Water management and stack design for solid polymer fuel cells

D.P. Wilkinson, H.H. Voss and K. Prater
Ballard Power Systems, Inc., 980 West 1st Street, Unit 107, North Vancouver, BC, V7P 3N4 (Canada)

Abstract

Water management has a major impact in the solid polymer fuel cell on overall system power, cost and efficiency. Single cell and stack performance may be adversely affected by the formation of liquid water, the dilution of reactant gases by water vapour, or by the dehydration of the solid polymer membrane. Peak fuel cell power is achieved typically at current densities at which performance is limited by mass transport. Improved water management at higher current densities not only increases peak power and efficiency but changes the profile of the power curve resulting in improved stability near the peak power operating point. Fuel cell water management can be accomplished by a number of approaches which include system design, stack operating conditions, stack hardware and membrane electrode assembly design. A number of these techniques have been successfully applied to both single cells and stacks. However, the options available for water management have to be assessed from an overall engineered system point of view.

Introduction

The development of a commercially viable fuel cell power generator is a system design exercise which is dependent on the application, available fuel supply and oxidant supply system components, and available fuel cell technology. All system components must be evaluated and design compromises made to achieve optimal system design. For example, the peak power point for the fuel cell stack may not be the desired operating point for maximum net system power. Improvements in solid polymer fuel cell technology can lead to significant changes in optimal system design. Water management is a very important component of stack and system design and can have a major impact on overall system power, cost, efficiency and control. This is particularly true for traction applications where peak power is normally achieved in a region where mass transport effects predominate. Higher cell power density reduces stack cost because fewer cells are required per unit power. Typically to achieve high efficiency (proportional to cell voltage) fuel cells must operate at lower current densities and hence lower power densities. A major goal for commercialization of solid polymer fuel cell technology is the ability to achieve high power density at high efficiency.

In recent years there has been an increased understanding of the role of water in electrolyte membranes and fuel cell structures [1–5]. This paper presents an overview of different methods of water management used at Ballard in fuel cell stacks, their impact on reducing or eliminating mass transport limiting effects and their system impact. Recent developments in water management have led to new and improved system designs.

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Impact of effective fuel cell water management

Water management has a direct impact upon system design because of its influence on the power curve of a fuel cell and the requirements it may place upon other system components. Generally, with stack water management there can be performance issues with respect to the formation of liquid water, the dilution of reactant gases by water vapour, or the dehydration of the solid polymer membrane.

Typically, the key performance issue is removal of product water from the cathode. This is a particular problem with air at higher current densities (>0.8 A/cm^2) at practical system operating conditions. The condensation of liquid water can result in mass transport limitations due to the restriction of oxygen transport through the porous gas diffusion electrode and flooding of active catalyst sites. Liquid water present within the electrode and/or gas flow channels can result in a nonuniform distribution of gases over the electrode active area and between cells in a stack. This can result in both reduced cell performance and voltage variation from cell to cell in a stack. Uniformity of cell performance is important for stack performance, control and safety. Figure 1 shows the cell-to-cell voltage variation at 0.86 A/cm^2 for 35-cell stacks with and without effective control of liquid water formation.

The reactant gases may become significantly diluted due to an increase in water vapour pressure especially at high temperatures and/or at low gas pressures. For any pressure, fuel cell performance falls off rapidly as the boiling point of water is approached at that pressure. Figure 2 shows the calculated effect on fuel cell performance of the increased dilution of reactant gas as the boiling point of water is approached for various pressures. For stack operation in the typical temperature range of 70 to

