JMEPEG (2006) 15:468-473
DOI: 10.1361/105994906X117323

A Radiation-Based Approach to Planar Solid Oxide Fuel Cell Modules

Kevin Krist and John Jewulski

(Submitted January 16, 2006; in revised form May 22, 2006)

This article describes the initial analysis underlying the design of a core module consisting of a 1 to 3 kW solid oxide fuel cell (SOFC) stack and a radiant air preheater (RAP) module. The design and testing of three SOFC stack/RAP modules was part of a California Energy Commission-sponsored project with the Gas Technology Institute. The objective of the design was to improve the thermal management of an SOFC system through radiant heat transfer from the stack walls to adjacent air preheater panels. The testing of this and subsequent modules has suggested that use of the radiation-based approach significantly improved the management of stack-generated heat.

Keywords radiant heat transfer, solid oxide fuel cells, thermal management

1. Introduction

The most fundamental way to improve heat management in solid oxide fuel cell (SOFC) systems is to minimize waste heat production through good electrochemical performance. However, at the operating point for most SOFC stacks, chemical, electrochemical, and transport losses produce significant amounts of heat. In larger systems that operate close to adiabatic conditions, the stack tends to overheat unless it is cooled with large amounts of excess air. This airflow leads to increased size and costs of key system components. In smaller systems (i.e., < 3 kW), rapid heat loss to the surroundings can make it difficult and expensive to insulate the system for thermally self-sustained operation.

Under the sponsorship of the California Energy Commission (CEC), and in coordination with the U.S. Department of Energy Solid State Energy Conversion Program, Fuel Cell Energy, the Gas Technology Institute (GTI), and its partners are improving both electrochemical performance and the transfer of stack-generated heat to develop an effective core module for 10 kW, planar, SOFC systems. The module combines radiantly heated gas flow panels with an improved anode-supported, planar SOFC stack technology that is under development at Materials and Systems Research Inc. (MSRI) and the University of Utah. Technologix Corporation and Nexant, Inc., are assisting in system design.

As a basis for the 10 kW system, the project consists of designing, constructing, and testing three, subscale, 1 to 3 kW breadboard units operating on blended gases to simulate hydrogen, natural gas, and reformate fuels. The first subscale module has been designed and fabricated. This article addresses the concepts underlying the design of this module as well as the initial test results.

2. Rationale for Radiant Heat Transfer

The inverse relationship between the heat generated by a fuel cell stack per unit of electricity produced and electric efficiency, as shown in the top curve of Fig. 1, illustrates that high electrical efficiency is an effective, but not perfect, way to minimize heat production (Ref 1). In the 30 to 55% electrical efficiency range anticipated for SOFCs, significant amounts of waste heat must be managed. Figure 1 also suggests that transferring even some of this heat to useful internal heat sinks such as complete internal reforming (middle curve of Fig. 1), or a minimal cathode gas airflow that is needed to maintain a suitable oxygen partial pressure for the electrochemical reaction (lower curve in Fig. 1 and approximated as twice the stoichiometric requirement), still leaves considerable stack-generated heat to be managed.

The conventional use of cathode gas cooling to remove heat from a system that would otherwise overheat is shown in Fig. 2. Stack heat is removed by airflow inside the cathode compartment. Depleted air is then combusted in an afterburner, and

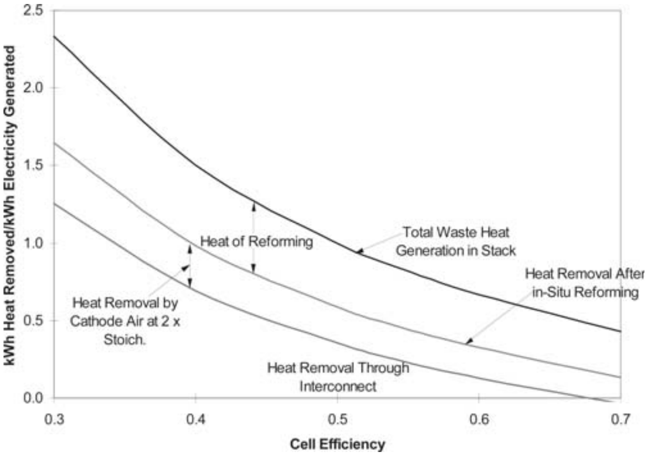

Fig. 1 Variation in the ratio of stack heat to electric energy production with electrical efficiency, assuming 100% fuel utilization

---

This paper was presented at the ASM Materials Solutions Conference & Show held October 18-21, 2004 in Columbus, OH.

