Abstract: Computer simulation is used to analyze the operation and efficiency of a carbonate fuel cell power plant under load perturbations. The plant model is based on a 2-MW system design used in the Santa Clara Demonstration Project and includes: internal reforming carbonate fuel cell stack, cathode gas preparation system, heat recovery unit, and fuel processing system. Model development for various processes is based on thermochemical principles and conservation of mass and energy. Overall plant efficiency is determined by net fuel consumption based on calculated gas compositions and auxiliary power consumption. During load maneuvering several key operational constraints must be maintained. Among these are: allowable stack temperature deviation, baseline fuel utilization, steam/carbon ratio, and pressure difference between anode and cathode. Actual plant control schemes are used in the simulation and are evaluated for performance under load changes. The results of these simulations will be used as a benchmark and development tool for advanced intelligent controllers for autonomous and efficient operation of fuel cell systems.

Keywords: fuel cell, balance-of-plant, efficiency, control, operation, load maneuvering.

I. INTRODUCTION

Fuel cell based power plants convert the chemical energy in a fuel directly to electricity without the requirement of conversion of energy into heat. This results in high efficiency (50-60% before heat recovery) even at part-load and in small ratings. Carbonate fuel cell technology is becoming increasingly attractive because it offers several advantages over conventional power plants, as well as today's market-entry (phosphoric acid) fuel cell systems:

- The projected cost of the technology is competitive. The technology exceeds all current and envisioned environmental regulations, producing water and carbon dioxide as the only emissions (the amount of carbon dioxide released per unit of electricity is considerably less than current power-generating technologies because of higher efficiencies).
- Fuel cell technology is modular and lends itself well to dispersed power generation. Fuel cells could be sited at electrical substations or at the point of end use, such as a hospital or a shopping mall.

The more efficient next generation molten carbonate fuel cell (MCFC) power plant is reaching commercial status. The evolution of MCFC power plant from research and development to a mature product has commenced with demonstration of MW-class power plant operation. Among fuel cell developers [1], Fuel Cell Energy (FCE) has designed, constructed and operated the 2-MW Santa Clara Demonstration Project (SCDP), the largest carbonate fuel cell power plant in the world [2]. With the successful conclusion of the Santa Clara project FCE completed an important milestone for introducing its commercial product line.

FuelCell Energy's carbonate fuel cell system features a unique Direct Fuel Cell™ (DFCTM) concept, which eliminates auxiliary equipment and simplifies the power system. The SCDP plant consisted of sixteen 125-kW stacks of 258 bel cells and 5570 cm² cell area and provisions for internal reforming of natural gas.

System configurations for MCFC power plants, both existing and proposed, vary considerably depending on how exhaust gases are recycled, how waste heat is recovered, whether reforming is direct or indirect, as well as other factors such as cogeneration. There are no "standard" configurations that represent a typical plant. Furthermore, the design may restrict the normal operation to base-load or operator-assisted setpoint changes. Autonomous operation is preferred however, since the MCFC power plant is expected to play a future role as a distributed generator in a deregulated industry. This motivates a computer study of operation and control system performance for MCFC power plants under electrical load perturbations.

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II. SCDP DYNAMIC MODEL

A dynamic simulation model has been based on the SCDP [3,4] and includes representation of all subsystems:

1. Direct reforming fuel cell stack
2. Heat recovery including boiler and fuel preheating
3. Cathode gas preparation including anode oxidizer
4. Fuel processing (preconverter, hydrodesulfurizer)
5. Power conversion unit (PCU)

Fig. 1 shows the basic plant process diagram specific to the SCDP including major control loops.

A. Direct Reforming Fuel Cell Stack

The cell stack in Fig. 1 is shown as a lumped representation of all sixteen stacks that are based on “Direct Fuel Cell™ technology”. This type of fuel cell utilizes internal reforming of natural gas resulting in the following chemical reactions on the anode side:

\[
\begin{align*}
H_2 + CO_3^- & \rightarrow H_2O + CO_2 + 2e^- & (1) \\
CH_4 + H_2O & \rightarrow CO + 3H_2 & \text{Reforming (2)} \\
CO + H_2O & \leftrightarrow CO_2 + H_2 & \text{Water-Gas Shift (3)}
\end{align*}
\]

and on the cathode side:

\[
\frac{1}{2}O_2 + CO_3^- + 2e^- \rightarrow CO_2^* & (4)
\]

Reactions (1) and (4) are electrochemical, exchanging carbonate ions (CO_3^-) with electrons (e^-) at the porous electrodes. These reactions require Hydrogen (derived from natural gas through steam reforming) and oxidant (O_2 and CO_2) to be introduced, respectively, at the anode and cathode compartments. Steam reforming is done internally within the cell by way of the reforming reaction (2) and the water gas shift (3). Electrons flow in the external circuit while carbonate ions flow through the molten salt electrolyte from cathode to anode. The dynamic model for the cell stack is based on the kinetics of reactions (1)-(4) involving the set of gases \{H_2, CH_4, CO, CO_2, H_2O, N_2, O_2\}.

