V.K.2 Low-Cost Manufacturable Microchannel Systems for Passive PEM Water Management

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Subcontractor:
ADMA Products, Inc., Hudson, OH

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Objectives

- Create a low-cost, passive technology for water management in proton exchange membrane (PEM) systems.
- Establish technical feasibility and characterize performance in a single channel device.
- Scale-up device and demonstrate performance in a 10 kW PEM fuel cell system.
- Develop and validate a manufacturing process that can hit 7% of the $30/kW$_e$ cost target at the 80 kW$_e$-scale.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(B) Cost

(E) System Thermal and Water Management

Technical Targets

PNNL is developing a low-cost, compact water management technology that will contribute to reducing size and weight of integrated fuel cell power systems operating on direct hydrogen. Project success will help meet system targets for power density, specific power, and cost. Focusing on automotive-scale 80 kW$_e$ integrated fuel cell power systems, targets for the technology as a percentage of total system metrics are:

- Cost: less than 7% of system or $170 for an 80 kW$_e$-scale device.
- Specific power: less than 9% of system or 11 kg for an 80 kW$_e$-scale device.
- Energy density: less than 7% of system or 9 L for an 80 kW$_e$-scale device.

Accomplishments

- Characteristic performance data were acquired from a single-channel test device confirming power density and specific power targets for the technology are achievable.
- Designs were completed for 1 kW$_e$-, 10 kW$_e$-, and 80 kW$_e$-scale devices. The latter has a power density and specific power of 42 kW$_e$/L and 9.2 kW$_e$/kg, respectively, exceeding the targets of 8 kW$_e$/L and 6 kW$_e$/kg for the technology.
- Porous wick materials made using low-cost powder rolling were acquired from ADMA Products and subjected to an array of tests that showed favorable performance to the baseline material. The incorporation of this low-cost material will enable meeting $170 for an 80 kW$_e$ device, based on the current manufactured cost model.
- A novel method of forming the wicking components and stacking the structure has been developed that reduces the number of parts and simplifies assembly. A 1 kW$_e$-scale device has been fabricated using this new approach.

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Introduction

The low operating temperatures and the need to maintain humidity in PEM fuel cells make thermal and water management in these systems challenging. Rejecting waste heat at lower temperatures means smaller heat transfer driving force leading to large heat exchangers that are detrimental to meeting system size and weight targets. The need to humidify the fuel cell feed streams, particularly the cathode air, requires water recovery in order to avoid the burden of continuously supplying water to the system. The ongoing need to reduce the cost, size, and weight of fuel cell systems requires developing novel compact, lightweight solutions to these balance-of-plant components that can also be made inexpensively.

Approach

The device under development uses the cathode exhaust stream to simultaneously heat and humidify the cathode inlet in a single passive step as shown in the schematic in Figure 1. In the device, condensation and evaporation occur simultaneously, and wicks are used to convey water between the streams. Using wicks that hydraulically conduct water not only allows passive operation but also facilitates distribution of water within a channel and between channels as well as managing liquid water inventory in the device to prevent flooding and dry-out. Because the device works passively and with low pressure drop, parasitic power demand is minimized.

The technical approach is based on a unique, patented family of technologies for two-phase processing in microchannels [1-3]. The technology relies on capillary forces that allow passive operation in a highly efficient architecture. The microchannel architecture offers straightforward scale-up through increasing the number of parallel channels. Cost targets are achieved through a design-for-manufacturing strategy that incorporates low-cost materials and high-volume, automated manufacturing processes, such as progressive die stamping and automated assembly.

Results

The project was successful in demonstrating and advancing the technology from a single-channel device to multi-channel devices, including developing novel methods for fabricating and assembling multi-channel devices. Significant progress was made in material development by acquiring and qualifying low-cost porous wicks made using a low-cost powder-rolling process. Testing was performed on the wick materials, including durability testing using freeze/thaw cycling in humid conditions. Finally, a manufactured cost estimate was compiled to validate that cost targets are achievable.

A single-channel device was fabricated to demonstrate and characterize the concept, evaluate alternative porous materials, acquire data to support validation of a heat and mass transfer model, and support scale-up to multichannel devices at the 1 kW_e- and 10 kW_e-scale. With the device configured with 0.38 mm and 0.5 mm deep channels, experiments were performed with a dry ambient cold stream and a saturated hot stream at varying temperatures and flow rates using equal air flows in both streams and at conditions that compensated for O_2 consumption in the fuel cell. Heat and mass balance data were acquired and used to characterize heat and mass transfer performance and to validate a 1-dimensional empirical heat and mass transfer model that is based on the Colburn-Hougen method [4]. Figure 2 shows data from the 0.5 mm channels that reveal a weak dependence on hot stream inlet temperature. The device consistently produced a saturated cold stream indicating that performance is constrained by cold-side heat transfer, which is also consistent with model predictions. Meeting size and weight targets relies on processing rates equivalent to 9 SLPM in the single-channel device.