Kevin Krist, Gas Technology Institute, 1700 S. Mount Prospect Road, Des Plaines, IL 60018-1804; and **John Jewulski,** Technologix Corporation, P.O. Box 3958, Naperville, IL 60567-3958. Contact e-mail: kevin.krist@gastechnology.org; hogix@spraynet.com.

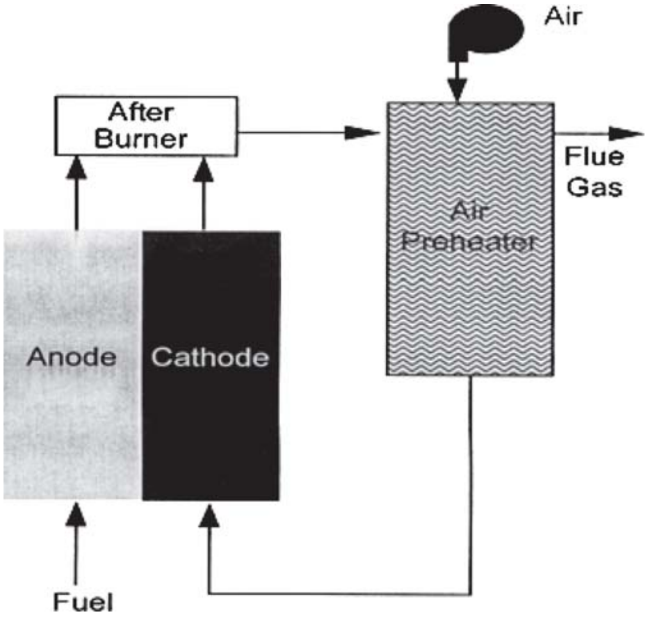

Fig. 2 Conventional heat transfer in relatively large or high power density SOFCs