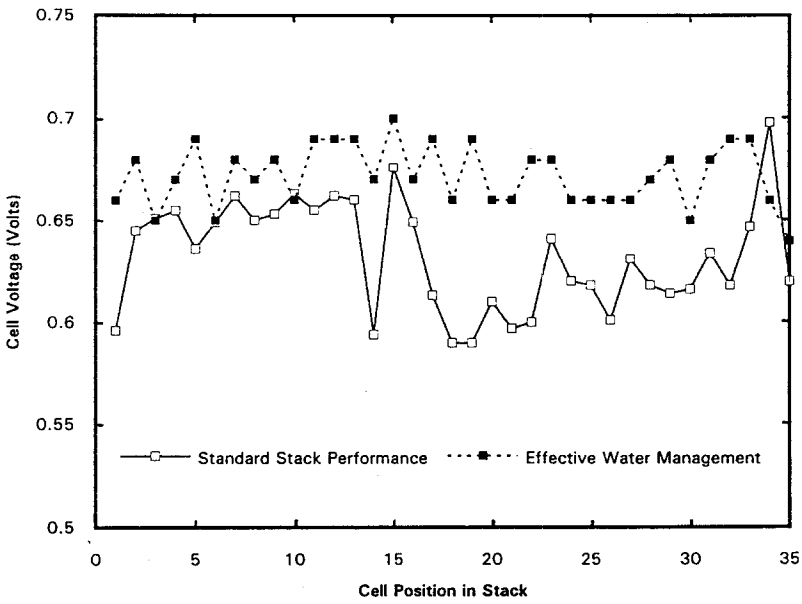

Fig. 1. Cell-to-cell voltage at 0.86 A/cm^2 for 35-cell stacks with and without effective water management (232 cm^2 active area, Dow XUS-13204.10 membrane, $P_{H_2}=3$ bar, $P_{air}=4.5$ bar, $T_{cell}=80$ °C).

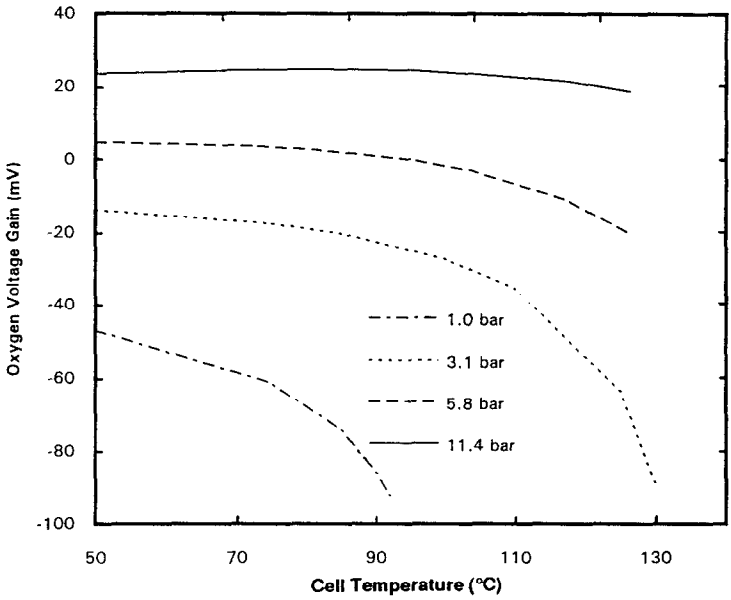

Fig. 2. Predicted oxidant dilution effect of water vapour at saturation with temperature for different air pressures.

90 °C reactant gas dilution can have a significant impact in the lower pressure range (<3 bar) typically considered for motive applications.

While lower relative humidities will increase reactant gas concentrations, lower humidities may dehydrate the polymer electrolyte membrane and result in an increase in membrane-ionic resistance. This can result in a large ohmic loss particularly at higher current densities.

An effective water management technique must be able to remove a substantial amount of liquid water without incurring substantial water vapour dilution effects and/or polymer electrolyte membrane dehydration. Typical measured fuel cell polarization plots with and without effective water management are shown in Fig. 3. The knee in the polarization curve is effectively removed resulting in improved stability and performance reproducibility. The impact of effective water management on cell power density and efficiency (proportional to voltage) is shown in Fig. 4. Clearly, the largest gains are made in the peak power range and the profile of the power curve exhibits improved stability near the peak power operating point.

Water management methods

For a particular stack design the operating conditions of pressure, temperature, gas flow rate, relative humidity and current density define conditions under which liquid condensation, reactant gas dilution or membrane dehydration occurs. Gas flow rate can be defined by stoichiometry which is the ratio of gas supply to that required to sustain cell current. For example, an air stoichiometry of 2.0 represents an air flow which delivers oxygen at twice the rate consumed by the electrochemical reaction. Each curve in Fig. 5 represents the condition of saturation at the fuel cell exit for