Testing was also performed to determine the difficulty of start-up. In one test, the system was simply shut off and the device left in a wet state. After two days, the device restarted with no difficulty. In a second test, the device was started from a dry state anticipated as a day-one start-up. There was significant crossover of air for approximately 30 minutes before normal steady-state operation was achieved, indicating start-up procedures will be straightforward and will not require additional controls.

Developing low-cost alternatives to the porous wick elements is critical to achieving manufactured cost targets. ADMA Products, Inc. provided multiple stainless steel sheet materials at varying thicknesses and densities made by a low-cost powder-rolling process. Comparisons of micrographs with the baseline Porous Products material indicate minimal differences

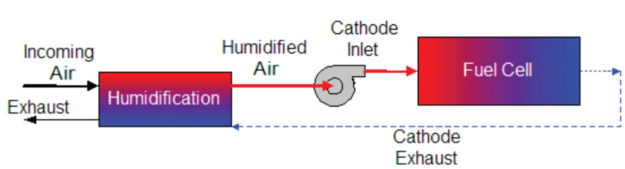

FIGURE 1. Process Schematic for Cathode air Humidification using Cathode Exhaust

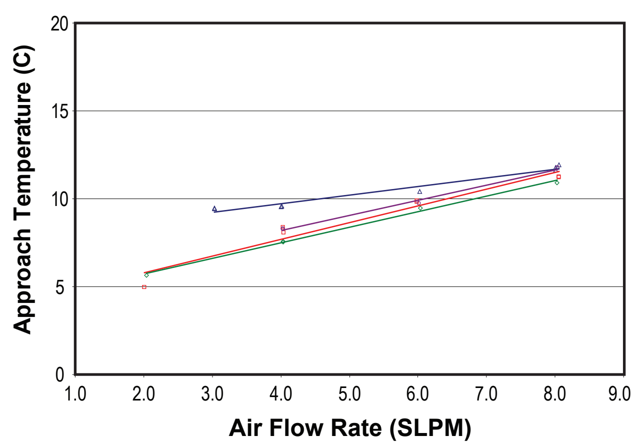

FIGURE 2. Performance of the single-channel humidifier with equal air flow rates in both streams as indicated by the temperature difference between the hot stream and cold stream at the hot end of the device as a function of flow rate for 60ºC (Δ), 70ºC (○), 80ºC (◊), and 90ºC (□) saturated hot stream inlet temperatures.

with the morphology. Measurements of bubble point and permeability indicated comparable or superior performance. In addition, materials were subjected to a MIL-STD-331C temperature humidity test involving 28-day cyclic exposure from -40°C to +95°C in 95% relative humidity. Standard ASTM E8 samples were tensile tested before and after exposure with no statistically significant difference in tensile fracture load. Successful development and qualification of these materials is a major step toward meeting a cost target of $170 for an 80 kW_e device.

A fabrication approach was developed for a multi-channel device that requires only two different parts along with endplates in a stacked-plate configuration. Internal channel dimensions are controlled by forming features into the porous wicks as illustrated in Figure 3a. The design is scalable by varying the number of layers and/or varying channel width. Prototypes are being fabricated using a low-temperature bonding process with epoxy sheets, but a lower-cost methodology for mass manufacturing is being developed using glass fiber mat spacers and vinyl ester epoxy resin intrusion for bonding and sealing and to reduce thermal expansion mismatch. The 1 kW_e device incorporating the prototype design and new fabrication approach is shown in Figure 3b.