The electrochemical reactions (1) and (4) have rates proportional to load current (Faraday's Law). The reforming reaction rate is dependent on stack temperature and anode gas composition. In practice, the water-gas shift (WGS) reaction equilibrates rapidly and is therefore assumed at equilibrium corresponding to stack temperature.

Two continuous lumped parameter reactor models are used to represent the anode and cathode compartments with interchange of mass (ions) through the electrolyte matrix separating the two sides. The heat produced in the fuel cell due to internal resistances is assumed to be exchanged with the stack lumped mass. This leads to two sets of dynamic component balances and a single dynamic energy balance, described by a set of nine 1st order differential equations (pressure states included). Ideal gases and mixtures are also assumed [4].
Open circuit voltage of the fuel cell is a function of temperature and gas composition, determined by the Nernst equation \[E = E^0 + \frac{RT}{F} \ln \left( \frac{P_{H_2}}{P_{H_2O}} \right)\]. Cell voltage under load is assumed to be affected only by ohmic losses.

B. Heat Recovery Unit

The fuel cell stack cathode exhaust gas is a mixture of CO\(_2\), H\(_2\)O, N\(_2\), and O\(_2\) at a temperature of about 1250°F. This exhaust gas then enters the HRU and first exchanges heat with the superheater tube-side gas, a mixture composed mainly of CH\(_4\), a, and H\(_2\), which then enters the stack anode. Following the fuel superheater in order of heat exchange are the steam superheater, steam boiler (not shown in Fig. 1), and fuel preheater, respectively. Associated with the fuel superheater is a three-way diverging valve or splitter used for controlling the temperature of the steam/methane fuel mixture entering the stack anode. Another valve is located between the fuel superheater and stack anode that is used for controlling anode inlet pressure. Each superheater is modeled assuming negligible mass storage but significant energy storage inside and outside of tubes, resulting in two state equations. A 5-state dynamic model describing the convection-type waste heat boiler is based on a set of mass and energy balance equations [6].

C. Cathode Gas Preparation

The cathode gas preparation system includes the anode exhaust oxidizer (catalytic burner) and variable speed-driven booster blower. At the stack cathode O\(_2\) is supplied by air and CO\(_2\) is made available by recycling the CO\(_2\) from the anode compartment. This is achieved by oxidizing the anode exhaust with air in a burner. The reactions taking place within the catalytic burner are:

- \(H_2 + \frac{1}{2}O_2 \rightarrow H_2O\)  \hspace{1cm} (5)
- \(CO + \frac{1}{2}O_2 \rightarrow CO_2\)  \hspace{1cm} (6)
- \(CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O\)  \hspace{1cm} (7)

Reaction (7) occurs during startup operation when supplementary CH\(_4\) is burned to maintain system temperature. Assumptions here are: the combustion chamber is a continuous stirred tank reactor (CSTR), gas mixtures are ideal, and chemical reactions are spontaneous and complete when minimum theoretical air is supplied. Similar to the stack, a set of component balances can be written, describing the resident gases within the burner: CO\(_2\), H\(_2\)O, N\(_2\), and O\(_2\). An energy balance also assumes energy storage within the large catalyst bed metal mass and takes the same form as the stack energy balance. Inclusion of a pressure state involves a total of 5 states to describe the burner. Excess air flow (above the theoretical minimum) into the burner is used for temperature control of gas into the stack cathode.

A booster blower is used to control differential pressure between anode and cathode. The blower model is described by a quadratic equation (using identified coefficients from performance data) relating static pressure at rated speed to actual cubic feet per minute at rated speed. Performance at off-rated speed is described using standard relationships. Temperature efficiency across the booster blower is determined empirically using plant performance data.