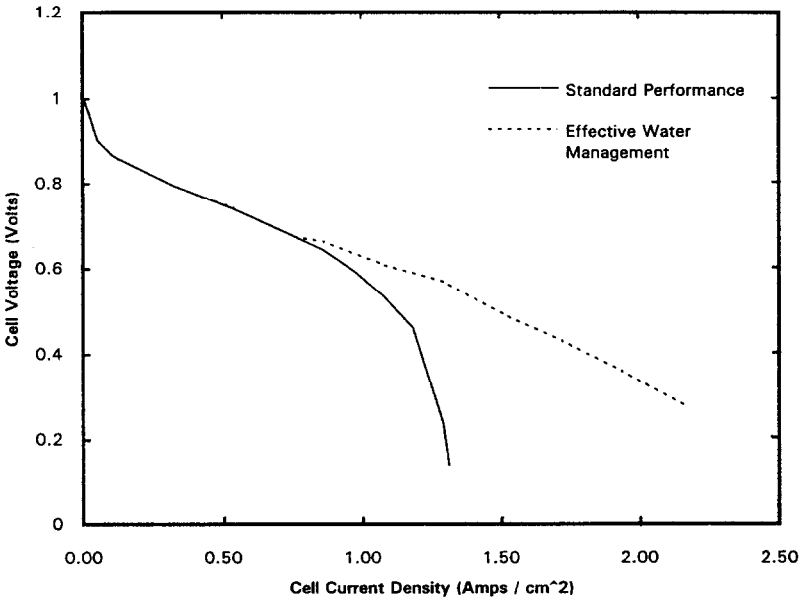

Fig. 3. Polarization curves for a single cell with and without effective water management (232 cm^2 active area, Dow XUS-13204.10 membrane, $P_{H_2} = P_{air} = 4.5$ bar, $T_{cell} = 70$ °C).

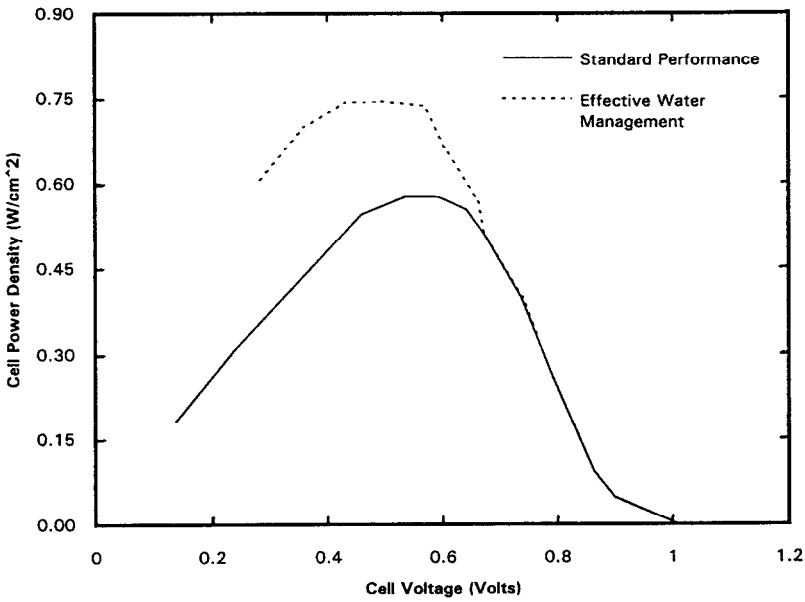

Fig. 4. Power density curves for a single cell with and without effective water management (232 cm^2 active area, Dow XUS-13204.10 membrane, $P_{H_2} = P_{air} = 4.5$ bar, $T_{cell} = 70$ °C).

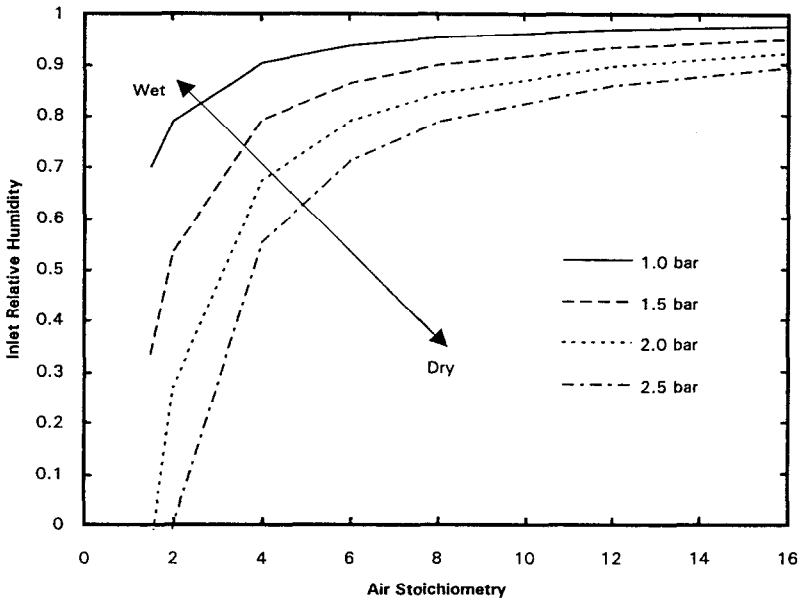

Fig. 5. Inlet conditions at 75 °C required to just obtain saturation at the fuel cell exit for different gas pressures.

