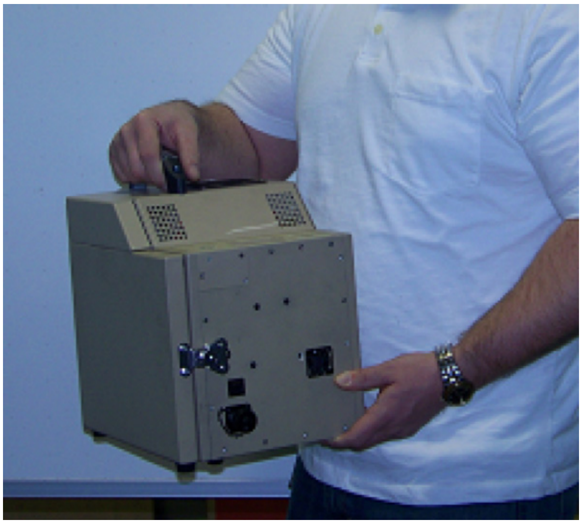

Fig. 13. A 50 W portable SOFC system with JP8 reforming.

24-h tank and a 72-h tank were designed to mate with the power module containing the SOFC stack and JP8 POX reformer unit, BoP, and control and power electronics. Fig. 10 shows the main unit along with the two fuel tank options. The prototype offers ease of use through a 4 button keypad and LCD screen with real time operation statistics. The enclosure is constructed of aluminum sheet metal which is durable yet weight efficient. The optimized SOFC stack/JP8 reformer was re-designed to easily integrate into a packaged system, as shown in Fig. 11.

A test-quality SOFC stack/JP8 reformer unit was installed and tested. Throughout testing, all critical flow, pressure, temperature and operation cycle parameters were monitored and logged for system analysis. As an example, thermal imagery was used to evaluate the thermal performance of the packaged unit (Fig. 12). The outer enclosure is shown to be <40 °C. The exhaust gases exit at temperatures below 50 °C.

2.5. Demonstration

The final man-portable technical demonstration unit (Fig. 13) was built and tested at both NanoDynamics Energy, Inc. facility and United States Army CECOM center located in Fort Belvoir, Virginia. The unit was designed as a hybrid unit with sufficient battery capacity to support startup and shut down of the SOFC stack/JP8 POX reformer. Short, peak power demands as a result of power surges can be tolerated up to 75 W for 2 s. The system has Serial and Ethernet communication capability, internal memory for field maintenance, an LCD status screen, a 4 button keypad, a regulated 12 VDC output, and has adaptable fuel tanks for 24 or 72 h tests. This unit demonstrated an autonomous startup, loading ability, and shutdown with desulfurized JP8 fuel. A programmable electronic load (Amrel, Model # 150-60-30) provided a continuous 50 W load through the duration of the test. All operation parameters were monitored and recorded through internal capability of the demonstrator as well as through a serial interface to a laptop. Fig. 14 shows the LCD displaying operation status, load, and fuel remaining during the test.

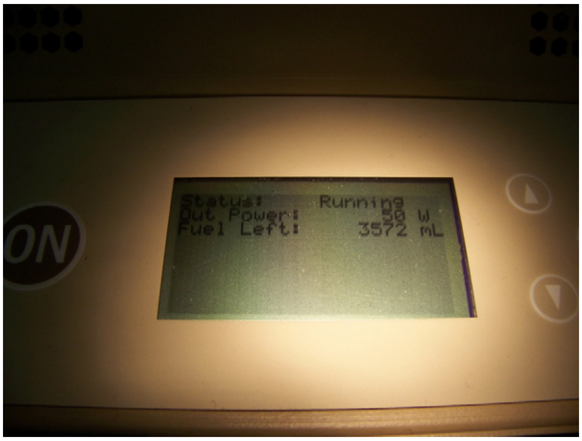

Fig. 14. Keypad screen during final system test.

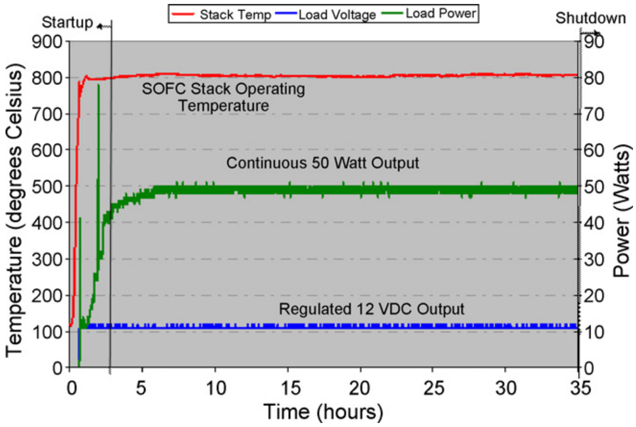

Fig. 15. Full system test showing the stack temperature and power output as a function of time while producing 50 W of electric power utilizing JP8/kerosene fuel.

A 24-h mission demonstration was conducted by pushing the “ON” button and left running for a total of over 35 h. The test was shut down so the prototype system could be packaged and delivered. This test included a complete startup, a 50-W continuous load for 30 h, and shutdown all on desulfurized logistic fuel. Fig. 15 shows the SOFC stack operational temperature, load output and regulated load voltage through the duration of the test. The shipped unit was later operated for more than 24 h at the CECOM facility at Fort Belvoir in Virginia, demonstrating stable power output of 50 W.

3. Summary

A man-portable solid oxide fuel cell based power generator producing 50 W of electric power from desulfurized JP8/kerosene fuel for military applications was successfully demonstrated. A catalytic partial oxidation based fuel reformer was thermally integrated with SOFC stack for optimal performance.

Acknowledgements

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