RESIDENTIAL EXPERIENCE WITH PROTON EXCHANGE MEMBRANE FUEL CELL SYSTEMS FOR COMBINED HEAT AND POWER

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ABSTRACT

As part of a one-year Department of Defense demonstration project, proton exchange membrane fuel cell systems have been installed at three residences to provide electrical power and waste heat for domestic hot water and space heating. The 5 kW-capacity fuel cells operate on reformed natural gas. These systems operate at preset levels providing power to the residence and to the utility grid. During grid outages, the residential power source is disconnected from the grid and the fuel cell system operates in standby mode to provide power to critical loads in the residence.

This paper describes lessons learned from installation and operation of these fuel cell systems in existing residences. Issues associated with installation of a fuel cell system for combined heat and power focus primarily on fuel cell siting, plumbing external to the fuel cell unit required to support heat recovery, and line connections between the fuel cell unit and the home interior for natural gas, water, electricity, and communications. Operational considerations of the fuel cell system are linked to heat recovery system design and conditions required for adequate flow of natural gas, air, water, and system communications. Based on actual experience with these systems in a residential setting, proper system design, component installation, and sustainment of required flows are essential for the fuel cell system to provide reliable power and waste heat.

INTRODUCTION

Fuel cell technology holds promise for more efficient conversion of fuel to electrical power and heat. The major challenge is to develop systems that perform as desired. Gunes and Ellis (2003) use mathematical models to.

The United States Department of Defense (DoD) supports research in proton exchange membrane (PEM) fuel cells as a potential alternative power source for military applications. Military installations located throughout the United States require power and heat for fixed facilities such as offices and residences. As such, recent funding has targeted PEM fuel cells for residential application. According to Holcomb, et al. (2004), the goals of this funding program are to assess fuel cells for providing power in support of sustainable design and to study their viability as an alternative power source to the DoD; to study the effect fuel cells have on the DoD's ability to construct, operate, and maintain facilities; to assess installation and operation issues associated with the use of PEM fuel cells; and to stimulate growth in the fuel cell industry.

As part of a one-year DoD demonstration project, identical PEM fuel cell systems have been installed at three residences located on a military installation in New York to provide electrical power and waste heat for domestic hot water and space heating. The 5 kW-capacity fuel cells operate on reformed natural gas. These systems operate at preset levels providing power to the residence and to the utility grid. During grid outages, the residential power source is disconnected from the grid and the fuel cell system provides power to critical loads in the residence. The fuel cell manufacturer is responsible for fuel cell system installation, all system operation and maintenance, and site restoration.

SYSTEM DESIGN

Figure 1 provides a simplified schematic of the fuel cell system. An autothermal reformer converts natural gas to hydrogen rich reformate. Deionized water provided from a storage tank is required for the reforming process. The fuel cell stack operating on air and reformate produces DC power. A cooling loop maintains the desired stack temperature by transferring energy from the stack either to the household water supply loop or to the environment via heat exchangers.

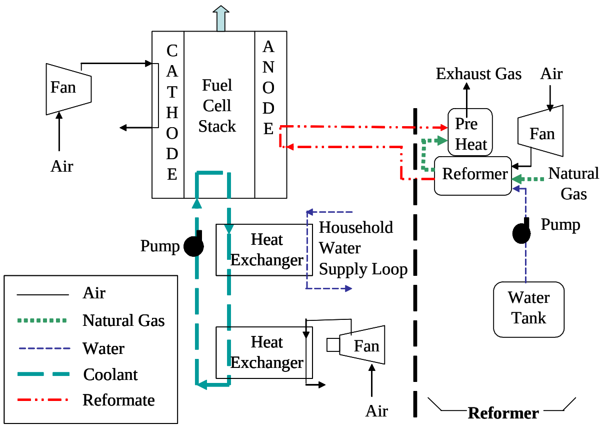

Fig. 1 Fuel cell system schematic

All three fuel cell systems are rated at 5 kW power output with user selected settings of 2.5, 4, and 5 kW. The fuel cell system's integrated battery allows the system to provide transient load following capability when the fuel cell system operates in standby mode. An inverter converts the DC supplied electricity to usable AC electricity for the residence. The fuel cells are configured to continually operate as standby power. With this configuration, power is continually supplied in parallel with grid-produced electricity. Any fuel cell system generated power that is in excess to residence demand is fed into the grid. During periods of grid outage, an automatic switch disconnects the fuel cell system from the grid and the fuel cell system provides power to the residence in response to the demand. When grid power is reestablished, the switch automatically synchronizes with the grid and then reconnects the fuel cell system.