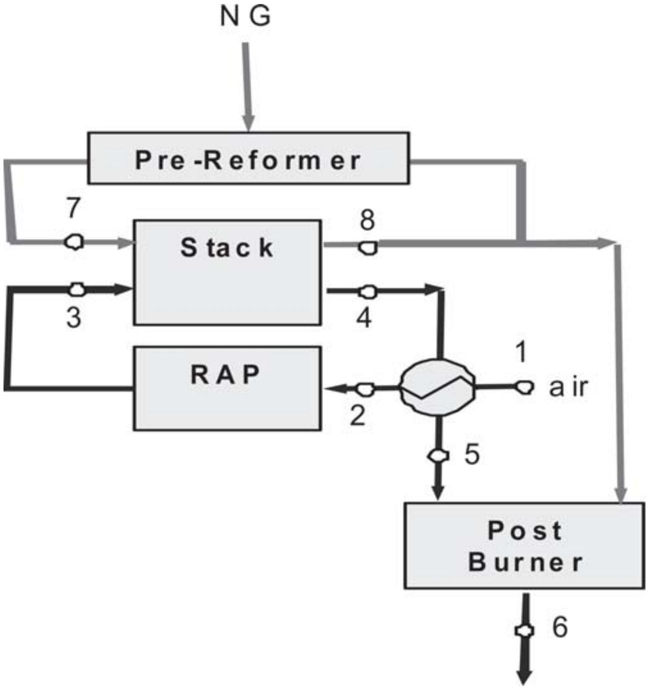

Fig. 3 Heat transfer to RAP panels

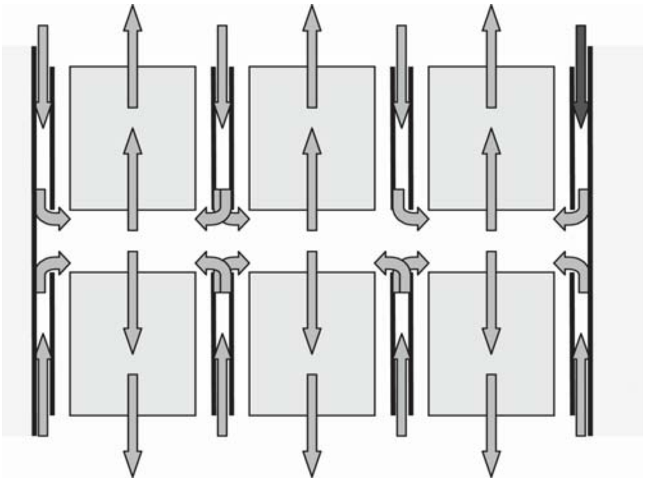

Fig. 4 Schematic array of stack/RAP modules

the resulting heat is transferred to preheat air in a gas-to-gas heat exchanger. A high airflow, anywhere from 4 to 12 times the stoichiometric requirement for the electrochemical reaction, depending on such factors as the system size, the degree of internal reforming, and the electrochemical performance, is typically required to maintain a small temperature gradient across the stack and mechanical integrity. The high airflow leads to high system pressure drops, large heat exchanger size and cost, large blower size and cost, and high parasitic power.

Figure 3 illustrates an alternative radiant heat transfer approach that has pursued under the CEC program. In this case, the stack is cooled outside of the cathode compartment by conduction to the external stack wall, radiation to adjacent radiant air preheater (RAP) panels (only one RAP is shown in Fig. 3 for simplicity), and convection to a reduced airflow through the RAP. (Figure 3 also shows a small heat exchanger remote to the hot module that may be needed, as well as a small and remote low-temperature postburner and a fuel prereformer with anode recycle. This article focuses on the stack/RAP module design.) The low airflow in this system has the potential to reduce system pressure drop, heat exchanger size and cost, blower size and cost, and parasitic power.

The stack/RAP module concept has other potential advantages. First, the RAP configuration will possibly improve cell performance. The RAP has been designed to selectively extract heat from the hottest parts of the stack to smooth out the in-plane distribution of temperatures in the stack and help to increase stack life. The reduced airflow associated with the increased reliance on radiant heat transfer can also decrease the pressure drop across the cells, and thus, improve the integrity of the stack seals.

Second, the stack/RAP approach may facilitate system compactness, modularization, and scale-up. Extending modularity to the air preheater in addition to the stack may facilitate scale-up to larger systems that use arrays of stack/RAP modules. A schematic example is shown in Fig. 4. These module arrays may have specific benefits such as preheater panels and manifolds that are common to more than one stack, and shared heat transfer among the modules. The RAPs also provide “active” insulation for small systems. Finally, their location close to the stack may improve overall system compactness.

3. Model for Module Design

Technologix Corporation has developed an engineering model for module design. The model supports adiabatic or nonadiabatic stack boundaries; internal reforming and air preheater panels; and coflow, counterflow, crossflow, and other flow configurations. Different stack designs are selectable as inputs.

The model has two-dimensional and three-dimensional versions; >100 independent parameters describing the module operation; and uses Butler-Volmer charge transfer equations,

