DEVELOPMENT OF REDUCED-TEMPERATURE SOLID OXIDE FUEL CELL POWER SYSTEMS

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ABSTRACT

AlliedSignal has been developing high-performance, portable SOFC power systems operating on a variety of fuels (including logistic fuels such as JP and diesel). The two key components of the system are a reduced-temperature SOFC module for electric power generation and a partial oxidation reformer for hydrocarbon fuel processing. The SOFC module is based on cells having micrometer-thick electrolytes made by tape calendering and thin-foil metallic interconnects. The fuel processor employs the partial oxidation of hydrocarbons with air to produce hydrogen and carbon monoxide. The system has many attractive features for portable uses including lightweight, low volume, and multifuel capability. This paper discusses the development status of this system with emphasis on the design, the SOFC module, and the fuel processor.

INTRODUCTION

AlliedSignal has been developing high-power density, reduced-temperature (< 800°C) solid oxide fuel cell (SOFC) technology for a broad spectrum of power generation applications. The AlliedSignal SOFC technology is a flat-plate (planar) design incorporating thin-electrolyte cells and thin-foil metallic interconnects for reduced-temperature operation (1). SOFC modules based on this technology have shown excellent performance, lightweight, and small volume and are particularly suitable for applications where weight and size are critical. Recent system work at AlliedSignal has focused on the development of portable systems operating on logistic fuels (JP and diesel fuels). This portable system consists of several key components and subsystems: (i) a reduced-temperature SOFC module for electrical power generation, (ii) a partial oxidation (POX) reformer for processing logistic fuels, (iii) a fuel storage and delivery subsystem, (iv) a startup subsystem, and (v) thermal control and management subsystem. The POX process has been selected because the technology leads to a compact reactor design required for this application. This paper discusses three aspects of the portable system: the fuel processor, the SOFC module, and the system design.
LOGISTIC FUEL PROCESSOR

A processor based on partial oxidation is being developed for converting logistic fuels to hydrogen and carbon monoxide. The partial oxidation process permits a compact design of the processor suitable for use in portable power systems. In the POX process, hydrocarbons in fuel and oxygen in air are mixed and react according to the following reaction:

$$C_nH_m + n/2 O_2 = m/2 H_2 + n CO$$

This reaction, like the combustion processes, occurs at high temperatures and is very fast. Residence times for complete conversion are on the order of a few milliseconds. Some of the key parameters of this process include carbon-to-oxygen ratio, temperature, and feed flow rate.

AlliedSignal has established the operating conditions for the processor to run on logistic fuels. These conditions have also been optimized to address two operation issues, carbon deposition and sulfur effects. Based on the established conditions, a reactor has been designed and successfully operated with JP and diesel fuels. Stable performance with up to 90% CO yield and 80% H2 yield has been obtained. The reactor has been tested with surrogate JP (a 12-component hydrocarbon mixture), real JP-8, and diesel fuels containing up to 1000 ppm sulfur (as benzothiophene or dibenzothiophene). The syngas product typically consists of 19% H2, 24% CO, 1% CO2, and 56% N2 on a dry basis. The low heating value (LHV) of the syngas is about 70-80% that of the fuel, depending on process conditions.

Figure 1 shows, as an example, the H2 and CO yields of a run on surrogate and real JP-8 fuels as a function of time. The sulfur content of the syngas product is shown in Figure 2. As can be seen from Figure 2, sulfur exits the processor as hydrogen sulfide, with little sulfur dioxide detected.

The processor has been operated for more than 650 h with logistic fuels. The processor has also shown scalability and has been thermal cycled without significant performance changes.

![Figure 1. H2 and CO Yields from Partial Oxidation Using JP-8 Fuels](image_url)
The design of SOFC modules or stacks for portable power systems is based on thin-electrolyte cells and thin-foil metallic interconnects. AlliedSignal has developed a simple and cost-effective process based on tape calendering for fabricating thin (1 to 10 micrometer) electrolyte cells (2). Thin-electrolyte cells of various sizes are routinely produced by this process. Recent performance tests of tape-calendered thin-electrolyte cells have shown peak power densities of more than 1 W/cm² with hydrogen fuel and 0.75 W/cm² with syngas at 800°C (Figure 3).

Two stack design configurations (crossflow and radial flow) have been evaluated for this application. The crossflow configuration has been described in previous publications (3,4). A schematic diagram of the radial configuration is shown in Figure 4. In this configuration, circular cells are connected in electrical series via metallic fins and interconnects (interconnect assemblies). An internal manifold with two sealed streams is located in the center of the stack to distribute fuel and oxidant gases to the cells. Fuel and oxidant flow radially from the center to the stack periphery. The key advantage of this configuration is its minimum seal requirement.

Figure 2. Sulfur Content of Syngas Product

Figure 3. Cell Performance at 800°C. Fuel is H₂ and Syngas; Oxidant is Air
To date, crossflow and radial flow stacks having various footprint areas and heights have been assembled and operated. Significant progress has been achieved in this area. For example, stack testing has consistently shown stable open-circuit voltages of about or more than 1 V per cell. High performance and high power densities (up to 0.6 W/cm² at 800°C with hydrogen) have been obtained and reproduced for multicell stacks. Preliminary thermal cycle tests have demonstrated stack thermal cyclability (Figure 5). Figure 5 shows that the open-circuit voltage, voltage under load, and temperature are the same before and after each cycle. This implies that the fuel cell goes through the thermal transients without significant performance and structure degradation.

Figure 4. Schematic Diagram of Radial Flow Stack Configuration

Figure 5. Thermal Cycle Test of Radial Flow Module
Recently, a 26-cell stack of crossflow configuration (10 cm by 10 cm footprint) was tested. The stack showed an open-circuit voltage of 26.7 V at 800°C and produced about 860 W at 18.2 V (0.7 V/cell) with a potential peak power of 1.2 kW (0.6 W/cm²) with hydrogen fuel (Figure 6). This is the first reduced-temperature kW-class stack reported in the literature.

PORTABLE SYSTEM DESIGN

While the SOFC module is the fundamental electrical power generating component, there are several other key components or subsystems required to support and control the operation of the fuel cell to meet the requirements of specified applications. AlliedSignal has performed extensive system design to integrate the SOFC into a complete system, including fuel and oxidant delivery, startup, fuel processing, thermal management, and various control and regulating devices. Modeling and analysis have been conducted to define all subsystems in terms of performance, weight, size, reliability, and costs. Several variations of system and subsystem configurations have been evaluated to determine the optimum combination of subsystems.

Figure 7 shows, as an example, the design of a portable 500-W power system operating on logistic fuels for military applications. The results of a preliminary analysis of this system are summarized in Table 1. The 500-W system, based on this analysis, will produce 28 V, and is estimated to weigh 7 kg in a volume of 17 by 11 by 9 inches (43 by 28 by 23 cm).
Table 1
Preliminary Performance Estimates of a Portable 500-W SOFC Power System

| SOFC Module          |                  |
|----------------------|------------------|
| Voltage              | 0.65 V/cell      |
| Fuel utilization     | 80%              |
| Stack weight         | 1.7 kg           |
| Thermal Management   |                  |
| Effectiveness        | 0.75             |
| Weight               | 1.8 kg           |
| Reactant Requirement |                  |
| Fuel flow            | 0.16 kg/h        |
| Air flow             | 18.2 kg/h        |

Figure 7. Portable 500-W SOFC Power System

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