There are design choices for the domestic hot water and space heat recovery systems. The original design called for an intermediate heat exchange loop to ensure that the domestic water line does not flow through the fuel cell unit. An example of this design is shown in Fig. 2. With this design, waste energy from the fuel cell is circulated into an intermediate heat exchanger tank. If the temperature in the intermediate heat exchanger tank is sufficient, energy can be moved to the hot water tank or space heat as required.

However, research concluded that local governmental regulation does not require separation between the domestic water and the fuel cell unit. Consequently, the design was amended to allow the domestic water line to flow from the hot water tank through the fuel cell unit and back to the hot water tank as shown in Fig. 3. This design precludes the requirement for an additional tank and costly heat exchangers and reduces the number of required pumps. The existing domestic hot water heater can be used if the drain valve is used to extract cold water from the hot water tank to send it back to the fuel cell unit.

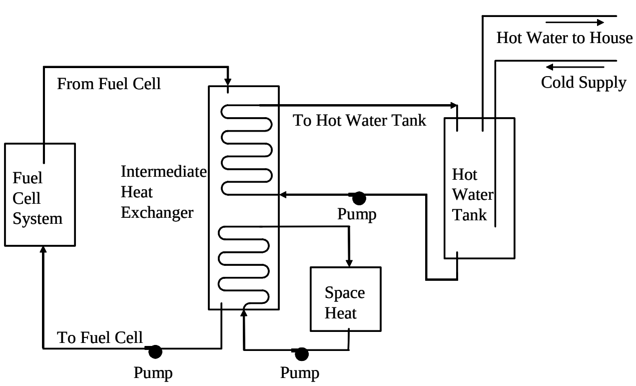

Fig. 2 Indirect heating system

The system designers considered three options for incorporating the space heat loop for the basement: 1) hot water flow from the fuel cell unit to the hot water heater and then to the space heater; 2) hot water flow from the fuel cell unit to the space heater and then to the hot water heater; and 3) hot water flow from the fuel cell unit to both the hot water heater and the space heater simultaneously in a parallel configuration similar to that shown in Fig. 2. The third option was rejected based on inherent complexities associated with controlling parallel flows. In the second option the temperature of the water is higher through the space heater than through the hot water tank while the reverse is true for the first option. The first option was selected since domestic hot water normally requires a higher temperature than space heating.

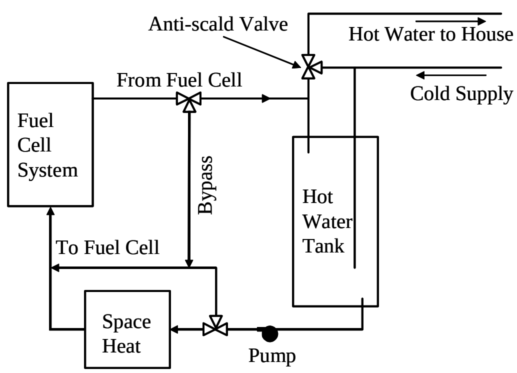

Fig. 3 Direct heating system

The selected design was further developed to provide three modes of water flow controlled by valves. Normal operating flow during periods when basement heating is not required is from the fuel cell unit through the hot water tank, and back to the fuel cell unit. During periods when basement heating is desired, the occupant can turn manual valves to allow water flow from the fuel cell unit, through the hot water heater, through the basement heat exchanger, and then back to the fuel cell unit. If the fuel cell completely shuts down, an automatic bypass valve allows the water to discontinue flow to the fuel cell. This bypass flow prevents unnecessary heat loss from the water line that would be associated with flow to a non-heat producing fuel cell unit.