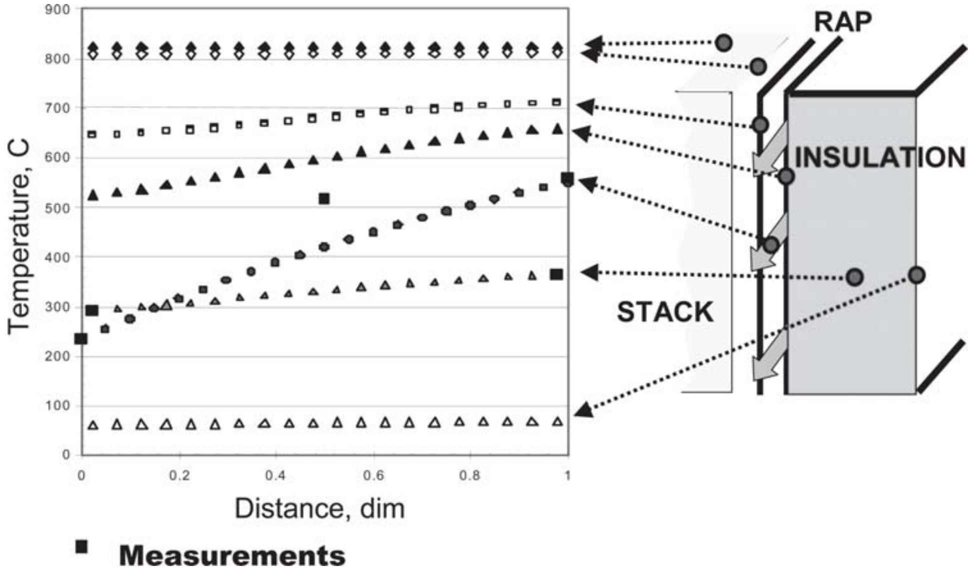

Fig. 5 Validation of the stack model, showing temperature predictions and measurements as a function of horizontal distance across the RAP

multicomponent diffusion, and kinetics based on published data. It is similar to a previous model that has been thoroughly validated for molten carbonate fuel cell (MCFC) operation.

Model inputs include stack quantities such as specified power output, stack geometry (e.g., cell area and the number of cells per inch), stack materials properties and design, current density and/or voltage, extent of internal reforming, initial steam-to-carbon ratio, average operating temperature, average fuel and oxidant utilization, and fuel inlet temperature. It also includes RAP heat-transfer quantities such as stack wall temperature, air inlet temperature to the RAP, stack/RAP wall emissivity, surface area of stack walls radiating to RAPs, RAP inlet molar flow rate, molar heat capacity of air, and RAP design.

The model outputs include: fuel and oxidant utilization range and spatial distributions (this gives the flow maldistribution as a function of stack size; pressure drop in the manifolds and cell channels); fuel and oxidant temperature range/spatial distributions; stack hardware temperature range/spatial distributions; heat transfer to internal reforming, water-gas shift, and sensible heat transfer to flowing gases and surroundings; equivalent methane content in the fuel; operating steam-to-carbon ratios; thermodynamic efficiency; available radiant heat transfer for air preheating; achievable air preheating by radiant heat transfer; and RAP hardware and gas temperature distributions.

The available stack heat for radiant air preheating, $Q_{radiant\_air\_preheat}$, is calculated as:

$$Q_{radiant\_air\_preheat} = Q_{stack\_net} - Q_{reactant\_cooling} - Q_{loss}$$

$$Q_{stack\_net} = Q_{stack} - Q_{internal\_reforming} - Q_{wgs}$$

where Q_{stack_net} is the heat generated in the stack less adjustments for internal reforming and water gas shift reactions in the fuel compartment; $Q_{reactant\_cooling}$ is primarily cathode gas cooling; and Q_{loss} is any heat lost through the insulation of the core hot module.

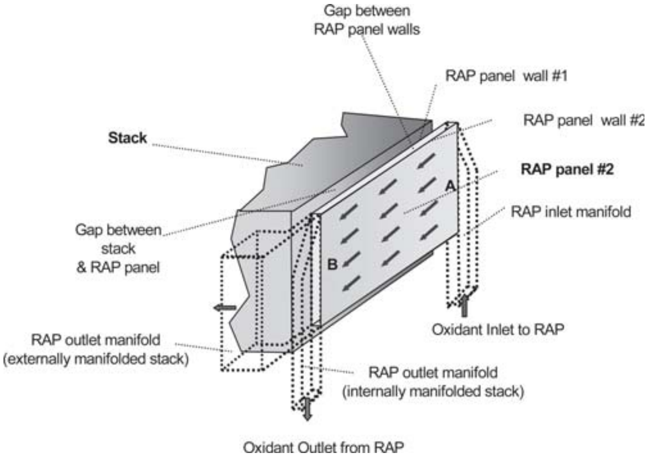

Fig. 6 Detailed RAP design

The model was validated in several ways. Figure 5 shows an experiment in which the model temperatures for a heated block and insulated RAP combination as a function of horizontal distance across the RAP were compared with thermocouple measurements at different locations. Model predictions agreed well with experimental results. A high level of air preheating (i.e., ~ 300 ℃) was achieved, while the hardware temperatures at other module locations remained relatively constant and at desired values.