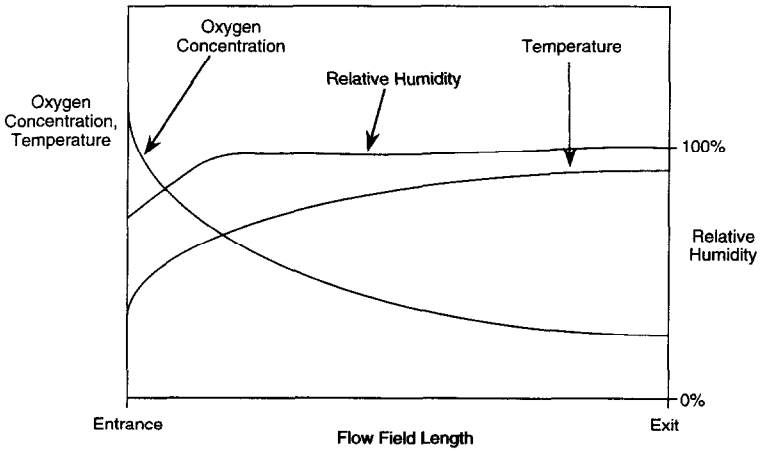

Fig. 6. Schematic of changing conditions along a gas flow field channel.

given inlet conditions. Conditions above the curve will result in condensation of liquid water and conditions below the curve will result in dehydration of the membrane. Generally, maximum performance with respect to water management should occur in this region where product and humidification water are just balanced with membrane drying [1].

In practical commercial fuel cells, effective operating conditions will change over the active area leading to overall optimal stack operating conditions that can be different from that predicted based on inlet and outlet conditions. As the reactant

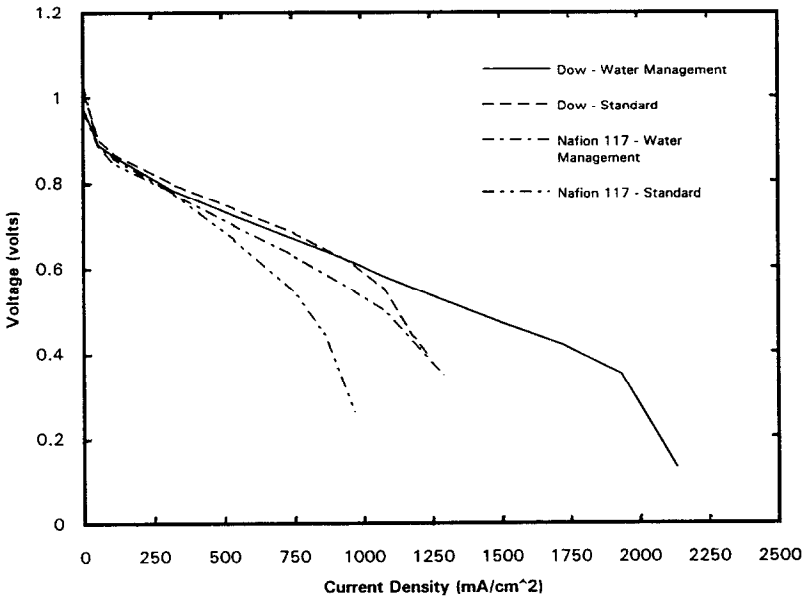

Fig. 7. Polarization curves for Nafion 117 and Dow membrane electrode assemblies with and without improved electrode design for water management (232 cm^2 active area, $P_{H_2}=P_{air}=3$ bar, $T_{cell}=75$ °C, 2.0 air stoichiometry, 1.5 H_2 stoichiometry).