The design also includes an expansion tank upstream of the hot water tank to accommodate any expansion due to high temperature of the water. A circulation pump ensures that the water flow in the line is continuous. When the resident turns on the faucet in the home, hot water is supplied from the water line coming directly from the fuel cell unit and the water tank. An anti-scald valve allows a flow of cold water from the cold water stream to mix with the domestic hot water to achieve temperatures of less than the nominal 60^{o}C provided by the fuel cell.

INSTALLATION ISSUES

The fuel cell units were delivered to the residences in December 2002. Site preparation required four months while fuel cell installation required only a few days. The site preparation period was longer than normal due to severe weather conditions during the winter of 2002-2003.

In order to site the fuel cell system, governmental regulation requires that the exhaust stack from the reformer be at least ten feet from the nearest window in the residence. The fuel cell unit was placed on a gravel pad to allow sufficient drainage and foundation support. The fuel cell unit requires access to various lines in the residence including natural gas, domestic water, communications lines, and electrical connections. Consideration for minimizing the distance to access these residential lines was a factor in choosing the fuel cell unit placement. Since the demonstration project is scheduled for a duration of only one year, all lines running from the fuel cell unit to the residence were left above ground and were encased in plywood rather than burying the lines. The encasement of the lines was for aesthetic purposes rather than operational necessity.

All three basements are unheated and unfinished with exposed piping in the ceiling. Space heaters (heat exchangers) were installed in all three basements and incorporated into the domestic water lines. Unfinished ceilings allowed easier installation of piping compared to the installation requirements in a finished basement. However, installation of the system as a retrofit to an existing home rather than installation as part of construction of a new home provided challenges associated with the constraints of existing structural components and lines. All new lines were run from the fuel cell unit located outside the residence through a basement window pane replaced by plywood to interior connections.

Since the fuel cell units installed are not sized to handle the entire household electrical load, the residents identified five critical circuits for the fuel cell to power during times the utility power grid is off. The limitation on the number of critical circuits was imposed to prevent the resident from exceeding the power generation capability of the fuel cell unit during periods of utility grid outages. In most cases, critical circuits included the refrigerator, boiler, freezer, and any lighting or receptacle load deemed critical to the user. The loads served were limited to 120 volt as the inverter is single-pole. Although not an issue with this demonstration, a step-up transformer could be added to serve 240 volt critical loads. A separate panel board was installed for these five circuits as well as a circuit to feed fuel cell instrumentation. The electrical feeders from the fuel cell unit inverter were run in conduit, through the basement window, to the main house panel and the critical load panel.

Massie, et al. (2003) discuss considerations for domestic water temperature to inhibit bacterial growth and the impact on system design to achieve desired temperatures. They identify a need for fuel cell awareness training for first responders recommending efforts to educate consumers and public safety officials on the underlying operating principles. They also suggest labeling all piping with the content and flow direction to assist orientation of the occupants and emergency personnel.

For the fuel cell unit manufacturer, this demonstration project is the first for combined heat and power. Sub-contractors from various disciplines took part in the system installation. Plumbers, electricians, natural gas workers, and fuel cell technicians all played important roles in the installation. While the quality of the work seemed adequate, the true test of installation quality occurred during operation.

OPERATIONAL ISSUES

All three fuel cell systems were commissioned on May 2, 2003. The residents discovered first-hand the importance of proper installation of the system and the criticality of the flows of water, air, and fuel for reliable fuel cell system operation. Interruption of any of these flows or sufficient degradation in the quality of these flows results in reduced performance by the fuel cell or shut down of the system altogether.

Overall System Availability

Table 1 provides performance statistics of the three units over an eight-month period. The overall availability was over 97%. This is particularly impressive given that scheduled outages are incorporated into this figure. For example, if a unit had to be shut down to upgrade software, that time was counted against the availability.

Electrical efficiency defined as (Energy Produced)/(Fuel Usage, LHV) was 24.4% while thermal efficiency defined as (Thermal Heat Recovery)/(Fuel Usage, LHV) was 5.3%. The sum of these two efficiencies provides an overall efficiency of 29.7%. Thermal efficiency was low for two reasons. First, data were collected in the summer when the demand for thermal energy was low. During this period cold water supply temperature was approximately 15.5^{o}C (60^{o}F) and there was no demand for space heat. Secondly, when thermal demand increased in the fall, the energy meters were removed for repair.