4. Stack/Radiant Air Preheater Module Design

Figure 6 shows the detailed design of one of two RAPs in the initial module, located at the fuel outlet side of the stack (Ref 2). Horizontal airflow in the RAP is arranged so that the relatively cold RAP inlet air is opposite to the potentially hot air outlet/fuel outlet quadrant of the stack. Figure 6 indicates that the RAP design is amenable to either internally or externally manifolded stacks. The design of the first stack/RAP module is shown in Fig. 7. The stack is internally manifolded with crossflow. Stack-generated heat radiates to two air preheater panels. The panels are opposite the fuel inlet and outlet sides of the stack. The panel airflow is perpendicular to the stacking direction (horizontal in the orientation of the figure) and counter to the airflow in the cells. The compression bellows and inlet piping to the RAP were arranged for testing and would not be present in a product module. Air flows into each of the RAPs from the split-inlet pipe, across the RAPs, into the stack plenum, through the stack, and back into the stack plenum before exiting the air outlet port shown in Fig. 7.

Two basic questions underlying stack/RAP module design are whether the RAPs can achieve sufficient air preheating to avoid supplemental combustion heating of the module and whether the RAP design can minimize the in-plane temperature gradient in the stack.

The model results on the left side of Fig. 8 suggest that a proper combination of internal reforming, radiant air preheating, and cathode gas cooling enables the stack to maintain its 800 °C operating temperature solely with the temperature rise that is achieved in the RAPs. This module design point is reached at a RAP inlet temperature of 217 °C. Below this temperature, make-up combustion heating is needed to bring the RAP outlet temperature up to the cathode inlet temperature required to maintain the stack at 800 °C. The case assumes adiabatic operation.

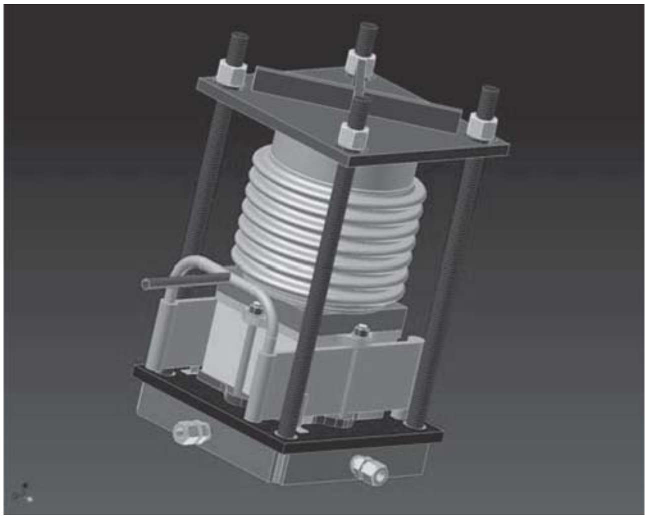

Fig. 7 Initial stack/RAP module

The right side of Fig. 8 indicates that for this crossflow configuration, the temperature gradient across the stack is a modest 65 °C, less than it would be without the addition of the RAPs.

The model predicts a close-to-linear variation of the oxidant temperature increase in the RAP, with both the RAP inlet temperature for a given stack operating temperature and the operating temperature of the stack at a given RAP inlet temperature. This simplifies the design of systems with different operating temperatures and RAP inlet temperatures.

A model component was developed for the effect of insulation in nonadiabatic situations. These effects were particularly important for the 1 to 3 kW CEC module tests. Figure 9 shows how heat loss from the module is related to the quantity and quality of stack insulation for two well-known insulation types. These studies suggest that not much can be gained in terms of reduced heat loss to the surroundings or in outside wall temperature by using more than four to five layers of 25 mm (1 in.) insulation.

Taking 100 mm (4 in.) of insulation, Fig. 10 shows the effect of heat loss per cell with the number of stacked cells (stack size). Because the fraction of effective surface area (surface area that radiates to the RAPs) increases with the number of cells, the heat loss to the surroundings per cell decreases with the number of cells. At about a 5-cell stack size for microtherm insulation, heat loss to the surroundings per cell approximates the stack heat generated per cell. This system could be considered to be thermally self-sustaining but would have no heat available for the air preheater panels. With a stack size of >40 cells, >80% of the net stack heat (after internal reforming and cathode gas cooling) is available to preheat air.

