IV.E.1 Hybrid Ceramic/Metallic Recuperator for SOFC Generator

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Objectives

- Enable the use of inexpensive metallic alloys in a solid oxide fuel (SOFC) exhaust recuperator through the use of a ceramic heat exchange section in the high temperature region.
- Design and develop methods to mechanically integrate the ceramic and metallic sections into a recuperator assembly.
- Evaluate and characterize the performance of a hybrid ceramic/metallic recuperator under typical SOFC operating conditions.
- Demonstrate the performance and durability of the hybrid recuperator through both long-term steady-state and thermal cycle testing.

Accomplishments

- Demonstrated that a ceramic monolith recuperator can be integrated into a multi-pass cross-flow assembly with additional metallic recuperator sections, while maintaining adequate gas sealing at the ceramic/metallic interface.
- Designed a hybrid recuperator assembly which successfully managed the differing thermal expansion properties of the ceramic and metallic sections.
- Validated the thermal model created for the ceramic core using empirical data collected during testing.
- Achieved sufficient heat exchange in the high temperature ceramic section reducing exhaust temperatures observed by the subsequent metallic sections to a level where lower grade alloys may be employed (target <750°C).
- Proved that a hybrid ceramic/metallic recuperator can achieve a heat exchange effectiveness of greater than 80% when operating at conditions typical of an SOFC generator.
- Subjected the hybrid recuperator to a multitude of thermal cycles with no observed change in performance or mechanical integrity.

Introduction

Acumentrics Corporation continues to focus on the development of efficient, reliable, and low-cost solid oxide fuel cell generators. A key component of the SOFC generator is the heat exchanger, or recuperator, which preheats the incoming cathode air using available heat in the exhaust stream. Typical exhaust temperatures of an SOFC generator are in the range of 800 to 1,000°C. While the use of full metallic recuperators requires expensive high-alloy metals for oxidation resistance, these operating temperatures are well within the capabilities of lower cost ceramic and refractory materials.

A proof-of-concept hybrid (ceramic/metallic) recuperator was designed, manufactured and tested. The hybrid design includes a ceramic monolith heat exchanger combined with additional metallic recuperator sections. This configuration takes advantage of the high temperature, low fouling capability of the ceramic section, while enabling the use of lower grade metallic alloys in the medium-to-low temperature regions. Results to date have shown that a ceramic monolith recuperator can be successfully integrated with additional metallic recuperator sections to achieve an overall heat exchange effectiveness required for use with an SOFC generator. These advances show significant promise that a recuperator capable of withstanding the severe operation conditions of an SOFC can be manufactured, while at the same time achieving significant cost reduction of the component.

Approach

Acumentrics worked closely with Blasch to design and manufacture a single pass cross-flow ceramic core, made of silicon carbide, as shown in Figure 1. A method of plenum attachment was devised and the ceramic core was combined with two standard metallic fin cores supplied by T.RAD to produce a three-pass cross-flow hybrid recuperator assembly. A model of the assembled recuperator depicting the multi-pass cross-flow arrangement is provided in Figure 2.

A test rig, shown in Figure 3, was constructed, instrumented and commissioned specifically for the

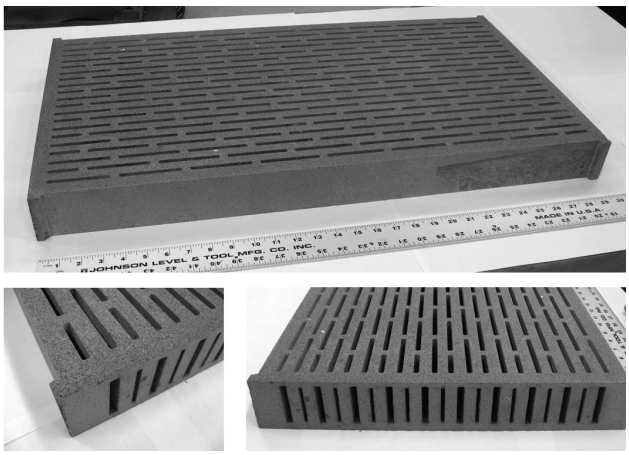

FIGURE 1. Single-Pass Cross-Flow Ceramic Recuperator Core

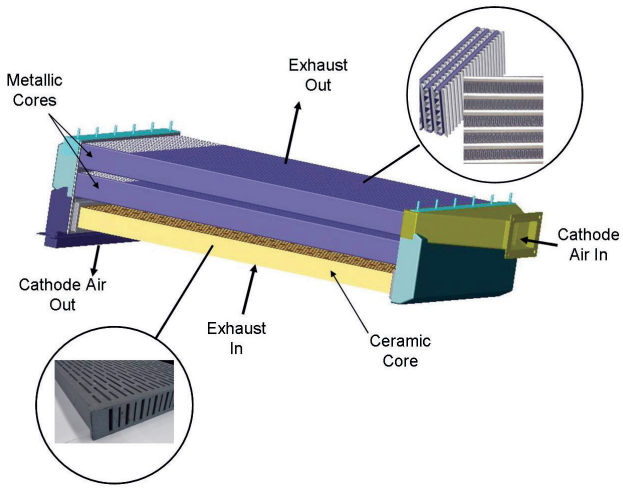

FIGURE 2. Hybrid Recuperator Assembly

FIGURE 3. Recuperator Test Rig

purposes of recuperator testing. The test rig was designed to enable the operator to simulate a variety of conditions typical of SOFC generator operation. Both the cathode air flow and exhaust flow could be regulated independently, and the inlet exhaust temperature was adjustable to enable simulation of operating points typical of start-up, steady-state and shutdown operation of an SOFC. Combined with measured flow rates, temperatures measured in the air and exhaust streams enabled a detailed analysis of recuperator effectiveness and performance characteristics of the hybrid assembly. Data collected during operation of a standard metallic 3-pass cross-flow recuperator, currently used on Acumentrics 5 kW SOFC generators, provided a baseline for comparison.