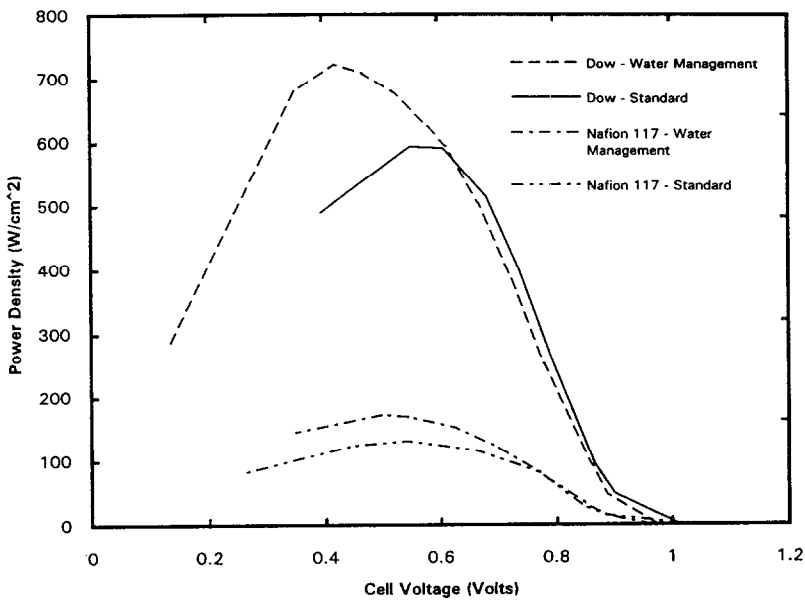

Fig. 8. Power density curves for Nafion 117 and Dow membrane electrode assemblies with and without improved electrode design for water management (232 cm^2 active area, $P_{H_2}=P_{air}=3$ bar, $T_{cell}=75$ °C, 2.0 air stoichiometry, 1.5 H_2 stoichiometry).

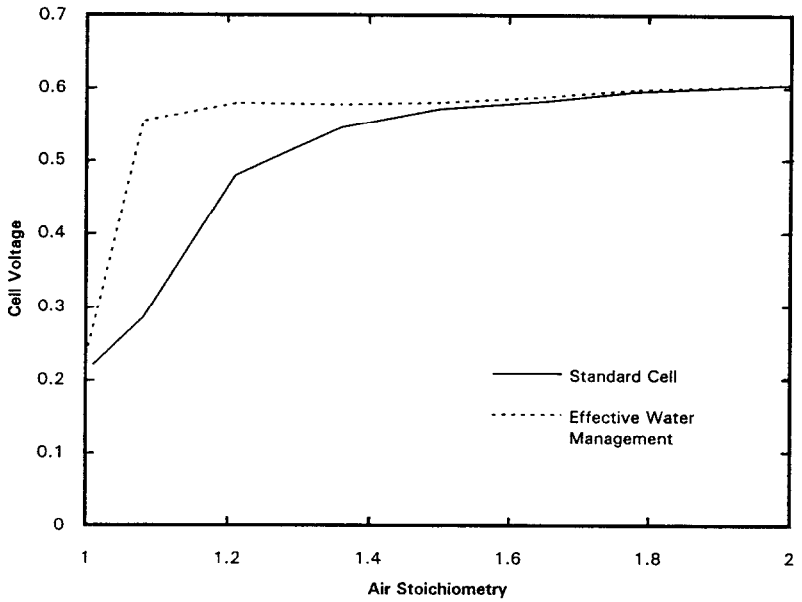

Fig. 9. Effect of anode water removal at low air stoichiometry on cell performance at 1.08 A/cm^2 (232 cm^2 active area, Dow XUS-13204.10 membrane, $P_{H_2} = P_{air} = 3$ bar, $T_{cell} = 80$ °C).

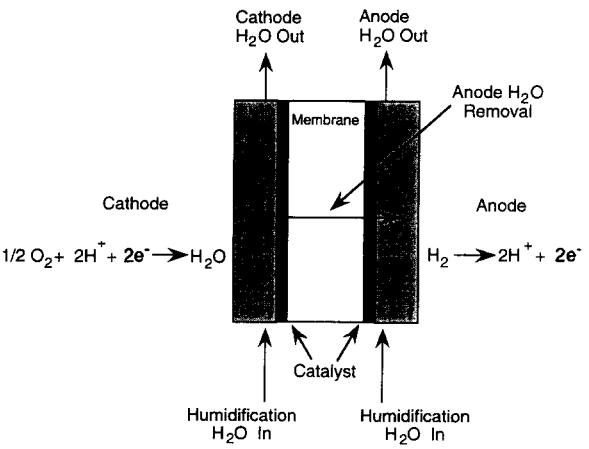

Fig. 10. Overall fuel cell water management scheme which includes anode water removal.

gases are consumed and product water is evaporated along the length of a gas flow channel, gas composition and relative humidity will change and waste heat generated will lead to a temperature profile across the cell. Figure 6 shows schematically how gas composition, relative humidity and temperature (adiabatic condition) might change along a gas flow field channel for a given set of inlet conditions.