Figure 11 addresses the ability of the RAPs to achieve the temperature rise needed for higher RAP inlet-temperature design points such as those occurring in nonadiabatic situations or from other process considerations. The design point here is 300 °C instead of 217 °C, as shown in Fig. 8. The bottom line is the baseline RAP panel. The top line is an “enhanced” RAP with a suitable filler material. This RAP produces more than

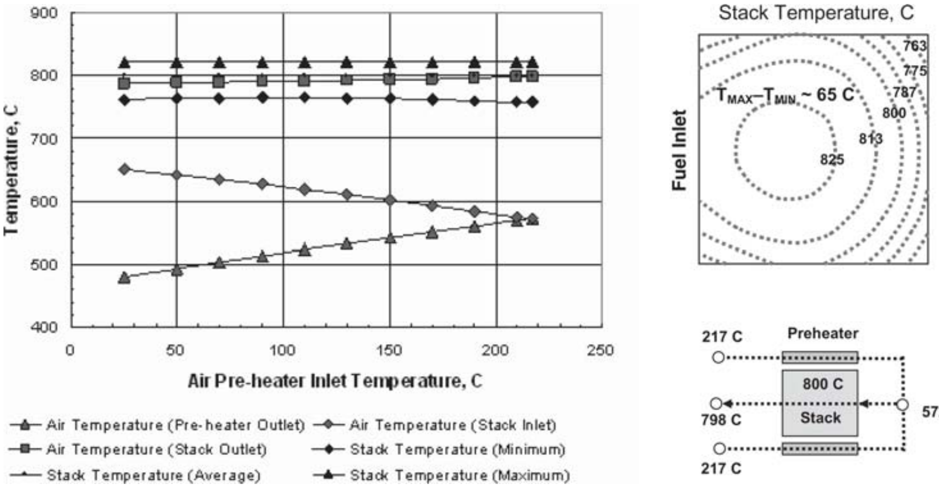

Fig. 8 Module operation for two RAPs integrated with a 4 × 4 in. active-area MSRI stack (as shown in Fig. 7), operating at 54% air utilization and having a heat transfer distribution at the design point of 40% internal reforming plus 37% radiant air preheating plus 23% cathode air cooling

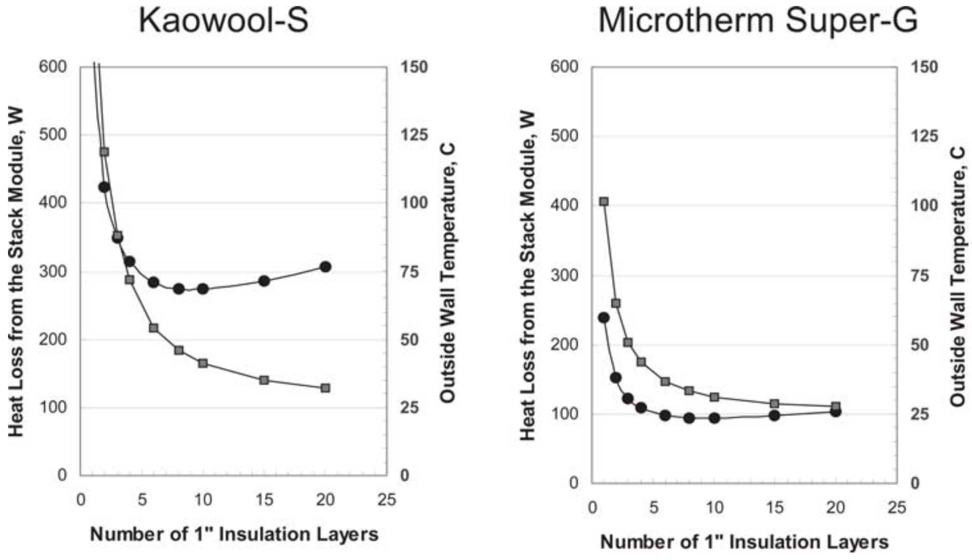

Fig. 9 Effect of insulation quality and quantity for a 1 kW net alternating current (AC), 44 cell MSRI stack module. Thermal conductivity was based on the manufacturer property sheet.