Table 1. System performance over an eight month period

Run Time (Hours)	17 062.32
Time in Period (Hours)	17 520
Availability (%)	97.39%
Fuel Cell Rated kW (kW)	5
Output Setting (kW)	2.50
Average Output (kW)	2.49
Total kW Hours (kW-hrs)	42 485.18
Energy Produced (kWe-hrs AC)	42 562.02
Capacity Factor (%)*	48.59
Fuel Usage, LHV (kJ)	6.28E+08
Fuel Usage (m^3)	16 667.0
Electrical Efficiency (%)	24.41
Thermal Heat Recovery (kJ)	33 523 950
Heat Recovery Rate (W)	545.6
Thermal Efficiency (%)	5.34
Overall Efficiency (%)	29.74
Number of Scheduled Outages	4
Scheduled Outage Hours	12.5
Number of Unscheduled Outages	17
Unscheduled Outage Hours	445.2

*Capacity Factor = Total kW Hours ÷ [Time in Period (Hours) × Fuel Cell Rated kW (kW)] and is an indication of the fraction of loading compared to rated capacity.

Water Flow Issues

Immediately after commissioning of the fuel cell systems, all three residences experienced discolored water in the domestic water supply. The two residences with older hot water tanks had more severe discoloration than the third residence that has a hot water tank less than one year old. The flow of water from the hot water heater bottom drain valve to the fuel cell unit and back through the top inlet to the hot water heater stirred up sediment in the bottom of the tanks. Flushing of the hot water tanks over a six-week period corrected the discolored water condition. Since completion of flushing, continual water circulation has minimized new build-up of sediment.

Upon initial commissioning of the fuel cell system, one residence experienced shuddering in the water pipes whenever a toilet was flushed. Troubleshooting led to the discovery that a required check valve between the water supplied from the street and the residence had not been installed causing water flow back to the street source. The wide pressure variation in the system during water use led to water hammer in the pipes. Installation of the check valve corrected the problem.

The fuel cell requires deionized water during reforming of natural gas. The deionization filter assembly is mounted on a basement wall and converts household water into deionized water for the fuel cell system. The deionized water flows to the fuel cell unit on demand. The line carrying deionized water to the fuel cell system is enclosed in a conduit that includes a heated liquid line to prevent freezing of the deionized water during very low ambient temperatures.

Within the first month following commissioning of the fuel cell systems, one unit shut down unexpectedly. Investigation revealed that the deionization system filters were clogged. Once th

Another issue related to the quality of the domestic water arose with the energy meters installed to measure the heat recovery from the fuel cell system. After approximately two months of operation, the energy meters became nonfunctional. After removing the meters, inspection revealed a calcium-carbonate buildup that was preventing the meters from working. In order to correct the water quality issue, a water treatment system was installed to condition all domestic water in the home. Whole-house water treatment was required since an intermediate heat exchanger is not used between the domestic water line and the fuel cell system.

After installation of whole-house water treatment in one residence, the water pressure in the house dropped significantly. All water flow (shower, toilet, faucet, washing machine) was extremely slow. When any water was used, the water pressure in the line dropped to 90 kPa (gage) (13 psig), so low that one toilet continuously flushed. The water treatment company technician returned to the residence and corrected the extreme low pressure problem. Upon proper installation, the water treatment system did lower the water pressure and flow rates, however, not to an unacceptable level. A benefit of whole-house water treatment should be an extended life for the deionization system pre-filters and filters.

The 60^oC (140^oF) fuel cell system water supply temperature is warmer than that typically provided by conventional hot water heaters. The residents observed that even at a high temperature setting, the hot water heater did not have to operate as the energy rejected by the fuel cell unit was sufficient to maintain hot water for the residence. The occupants eventually turned off their hot water heaters. However, a disadvantage to turning off the hot water heaters was discovered when the fuel cell unit shut down and there was limited hot water supply. Even with the hot water heaters left at a high temperature setting, the first indicator to the resident that the fuel cell unit shuts down is the noticeably cooler hot water temperature.