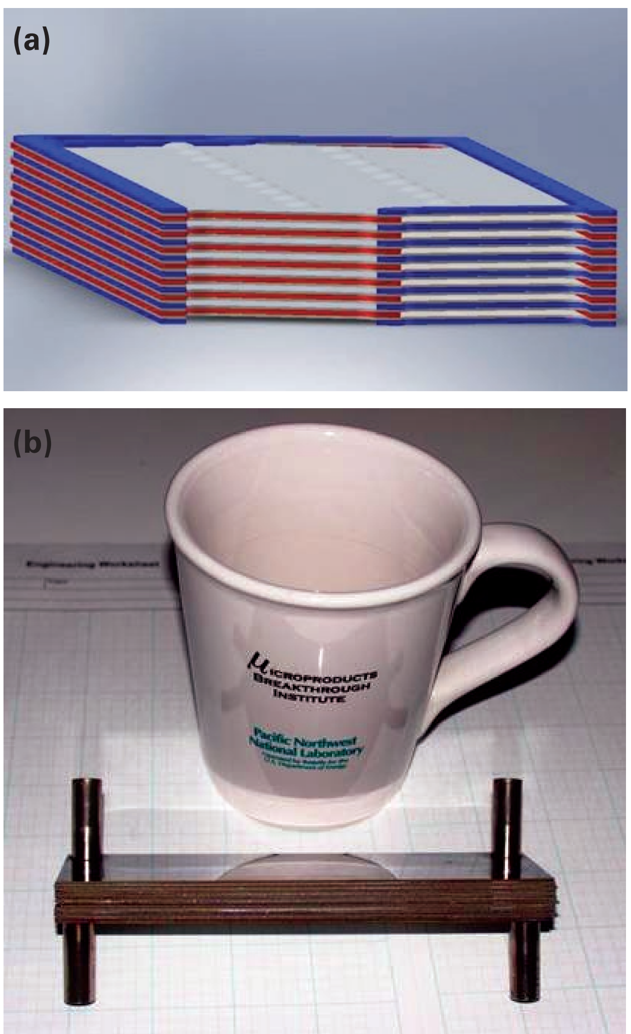

FIGURE 3. Design drawing of the 1 kW_e-scale device with (a) a cut-away through the headers showing the stack configuration and (b) the completed 1 kW_e device.

Designs have been produced for 1 kW_e-, 10 kW_e-, and 80 kW_e-scales, and projected sizes and weights are shown in Table 1. Targets for power density and specific power are exceeded with the exception of the specific power of the 1 kW_e device. A manufactured cost model has been developed for the production of 150,000 80 kW_e units a year that predicts a wick cost of $110 per device as the predominant cost. With on the order of 250 parts per device, cycle time in the assembly process will be critical, but the cost model indicates the $170 cost target is achievable.

TABLE 1. Size and Weight of Humidifier Designs Compared to Project Targets

Scale	Volume (L)	Weight (kg)	Power Density (kW_e/L)	Specific power (kW_e/kg)
Target			8	6
1 kW_e	0.045	0.24	22	4.2
10 kW_e	0.28	1.4	35	7.0
80 kW_e	1.9	8.7	42	9.2

Conclusions and Future Directions

The technical approach has been demonstrated at the single-channel level and a heat and mass transfer model established. Wick material development has been successful in reducing cost. Multi-channel designs have been completed that project that size and weight targets are achievable, and a simplified fabrication approach established for meeting the cost target.

Fabrication of 1 kW_e and 10 kW_e devices are in progress and will be completed and tested. The larger scale unit will be demonstrated in an operating fuel cell system. Attention will be focused on strategies for integrating the microchannel humidifier technology in fuel cell systems to address potential issues and facilitate design modifications.

Special Recognitions & Awards/Patents Issued

1. TeGrotenhuis, W.E., and V.S. Stenkamp, Conditions for fluid separations in microchannels, capillary-driven fluid separations, and laminated devices capable of separating fluids, U.S. Patent 7,344,576, March 2008.

2. TeGrotenhuis, W.E. and V.S. Stenkamp, Method for Fluid Separation, and Devices Capable of Separating Fluids, U.S. Patent 7,272,941, September 2007.

FY 2008 Publications/Presentations

1. TeGrotenhuis, W.E., D.D. Caldwell, C.A. Lavender, B.Q. Roberts, V.S. Stenkamp, and K.S. Weil, "Passive Microchannel Humidifier for PEM Fuel Cell Water Management", presented at the ACS National Meeting, Boston, MA, August, 2007.

2. TeGrotenhuis, WE., D.D. Caldwell, C.A. Lavender, and B.Q. Roberts, "Heat and Mass Transfer in a Passive Microchannel Humidifier", accepted for the 3rd ECI International Conference on Heat Transfer and Fluid Flow in Microscale, Whistler, Canada, September, 2008.

References

1. TeGrotenhuis, W.E., and V.S. Stenkamp, Improved Conditions for Fluid Separations in Microchannels, Capillary-Driven Fluid Separations, and Laminated Devices Capable of Separating Fluids, U.S. Patent 6,875,247, April 2005.

2. TeGrotenhuis, W.E., R.S. Wegeng, G.A. Whyatt, V.S. Stenkamp, P.A. Gauglitz, Microsystem Capillary Separations, U.S. Patent 6,666,909, December 2003.

3. TeGrotenhuis, W.E. and V.S. Stenkamp, "Gas-Liquid Processing in Microchannels." In Microreactor Technology and Process Intensification, eds. Y. Wang and J.D. Holladay, **ACS Symposium Series 914**, ACS, Washington, DC, 2005, pp. 360-377.

4. Colburn, A. P. and O. A. Hougen (1934). "Design of Cooler Condensers for Mixtures of Vapors with Noncondensing Gases." Ind. Eng. Chem. **26**: 1178-1182.