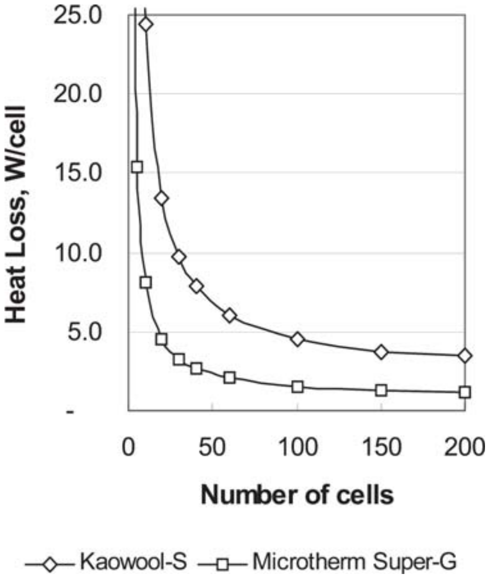

Fig. 10 Variation in heat loss per cell through 4 in. insulation with the number of stacked cells

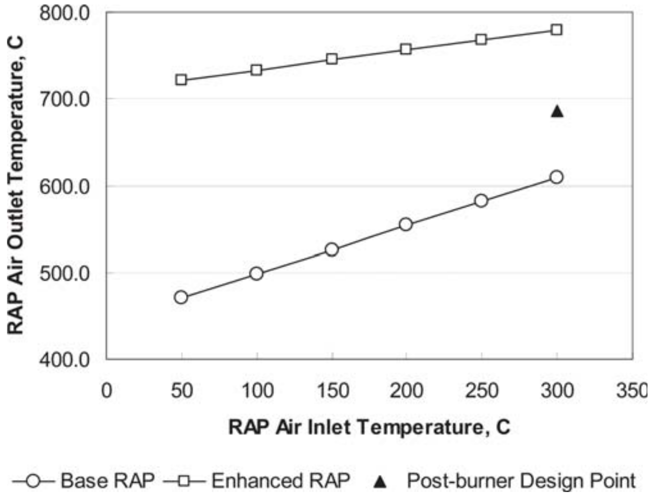

Fig. 11 Comparative performance of two RAPs in relation to the module design point RAP inlet temperature

the requisite temperature rise for the case involved, whereas a simpler RAP with no filler material does not.

5. Module Development

The anode-supported stack technology for the CEC project is under development at MSRI in Salt Lake City. The general goal of the work is to achieve a stack technology that operates with high power density at 650 to 750 °C. The technology involves flat cells whose active area is integrated with internal manifolds built into the cell borders as well as a highly simplified interconnect design. Further details of the technology will be omitted here as MSRI often presents their results in technical publications.

The extensive development of anodes (including thin and highly porous anode supports), cathodes, seals, interconnects, and stack testing is taking place. MSRI has tested multiple 5, 10, 20, 25, and 40 cell stacks on H_2, simulated reformate, and CH_4/steam at 650 to 800 °C. The results, thus far, suggest that power densities on the order of ~0.5 W/cm^2 on a multi-kilowatt level can be obtained with realistic operating conditions and fuels at 700 to 800 °C. Stack testing has included sensitivity to fuel and air utilization, O_2 content, clamping force, individual cell performance, temperature distribution, pressure drop, seal efficiency, and leak rate.

The GTI has designed and fabricated a module plenum, compression bellows, clamping fixture, and air preheater panel components, as shown in Fig. 12. The module was tested in a GTI facility that has extensive diagnostic capabilities, including the ability to blend gases to simulate different fuels; the gas chromatographic measurement of seal efficiency and blending accuracy; and the measurement of individual cell voltages and stack internal resistance. After completing a facility “shake-