In order to heat the water in the hot water tank shown in Fig. 3, water that has been heated by the fuel cell travels to the T-junction located below the anti-scald valve and then goes into the tank. This in turn pushes the colder water located in the bottom of the tank back to the fuel cell to be heated. If the water does not require additional heating, the fuel cell unit heat exchanger with the outdoor environment handles the heat rejection from the fuel cell.

When there is demand for household hot water, the flow from the fuel cell unit is designed to mix with water coming out of the hot water tank (flow direction changes) to supply the demand. It was anticipated that the hot water tank pressure would in theory be greater than the pressure of the water supply coming from the fuel cell unit. Consequently, water would be forced out of the tank to be mixed with hot water coming from the fuel cell unit. The anti-scald valve would then regulate a constant supply temperature.

Water temperatures at various locations were recorded while the occupant took a seven-minute shower. Figure 4 shows these water temperatures during the shower (first seven minutes) and after the shower (following 13 minutes). The cold water supply temperature was recorded at a constant 6^oC (43^oF). Recorded points were the water temperatures at the inlet and exit of the fuel cell, temperature of the domestic hot water supply to house, and temperature of hot water tank supply (located below the T-junction, below the anti-scald valve).

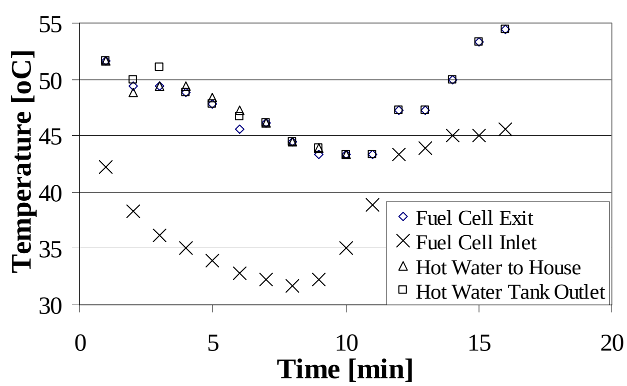

Fig. 4 Water temperatures during occupant use

Recorded temperatures indicate that the hot water supply comes predominantly from the fuel cell with virtually no flow coming from the thermal storage located in the hot water tank. Had the tank supplied water to the occupant, there would have been a variation between temperatures that feed into the T-junction. It is assumed the thermal mass of the storage would have remained relatively constant. We conclude that the pump located in the combined heat and power (CHP) loop increases the pressure such that the flow never reverses direction out of the hot water tank as anticipated. The pump was sized to ensure adequate flow (including the space heat loop) through the CHP loop. Pressures throughout the loops are unavailable.

Fuel Flow Issues

One fuel cell unit experienced repeated shutdowns during a four day period. Initial indications were that the quality of reformate was out of tolerance. Upon further investigation, the technician discovered that a flow meter that operated using a venturi was malfunctioning. Based on the air intake flow, the meter was drawing too much natural gas into the system creating a mixture that was too rich in fuel. Consequently, the reformer was not able to oxidize all of the natural gas which then flowed to the fuel cell stack. The system detected the poor quality reformate and signaled the unit to shut down. Upon replacement of the defective flow meter, the fuel cell unit operated flawlessly.

Air Flow Issues

In June 2003 an unscheduled shutdown of one fuel cell unit occurred during a planned utility grid power outage. The system shut down during the outage as a result of a plugged air inlet screen mainly due to seasonal pollen. After clearing the screen and restarting the unit, the fuel cell unit operated well. Regular preventive maintenance to clean all screens should alleviate this problem.

During blizzard-like conditions on December 6, 2003, the fuel cell systems at all three residences shut down. The shutdowns were due to insufficient air intake to the systems. Drifting of snow around the fuel cell unit became high enough to block the air intake port thus restricting air flow into the system. Upon clearing the snow from the air intake and restarting the systems, the fuel cell systems operated fine. The manufacturer has raised the air intake port on more recent fuel cell system models to avoid this type of problem.

Communications Issues

The fuel cell units were originally equipped with communications systems (hardware and software) that allowed the system to phone the manufacturer to report data. The communications system was incorporated into the residents' existing phone lines to avoid the installation of additional lines.