D. Fuel Processing

Referring to Fig. 1, the fuel processing subsystem consists of the hydrodesulfurizer and the fuel preconverter. The hydrodesulfurization reactor removes odorants and impurities from natural gas to the level required for fuel cell operation. This reactor has minimal effect on key operating conditions such as temperature and pressure because it is primarily used to remove trace amounts (parts per million, ppm) of sulfur compounds. The preconverter in the system removes higher hydrocarbons from the gas to preclude the formation of carbon in the stack during temperature transients. This is accomplished by steam reforming at lower temperature. The kinetics of reforming reaction in the preconverter is typically fast enough so that equilibrium for reforming reaction can be assumed. Since the size of the catalyst bed is small dynamic effects are minimal and steady-state operation is assumed. The model equations describing the preconverter are static assuming both the WGS reaction and the reforming reaction at equilibrium. A static energy balance is also applied.

III. SCDP OPERATION AND CONTROL

Referring to Fig. 1, cathode inlet temperature is controlled by manipulating the flow of excess air into the burner while stack differential pressure is controlled by varying the speed of the booster blower. Anode inlet temperature is controlled by positioning the fuel superheater splitter valve. A valve is placed just before the anode to regulate anode inlet pressure.

A load change on the stack is accompanied by a change in both natural gas flow and steam flow. The steam flow setpoint is maintained at exactly twice the natural gas flow for a steam to methane ratio (or steam to carbon ratio) of 2, a design constraint imposed by the manufacturer to preclude carbon formation with the stack. The calculation of the required natural gas flow corresponding to a power demand is based on the definition of utilization [5]:

\[U_f = \frac{H_{2,liq} - H_{2,our}}{H_{2,liq}}\]  \hspace{1cm} (8)

where \(H_{2,liq}\) and \(H_{2,our}\) are the molar flowrates at the inlet and outlet of the fuel cell, respectively. Since H\(_2\) is produced by the reforming and WGS reactions, an equivalent fuel flow is defined to account for the extra production:
\[ N_f = N_r \left( x_{H_2} + x_{CO} + 4x_{CH_4} \right) \]

where:
- \( N_f \): equivalent fuel molar flowrate
- \( N_r \): total molar flowrate
- \( x_i \): mole fraction of species \( i \)

Utilization is further related to stack dc current:

\[ I_{dc} = \frac{24319 N_f U_f}{n_{cell} n_s} \]

where:
- \( n_{cell} \): number of cells per stack (258 for SCDP)
- \( n_s \): number of stacks in plant (16 for SCDP)

In the SCDP, a baseline 75% fuel utilization is maintained over the upper power region and represents a compromise between efficient use of fuel and stack performance (voltage). Given a load current, (9) and (10) are used to calculate the required natural gas flow as shown in Fig. 2. Note that this is an open-loop control law.

![Fig. 2. Calculation of Plant Load Signal.](image)

IV. SIMULATION RESULTS

The differential/algebraic model equations for the SCDP were implemented using the MATLAB/SIMULINK software. Parameter values were obtained from FCE's 2-MW conceptual system design leading to the Santa Clara Demonstration Project.

The SCDP is rated at 1962-kW Gross DC (1809-kW Net AC) with a current density of 130 mA/cm² and a system voltage of 791 VDC. To examine the effect of load cycling on the efficiency and plant control, the load profile of Fig. 3 was chosen. This represents a 10%/min ramp down in power from rated load to 75% power followed by a 20%/min ramp up in power to full load.

A number of control objectives are to be met. Differential pressure should be as close as possible to its setpoint of 0.012 psia for minimal stress between plates. Stack temperature is not controlled but should be in the neighborhood of 1250°F. This is achieved by applying a cathode inlet temperature setpoint profile corresponding to load. The anode inlet temperature is maintained constant at 1125°F over the load range. Natural gas flow, and hence steam flow, is controlled to the value computed in (9) and (10) for 75% utilization. Other setpoints are constant: anode inlet pressure, fuel preheater temperature, drum level, and drum pressure. Responses to the load in Fig. 3 are shown in Figs. 4-8.

![Fig. 3. Load Power Profile.](image)

![Fig. 4. Stack Temperature.](image)

![Fig. 5. Anode and Cathode Pressures.](image)
MW-scale demonstration plant includes all plant processes as well as actual control elements. Using the simulation results, it is seen that operational constraints are satisfied during load cycling over the top 75% load range. Calculated plant efficiency is near the expected value of 50% over this range.

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VII. REFERENCES


VIII. BIOGRAPHIES

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