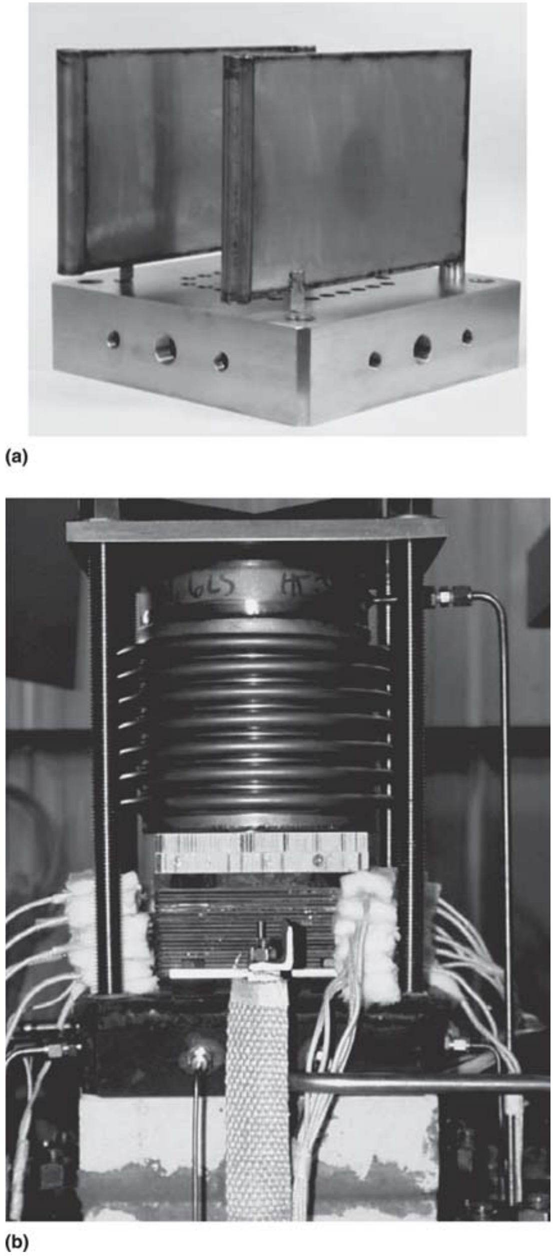

Fig. 12 Assembled RAPs and plenum (a) and test 1 kW stack with bellows and clamping fixture (b)

down" test on a 20 cell stack without RAPs, a full 1 kW module with RAPs was tested.

5.1 First Module Test Results

The first module consisted of a 40 cell, 100 cm^2 stack with two RAPs in the configuration discussed above. The test was considered to be preliminary and was intended only to demonstrate module operation. As discussed below, the GTI test facility is designed for tests of the performance of individual, uninsulated stacks at a constant, uniform temperature rather than the performance of a core module that transfers stack-generated heat to designated heat sinks (i.e., the RAPs).

Measurements were made on 50/50 H_2/N_2 at ~750 ℃ at constant gas flow and without insulation. The module produced ~550 W. Power densities of ~200 mW/cm^2 were measured. The basic RAP concept was demonstrated by obtaining a ~105 ℃ air temperature rise with only a ~120 ℃ temperature difference between the stack and the RAP. The module was operated for ~3 to 4 weeks and through approximately five thermal cycles.

The large-furnace test facility with heating coils in the furnace walls far removed from the core module did not thermally isolate the stack/RAP module from its surroundings, allow for the adequate control of the air inlet temperature to the RAPs, or avoid interference from the secondary heat source (the electric heating coils). The project has now designed, and started fabrication of, a second module test unit in Salt Lake City. This unit is insulated for thermally self-sustaining operation, so that it requires no additional heat input during steady-state operation. Heating coils are placed inside the insulation for rapid start-up. The assembly is small enough so that the air in the inlet manifolds is not heated significantly before it reaches the RAP inlets. Thermal losses are minimized at all stages, while maintaining the compact geometry.

6. Conclusions

Progress toward a core module for a 10 kW SOFC plant includes:

- A validated, engineering model for the design of stack/RAP power modules.
- Testing of a 1 kW stack/RAP power module that demonstrates the basic RAP concept.
- Numerous design, seal, interconnect, testing, and other cell/stack improvements resulting in a power density improvement of >50%.
- A promising concept for subsequent module designs.

Modules for the radiant transfer of SOFC stack-generated heat to adjacent process panels are a potential pathway for improving performance, cost, compactness, and scale-up

Acknowledgment

The authors wish to acknowledge the financial support of the CEC under contract No. 500-02-029.

References

1. K. Krist, K. Gleason, and J.D. Wright, The Effect of SOFC Stack Heat Rejection on Electrical Generation Costs, Palm Springs, CA: Fuel Cell Seminar Abstracts, 1998, p 519-522
2. J. Jewulski, K. Krist, C. Sishtla, J. Pondo, R. Petri, and D. Goodwin, Gas Flow Panels Integrated with Solid Oxide Fuel Cell Stacks, U.S. Patent application, 2004