Fuel cell flow field design can be used to optimize conditions along a flow channel and over the active cell area for effective water management but usually this has an associated system parasitic load. Typically, stack flow field design for effective water

management involves creating a pressure drop and/or relies on high velocity gas flow (increased stoichiometry) to evaporate liquid water and/or to assist liquid water to become entrained into the gas stream. The parasitic load or energy required for gas delivery is directly related to pressure, volume flow rate and pressure drop.

A preferred method for water management is membrane electrode assembly (MEA) design because it does not usually have an associated parasitic load. This involves improving the ability of the gas diffusion electrode and associated electrocatalyst layer to function in the presence of liquid water and to expel liquid water. Figure 7 shows typical measured fuel cell polarization plots for Nafion 117 and Dow MEAs compared with an improved MEA design incorporating a better gas diffusion electrode. Corresponding cell power density plots are shown in Fig. 8. For the same operating conditions and stack hardware, improved electrode design has resulted in effective water management with no associated additional parasitic load.

Recently, a novel method of water management has been developed at Ballard. By appropriate stack design, liquid water accumulated in the cathode can be drawn by a concentration gradient across the membrane to the anode and removed in the fuel stream. This method of water management, 'anode water removal', can significantly reduce parasitic loads associated with the oxidant side of the fuel cell and results in a totally new approach to fuel cell system design. Using this approach, Ballard had been able to run fuel cells on air at stoichiometries close to 1.0 with no significant loss in performance as shown in Fig. 9. New system approaches are possible such as the ability to run substantially pure oxygen in a dead-ended mode thus eliminating the need for an oxygen recirculation pump. The impact of anode water removal on cell performance clearly indicates the importance of effective water management in removing mass transport limitations. An overall water management scheme for the fuel cell must now include anode water removal in addition to control of inlet and outlet water as shown in Fig. 10.

System impact of different water management methods

Fuel cell water management typically has the largest effect on the air delivery system. Energy required to compress the incoming air is typically derived from a motor powered by the fuel cell stack and can be augmented by energy recovered from the outgoing oxidant stream. A simple schematic for a fuel cell stack with air compressor delivery, external humidification, and turbine power recovery from the oxidant exiting the stack is shown in Fig. 11. This does not take into account the system aspects of the fuel side such as fuel processing, fuel delivery and turbine power recovery from the fuel exiting the stack. These system aspects would generally not be that important for water management.

Figure 12 shows the effect of gas flow rate or stoichiometry on gross power, parasitic power (air compressor only) and net power for a 35-cell stack. Clearly, peak net power is at a different point than peak gross power and increased stoichiometry results in an increased parasitic power load. Table 1 presents the air delivery and recovery system impact on net power for different water management methods. Improvement of existing air compressor and turbine efficiencies (typically in the 0.8–0.9 range) would significantly improve net system power.

The different water management methods all result in similar cell performance to that shown in Figs. 3 and 4 but have very different effects on net system power.

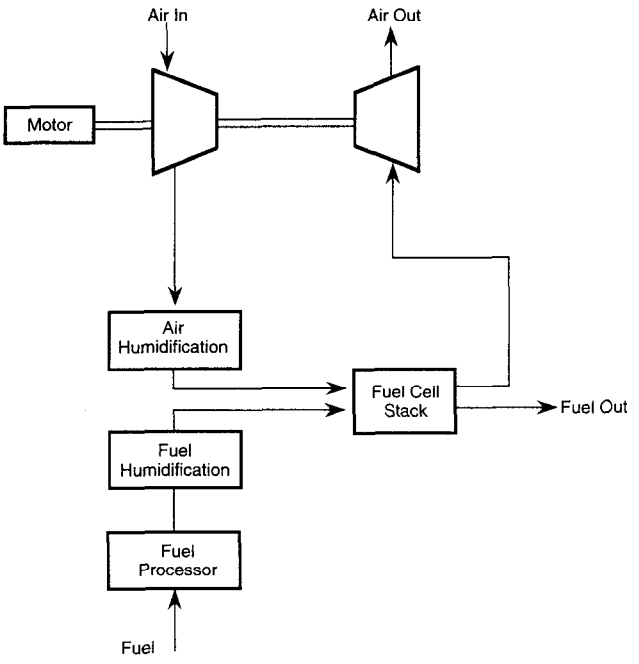

Fig. 11. Simple system schematic for the oxidant side of a fuel cell stack.

