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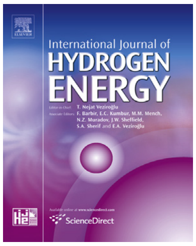

Development and modeling for process control purposes in PEMs[☆]

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ABSTRACT

To maintain suitable operating conditions, polymer electrolyte membrane (PEM) fuel cell stacks require additional equipment and control systems. Fuel supply, power and thermal management, purge strategy and individual cell voltage control must be in place and operate reliably for a fuel cell system to achieve similar levels of performance as conventional energy generators. System design, auxiliary equipment selection and selection of control strategies have effects on fuel cell efficiency, durability and reliability. In this study we report on our efforts to develop the piping and instrumentation diagram of a 3 kW PEM fuel cell, including the control instrumentation. A semi-empirical model was put together to understand dynamic system behavior for purpose of evaluating possible operating scenarios, in an effort to have useful insight into the system during the equipment selection stage. The model complexity was reduced by ignoring the spatial variations and assuming isothermal stack operation. The stack, cooling system, humidifier, compressor, inlet and outlet manifold were modeled and integrated to formulate a comprehensive prototype model. This model was subsequently used to generate predictions for the responses of the compressor, humidifier, humidification of the stack, power and heat generation for a multitude of dynamic changes in load. With the predictive capability enabled by the model, equipment and algorithm selections can be made in a more directed fashion, reducing the initial design and development costs by delivering a hardware configuration that is close to an ideal one with minimal iterations.

Introduction

PEM fuel cells are the electrochemical reactors that directly convert chemical energy of hydrogen into DC (direct current) electricity. A single PEM fuel cell consists of a proton conducting membrane that is sandwiched between a pair of catalyst and gas diffusion layers encapsulated by bipolar plates. In order to deliver useful power levels, single cells are connected in series to build a stack. This stack of multiple individual cells must be complemented by auxiliary equipment and control systems in order to fulfill the requirements for efficient and reliable power generation. The auxiliary equipment and process control algorithms can be divided into

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Nomenclature

A	area, m^2, cm^2
C_p	constant pressure heat capacity, J kg^{-1} K^{-1}
C_v	constant volume heat capacity, J kg^{-1} K^{-1}
$C_{v,i}$	membrane water concentration, mol cm^{-3}
D	Diameter, m
D_w	diffusion coefficient of water, cm^2 s^{-1}
f	friction factor
$\widehat{H_i}$	enthalpy, J kg^{-1}
i	stack current density, A cm^{-2}
J	inertia, kg m^2
m	mass, kg
$\dot{m}$	mass flow rate, kg s^{-1}
M	molecular weight, kg mol^{-1}
L	Length, m
n_d	electroosmotic drag coefficient, –
n_{cell}	number of cells, –
$N_{v,membrane}$	water flux, mol cm^{-2} s^{-1}
P	pressure, bar
P	power, W
Q	heat transfer, W
t	membrane thickness, cm
T	temperature, K, °C
u	overall heat transfer coefficient, W m^{-2} K^{-1}
U	internal energy, J
V	Mean velocity
V	voltage, V
V_i	volume, m^3
W	mass Flow rate, kg s^{-1}
w_{cp}	compressor speed, rad sec^{-1}
T_{lm}	log-mean temperature, –

Greek letters

η	efficiency, –
ρ	density, kg m^{-3}
τ	torque,N m

Subscripts

cm	compressor motor
cp	Compressor
i,anode	anode compartment
i,cathode	cathode compartment
v	Vapor
∞	ambient air

subsystems of fuel supply, water management, thermal management, power management, purge strategy and cell voltage tracking.

To assure uninterrupted power, the reactants should be delivered to the stack in sufficient amounts and proper molar ratios under all load conditions. Undersupply, low partial pressures and mis-matched molar ratios must be avoided by properly adjusting the hydrogen and oxygen supplies while minimizing parasitic losses to deliver these requirements. Hydrogen is generally delivered from a pressurized tank by adjusting the hydrogen flow with proportional regulation valves according to the pressure difference between cathode and anode. Fuel delivery systems can be designed to recirculate the excess hydrogen to avoid extra fuel usage [1]. Air is the preferred supply of oxygen in most configurations and is usually provided by compressors, blowers or similar equipment from the ambient, which can consume significant amounts of parasitic power and tend to react slower than the regulation valves used on the hydrogen side. The air line should contain filters and leak-proof lubrication systems to eliminate contamination risks [2]. Different control strategies for fuel cell air supply are reported in the literature [3,4].

Water management subsystem provides the required level of humidity for proton conduction in the porous media of the system. Too little water reduces conduction while too much water causes flooding. External humidifiers such as nozzle spray, static injector, gas bubbling, enthalpy wheel and membrane humidifiers are used to regulate the water content in the stack [4–7]. Membrane type humidifiers with different geometries exchange heat and water in the presence of temperature and vapor concentration gradients. Stack exhaust gas is often used for humidification in membrane type humidifiers [8,9].

Purging can be utilized as both a water management and an impurity elimination approach. Particularly for dead-end operation of the anode, a purge valve is opened at required intervals to remove the water and impurities that have accumulated at the anode. Unless effective purging is applied, both in frequency and duration, uneven distribution of hydrogen and fuel starvation is observed [10]. The frequency and duration of purges should be determined for an efficient purge while ensuring minimum fuel consumption [11].

Fuel cell system thermal management has a significant role on safe and efficient operation of fuel cells. Stack overheating can cause dehydration in the polymer membrane, resulting in performance losses. High temperatures can also cause membrane leaks formed by hot spots which can result in an unsafe position due to the mixing of hydrogen and oxygen [12]. Some of these modes of damage may be permanent, some are recoverable. Air cooled [3] and water cooled [13,14] systems with different designs can be used for thermal management of fuel cells – the selection usually depending on the capacity of the stack impacting the amount of heat to be removed.

The individual cell voltages in the stack should ideally be monitored for safety, control and long-term analysis. Cell voltage losses can be caused by internal problems appearing in the membrane electrode assembly, such as water droplets that prevents gas flow or pinholes and hotspots. Cell voltages quickly respond to the conditions such as impurity accumulations, water droplets in the gas pathways, unequal gas distribution, membrane drying or flooding and electrical connectivity problems, allowing them to be used for control, monitoring and troubleshooting purposes [15]. Cell voltage monitoring also allows for the tracking of fuel cell degradation over extended periods of operation [16]. While the current delivered from the system is increased, the reactant consumption and water production rates also increase. This manifests itself as a decrease in cell voltages, observed in typical polarization curves. In operation, the current density should be limited by keeping the individual cell voltages above 0.4 V to prevent reactant starvation and water flooding [17].