Results

Empirical data collected during the testing of the hybrid recuperator was analyzed and compared against the original spreadsheet-based thermal model created for the ceramic core. A strong correlation between the model data and that collected experimentally was observed. The graph in Figure 4 depicts the actual performance of the ceramic core against the curves generated by the model while operating at conditions typical of an Acumentrics 5 kW fuel cell generator.

The performance of the three-pass hybrid assembly (one ceramic core + two metallic cores) was evaluated at a variety of operating conditions. The recuperator consistently operated at an effectiveness of greater than 80%, reaching over 85% at some conditions. During testing at maximum exhaust inlet temperatures (approximately 850ºC) the ceramic core was capable of reducing the exhaust temperature observed by the subsequent metallic section to below 725ºC, allowing the

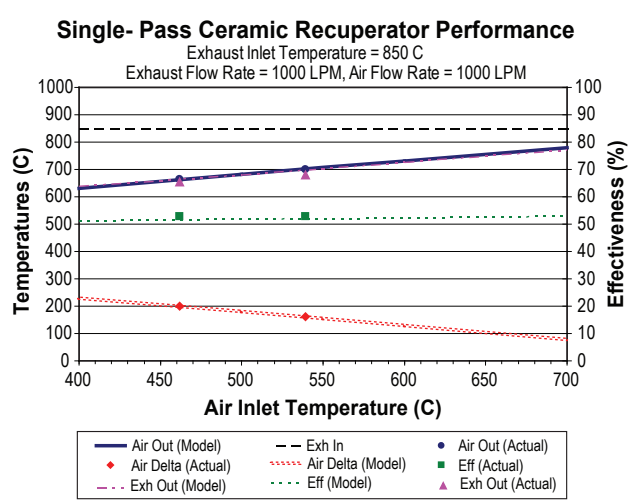

FIGURE 4. Ceramic Core Performance – Exhaust Temperature = 850ºC

use of lower grade alloys in the metallic sections. Air outlet temperatures of greater than 700ºC were achieved, thereby meeting the system requirements. The table provided below summarizes some proof-of-concept operational data collected during testing.

Air/Exhaust Flow	Exhaust Inlet Temp	Air Outlet Temp	Effectiveness
(kg/hr)	(°C)	(°C)	%
80.4	586	516	87.3
55.4	596	520	86.4
48	753	631	83.2
83.7	849	727	85.2
64.5	952	810	83.7
Air Inlet Temperature = 24°C			

Pressure drops measured on both the air and exhaust side were lower than those observed on the standard 3-pass metallic recuperator for the same temperature and flow conditions. This indicates that additional work may be conducted to enhance the heat exchange capabilities of the ceramic core by possibly reducing the dimensions of the flow passages to increase flow velocities, or by introducing ceramic inserts to promote turbulent flow and thereby increase the heat exchange in the ceramic core.

Following over 500 hours of operation at temperature and over 10 full thermal cycles, the ceramic core showed no signs of degradation after operating in the highly oxidizing environment. The core did not exhibit any cracking due to thermal stresses it may have been subjected to during operation in the hybrid configuration. Leakage tests were conducted following 500 hours of operation by statically pressurizing the air side of the recuperator and monitoring leakage flow rates through the material. There was no change in leakage flow rates when compared to the results of leakage testing which was performed in the as-manufactured state. Leakage rates at pressures typical of operation on an Acumentrics 5 kW SOFC were less than 2% of full cathode air flow rates.

Additional testing was conducted with an alternate hybrid configuration of one ceramic core and one metallic core. Although the ceramic core was able to drop the exhaust temperatures to levels below 750ºC, air outlet temperatures were slightly below 700ºC. The overall effectiveness of this arrangement was slightly below 80%. Future work to enhance the effectiveness of the ceramic recuperator may enable the 1+1 hybrid configuration to meet the required performance criteria for use on a 5 kW SOFC generator while significantly reducing the cost, parts count and weight of this component.

Conclusions and Future Directions

Acumentrics Corporation, in conjunction with Blasch Precision Ceramics, has successfully integrated a ceramic monolith into a multi-pass cross-flow recuperator and obtained greater than 80% effectiveness. The thermal model that was created for the ceramic core has been validated by empirical data, enabling the engineering team to use the model to accurately assess the effects of design changes to the ceramic core geometries prior to commitment of funds for new molds. Temperatures measured at intermediate stages in the recuperator during testing show that targets have been met for the use of lower grade alloys in the metallic sections. The initial steps to determine the feasibility of a hybrid ceramic/metallic recuperator have been successfully completed.

Future work will see the design, construction, and testing of pre-production hybrid recuperators. The following is a summary of future technical objectives:

- Evaluate ceramic component manufacturing techniques to optimize the ceramic core heat transfer rates.
- Design and manufacture custom molds for ceramic cores optimized to meet the performance and integration requirements of a hybrid recuperator suitable for volume production.
- Finalize a detailed hybrid recuperator design package incorporating all knowledge acquired regarding sealing and support techniques and integrated system performance.
- Manufacture several pre-commercial prototypes for testing and evaluation of construction techniques.
- Conduct both long term steady-state and thermal cycle testing to verify the performance and durability of the hybrid recuperator.
- Evaluate a combined cross-flow ceramic/counter-flow metallic hybrid configuration which may provide synergistic benefits in size, performance and cost for systems such as large scale coal-based power plants, or sub-1 kW portable generators.