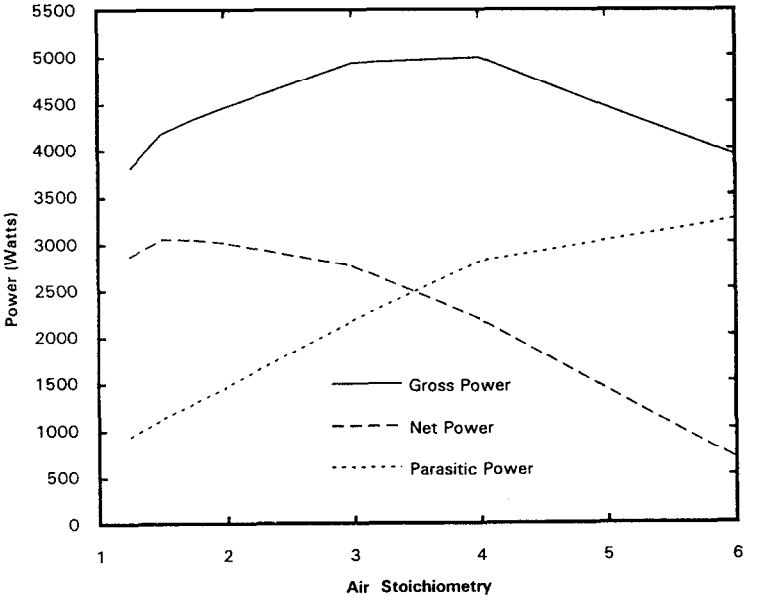

Fig. 12. Effects of air stoichiometry on gross power, parasitic power and net power for a 35-cell stack (232 cm^2 active area, 0.6 V/cell, Dow XUS-13204.10 membrane, $P_{H_2}=P_{air}=3$ bar, $T_{stack}=80$ °C).

TABLE 1

System impact of an air compressor and turbine recovery on cell net power for different water management methods (conditions unless otherwise stated: 0.6V/cell, 3.1/3.1 bar air/H_2, pressure drop <0.07 bar, 2/1.5 air/H_2 stoichiometry, Dow XUS-13204.10 membrane)

Water management type	Peak gross power at 0.6 V (W/cm^2)	Parasitic load (air compressor) (W/cm^2)	Recovery (turbine) (W/cm^2)	Net power at 0.6 V (W/cm^2)
Ineffective water management	0.540	0.098	0.059	0.501
Temperature/relative humidity	0.647	0.117	0.071	0.601
Temperature/relative humidity (no turbine recovery)	0.647	0.117	0.000	0.530
Cell design (air pressure drop = 0.7 bar)	0.647	0.117	0.034	0.564
Cell design (air stoichiometry = 3.5)	0.647	0.205	0.124	0.566
Membrane electrode assembly design	0.647	0.117	0.071	0.601
Anode water removal (air stoichiometry = 1.2)	0.637	0.070	0.042	0.609

It is clear that ineffective water management can lead to substantial system power losses. Turbine power recovery from the oxidant gas exiting the stack can significantly improve net system power but this option is not always available. In the typical case where cell/stack design results in a pressure drop between the inlet and outlet of the stack this will result in less recovered power and hence lower net system power. MEA design, control of stack temperature and inlet relative humidity are desirable techniques for water management as they generally do not have an associated parasitic load. However, there are material limitations for temperature, and saturation at higher temperatures can lead to reactant gas dilution. Water management techniques such as anode water removal which allow operation on lower air stoichiometries can result in substantial system power gains because of the effect of gas flow rate on parasitic power loss.

Summary

The commercialization of solid polymer fuel cell technology is an overall system design exercise in which water management plays a significant role. Effective water management with respect to the overall system has been shown to significantly improve power density, and efficiency at higher power densities, key objectives for commercialization of the technology. These water management techniques are being applied in Ballard's product development programs.

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