Humidity Control of a Polymer Electrolyte Membrane Fuel Cell (PEMFC)

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Outline

• Background and PEMFC Modeling

• Steady State Analysis
  – Desired Operating Window

• Temperature Control
  – Open-Loop/Closed-Loop Responses

• Power Control
  – Open-Loop/Closed-Loop Responses

• Humidity Control
  – Open-Loop/Closed-Loop Responses
PEMFC system

Focus of our model
PEMFC Model

Oxygen Balance:
\[ V_c \frac{dC_{O_2}}{dt} = F_a^{in} C_{O_2}^{in} - F_a C_{O_2} - \frac{1}{2} r_{H_2O}(j) \]

Water Balance:
\[ V_c \frac{dC_{H_2O}}{dt} = F_a^{in} C_{H_2O}^{in} - F_a C_{H_2O} + r_{H_2O}(j) \]

Gas Phase Energy Balance:
\[ V_c \frac{dT_{air}}{dt} = F_a^{in} T_{air}^{in} - F_a T_{air} + \frac{UA}{(\rho C_p)_{air}} (T_m - T_{air}) \]

Membrane Energy Balance:
\[ \frac{dT_m}{dt} = \frac{UA}{(mC_p)_{mem}} (T_{air} - T_m) + \frac{Q_{heat}(j)}{(mC_p)_{mem}} - Q_{cool} \]

where: \( j = \text{Current Density (mA/cm}^2) \)

\[ F_a = F_a^{in} + \frac{r_{H_2O}(j)}{C_T^{in}} \]
Rate of Water Production

\[ r_{H_2O}(j) = \frac{jA}{2F} \]

Where the current density is defined by the Nernst Equation:

\[ j = \frac{\sigma}{t_m} \left[ E_o - V_{cell} + \frac{RT^m}{2F} \log\left( \frac{C_{H_2}}{C_{H_2O}} \frac{1}{C_{O_2}^2 (RT_{air})^2} \right) \right] \]

Where:

- \( C_i \sim \text{Concentration of Species } i \)
- \( V_{cell} \sim \text{Operating Voltage (0.8 V)} \)
Heat Generation Rate

- Heat Generation = Reversible losses + Irreversible losses

\[ Q_{\text{heat}}(j) = (\Delta H_{353}^o - \Delta G_{353}^o) \frac{jA}{2F} + (jA)^2 R \]

Where:

Resistance is \[ R = \frac{1}{\sigma} \left[ \frac{t_m}{A} \right] \]

\[ \sigma \sim \text{Membrane Conductivity} \]

\[ t_m \sim \text{Membrane Thickness} \]
Ohmic Resistance

Electrical Conductivity, $\sigma$, Increases with Humidity

$$RH = x_w \frac{P}{P_{sat}(T)}$$

$x_w = 0.35$
Mass Transfer Resistance

\[ K(x^B_{O_2} - x^S_{O_2}) = \frac{1}{2} r_{H_2O}(j(C^S_{O_2})) \]

Flooding:

\( K \rightarrow 0 \) as \( RH \rightarrow 100\% \), due to a liquid film formation
PEMFC Operating Window

Membrane too dry (Large Ohmic Resistance) \[ 80\% \leq RH \leq 100\% \]

Membrane Flooded (Large Mass Transfer Resistance)

\[ 60^\circ C \leq T_{air} \leq 100^\circ C \]

\[ RH = x_w \frac{P}{P_{sat}(T)} \]
Steady State Analysis
(Current Density vs. Air Flow and Temperature)
Steady State Analysis
(Relative Humidity vs. Air Flow and Temperature)
Steady State Recap
(Current Density & RH vs Air Flow and Temperature)
Possible MV’s and CV’s

• Control Variables:
  – Relative Humidity, Temperature, Current / Power Output

• Manipulated Variables:
  – Cooling Rate, Air Flow Rate, Stack Voltage, Pressure
Open Loop Temperature Response

- With Absolutely no Control the System is **Unstable**.
- This observation is supported by the Multiple Steady-State Results of Benziger (2002) and Debenedetti (1983).
Temperature Control-Loop

\[ T_{\text{mem}}^{(sp)} \rightarrow \text{PI} \rightarrow Q_{\text{cool}} \rightarrow \text{PEMFC} \rightarrow T_{\text{mem}} \]
Temperature Control Set Point Changes
Temperature Control Set Point Changes
Air Flow Step Tests
Air Flow Step Test Results
Air Flow Step Tests (cont)
Power Control

\[ \text{Power}^{sp} \rightarrow \text{PI} \rightarrow \text{Air Flow} \rightarrow \text{PEMFC} \rightarrow \text{Power} \]

\[ T^{(sp)}_{mem} \rightarrow \text{PI} \rightarrow Q_{\text{cool}} \rightarrow \text{PEMFC} \rightarrow T_{mem} \]
Power Set Point Changes
Power Set Point Changes (cont)

Graph showing changes in RH, Tmem(C), and Tgas(C) over time with corresponding air flow in m³/s.
Ohmic Resistance

Electrical Conductivity, \( \sigma \), Increases with Humidity

\[ RH = x_w \frac{P}{P_{sat}(T)} \]

\[ \sigma \]

\[ \text{Relative Humidity (\%)} \]

\[ \text{Temperature (Celsius)} \]

\[ x_w = 0.35 \]
Integration of Humidity Control

\[ \text{RH}^{sp} \]

\[ T_{\text{mem}}^{sp} \]

\[ \frac{\text{Power}^{sp}}{\text{Air Flow}} \]

\[ Q_{\text{cool}} \]

\[ \text{PI} \]

\[ \text{PEMFC} \]

\[ T_{\text{mem}} \]

\[ \text{RH} \]

\[ \text{Power} \]
Closed Loop Response with Humidity Controller (cont)
Closed Loop Response with Humidity Controller

\[ \text{RH}^{\text{sp}} = 90\% \]

\[ \text{T}_{\text{mem}}(C) \]

\[ \text{T}_{\text{gas}}(C) \]
Summary

• Water Management Critical to Cell Operation
• Identified Possible MV’s and CV’s
• System Unstable Without Temperature Control
• Suggested a Multilevel Feedback Structure
• Relative Humidity Control Loop Can Improve Efficiency
Future Work

• Expand Model
  – Anode Chamber with Non-Pure Hydrogen
  – Longer Channel (similar to PFR)

• Investigate other MV’s
  – Operating Pressure and Voltage
  – Inlet Temperature and Relative Humidity

• Multiple Input & Multiple Output Controller
  – Model Based
  – Constraint Handling
  – Explicit Efficiency Calculations
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