Subsequent updates to the software allowed the manufacturer to call into the system, retrieve data, and actively control the system. Upon installation of the new communications software, a switch programming error caused every incoming call to the residence to be treated as an incoming data communications request to the fuel cell unit. For all incoming calls, residents were greeted with a high piercing tone (similar to a fax line) and were unable to receive calls. The fuel cell manufacturer arranged for installation of a second phone line, which corrected the situation. The benefit of the software upgrade was the ability of the manufacturer to remotely control the system and thus increase system performance and availability.

Additionally, there were multiple failures of hardware communications such as modems. The causes of hardware failures were not determined, however, an electrical spike is believed to have damaged the modems.

These problems, while not detrimental to the demonstration, highlight the challenges should the units be aggregated for use as a Distributed Power Plant. Distributed Power Plants or "Virtual" plants are one way to overcome the unfavorable tariff structure hindering small producers/sellers of electricity. This tariff structure requires independent generators to buy electricity at a much greater rate than they can sell it, preventing small electrical producers from selling excess electricity at competitive rates. However, if the total on-demand capacity exceeds a threshold, then economically competitive rate structures are permitted for the independent generators. The minimum capacity typically falls in the megawatt (MW) range with a minimum generation capacity of 20 or 50 MW not uncommon. To qualify for a more competitive rate structure, small generators consolidate assets into a single account although generating hardware is distributed over a large area.

Key to the operation of a Distributed Power Plant is a communications system that can dispatch assets in an economical manner. Two-way communications to update the dispatcher about thermal and electrical loads, to report operating characteristics of the power plant, and to dispatch operational set points to the power plant are required.

Electricity Issues

The fuel cell system provides AC electricity to the residence via a 50 ampere circuit breaker to the critical load panel board. It also feeds the main house panel board through a contactor and breaker, allowing excess power to feed the grid. In case of loss of normal power, the fuel cell system disconnects itself from the main panel and feeds only those loads served by the critical load sub-panel. Once utility power is reestablished, the fuel cell synchronizes with the grid and reconnects itself to the main panel board.

One residence had repeated but intermittent problems with the fuel cell system upon loss of normal power. Upon sensing loss of normal power, the fuel cell unit would disconnect itself from the grid as expected and provide power to the critical load panel. However, when normal power was reestablished, the fuel cell would not synchronize with the utility and reconnect. After approximately one hour, the system would shut down causing complete loss of power to the critical load panel. To feed the critical load panel with utility power, the resident had to manually disconnect the fuel cell. This problem appears to be peculiar to this one unit and the cause has not been determined, however, fuel cell reliability should be considered when selecting critical circuits.

During the major blackout in the northeastern United States on August 14, 2003, the fuel cell systems disconnected from the power grid and provided power to the residences. The five critical circuits selected by each resident received power from the fuel cell. By monitoring the Customer Interface Panel as various devices were operated in the home, the residents observed the ability of the fuel cell system to follow the load. There appeared to be a noticeable lag in response to power demands. The power produced tended to overshoot the power demand and then overcompensate in correcting the excess power production. Even with the fluctuation in power production, devices such as overhead lighting, coffeemaker, refrigerator, television, DVD player, computer, etc., operated reliably on the power provided by the fuel cell. The microwave oven in one residence was the only device that did not operate reliably. This microwave oven operates with an older style step-down transformer that is more sensitive to variations in voltage. Another resident with a newer model microwave oven reported no problems with its operation. All three fuel cell systems provided continuous power during the 5.5 hour blackout experienced in the West Point, New York, area.

CONCLUSIONS

In the pursuit for more efficient conversion of fuel to electrical power and heat, fuel cell technology is being considered. Major challenges are to develop efficient fuel cells systems and to install these systems so that they are reliable and perform as desired. This demonstration project provides many lessons with regard to design, installation, and operation of fuel cell systems for combined heat and power applications. Appropriate integration of the residential heating system and power lines with the fuel cell unit is crucial. Suitable design and proper installation of all components in the system are critical for successful operation. Retrofit installation of fuel cell systems poses practical challenges for the system designers, manufacturers, and residents. Appropriate flows of air, water, and fuel are vital for reliable fuel cell operation. Preventive maintenance is essential to maintain quality flows.

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FIGURE AND TABLE CAPTIONS