CONDITION MONITORING OF A SOLID OXIDE FUEL CELL UNIT

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ABSTRACT

In December 1997, the first 100 kWe Solid Oxide Fuel Cell Field Unit started to operate in Westervoort (The Netherlands). Important issue of this field test is the performance of the Field Unit during the two years test period: does the Field Unit perform as well as its design specifications and is the performance increasing or decreasing during the test period? A practical problem herewith is that the performance of the Field Unit depends on the operating conditions and these are always (slightly) different from the nominal operating conditions, normally used as a reference. Therefore, KEMA developed a condition-monitoring model that calculates the performance of the Field Unit at nominal operating conditions from measured data at any operating condition. This paper will discuss the principles of the condition-monitoring model. It will focus on the monitoring of the condition of the SOFC module although any part of the Field Unit (heat exchangers, air blower) can be monitored in a similar way. The model for calculating the cell voltage will be discussed, as will be the method used for determining the value of the model parameters from available data. Finally the initial results of this condition-monitoring model, used together with measured data from the SOFC Field Unit, will be shown and discussed.

INTRODUCTION

In December 1997, the first 100 kWe Solid Oxide Fuel Cell Field Unit started to operate in Westervoort (The Netherlands). The Field Unit was built by Siemens Westinghouse for a consortium of Dutch and Danish utilities (EDB/ELSAM) and is now operated in a district heating boiler house of NUON (one of the participating Dutch utilities).

Important issue of this field test is the performance of the Field Unit during the two years test period: does the Field Unit perform as well as its design specifications and is the performance increasing or decreasing during the test period? One of the practical problems is that the performance of the Field Unit depends on the operating conditions. Therefore, the performance is most of the times measured at certain standard conditions. However, the Field Unit never operates at exactly the standard operating conditions, there are always (slight) deviations. KEMA developed a condition-monitoring model that cal-
ulates the performance of the Field Unit at standard operating conditions from measured data at any operating condition of the SOFC Field Unit (3,4,5). This is done on a two week basis, based on history data files but there are no impediments to do it on-line. The principal ideas behind the condition-monitoring model can be used for any type of fuel cell.

**PRINCIPLES OF THE CONDITION MONITORING MODEL**

In essence, the condition-monitoring model is a reversed flow sheet model. Normally, flow sheet models use mathematical models for each part of, for instance, a power plant. Each part of the plant (compressors, heat exchangers, gas turbines et cetera) is characterized by its equipment properties. The flow sheet model ties the individual parts together and, given the incoming flow data (fuel, air, electric power), calculates the performance of the power plant. The condition model does the reverse: given the measured performance of the Field Unit it calculates the equipment properties (Figure 1).

![Diagram of design model and condition monitoring model](image)

**Figure 1**: The functionality of a design model and a condition monitoring model.

After the equipment properties are calculated, these can be compared to the design properties at the measured operating conditions, thus showing any deviation. Another approach is to use a design model to calculate the performance at exactly nominal conditions (Figure 2). This performance can be compared to the design performance at nominal conditions. The first approach is used for monitoring the condition of the air blower and the heat exchangers, the second approach is used for monitoring the condition of the SOFC module.

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FIELD UNIT FLOW SHEET

As mentioned before, the condition monitoring model is a reversed flow sheet model. It uses a flow sheet to identify the individual processes in the SOFC Field Unit and the links between the processes. Figure 3 shows the flow sheet of the Field Unit. The blower, both recuperators (HT HEX and LT HEX) and the heat exchanger for the district-heating grid (HES) are modeled using standard models available in the flow sheet program (6). The SOFC module is modeled separately. Chemical reactor models are used to simulate the processes in the prereformer, the stack reformer and in the fuel cell stack and to establish thermal equilibrium after the electrochemical processes on the cell surface. A burner model is used to represent the catalytic burning of residual fuel in the combustion plenum and a heat exchanger model is used to simulate the heating of the incoming air in the injection tubes.

Figure 3: Lay out of the flow sheet model of the SOFC Field Unit.
CELL VOLTAGE MODELING

The condition of the SOFC module is based on the average cell performance. Based on (7), the condition-monitoring model assumes the following relation for the cell voltage:

\[ V_{\text{cell}} = (1 - \alpha) \cdot V_{\text{in}} + \alpha \cdot V_{\text{out}} - I_{\text{cell}} \cdot R_{\text{eff}}(T_{\text{cell}}) + \frac{R \cdot T_{\text{cell}}}{2 \cdot F} \ln(1 - \frac{I_{\text{cell}}}{I_{\lim}}) \]

[1]

Where:
- \( V_{\text{cell}} \) = cell voltage (V)
- \( I_{\text{cell}} \) = cell current (A)
- \( T_{\text{cell}} \) = cell temperature (K)
- \( V_{\text{in}} \) = Nernst voltage for inlet conditions (V)
- \( V_{\text{out}} \) = Nernst voltage for outlet conditions (V)
- \( \alpha \) = weighting factor for open cell voltage
- \( I_{\lim} \) = limiting current (A)
- \( R_{\text{eff}}(T_{\text{cell}}) \) = effective cell resistance at temperature \( T_{\text{cell}} \) (Ω)
- \( R \) = gas constant (8.31441 J/(moleK))
- \( F \) = Faraday constant (96485 C/mole)

This is an isothermal model assuming one dominant process for the concentration polarization and neglecting the activation polarization. The condition-monitoring model uses a fixed value for \( \alpha \) and \( I_{\text{cell}} \) to calculate the effective cell resistance \( R_{\text{eff}} \) from measured data. This is why it is called an effective resistance because any unmodeled deviation in the cell voltage is attributed to an alteration of the effective cell resistance whether it is related to a physical alteration or not.

The cell voltage at inlet conditions (\( V_{\text{in}} \)) and at outlet conditions (\( V_{\text{out}} \)) are calculated based on the Nernst potential for the hydrogen reaction, assuming an equal flow of air and fuel throughout the stack:

\[ V_i = V_0(T_{\text{cell}}) - \frac{R \cdot T_{\text{cell}}}{2 \cdot F} \ln\left(\frac{P(H_2O)_i}{P(H_2)_i \cdot P(O_2)_i^{1/2}}\right) \]

[2]

Where:
- \( i \) (index) = in, out
- \( V_i \) = cell voltage at inlet or outlet conditions (V)
- \( V_0 \) = cell voltage based on Gibbs energy of the hydrogen reaction at \( T_{\text{cell}} \) (V)
- \( P(H_2O)_i \) = partial pressure for water vapor at anode inlet or outlet (bar)
- \( P(H_2)_i \) = partial pressure for hydrogen at anode inlet or outlet (bar)
- \( P(O_2)_i \) = partial pressure for oxygen at cathode inlet or outlet (bar)

Using available data (8) for the performance of a single cell of the Field Unit, the model parameters from equation [1] can be calculated, using a least square approximation. Figure 4 shows the results of this procedure. It shows that the voltage model gives an adequate description of the cell voltage at different cell currents. The dependency of the cell voltage on the fuel utilization, the air utilization and the cell
pressure is assumed to be incorporated in the effects on the Nernst voltage. For the cell pressure, this is correct (9), for the fuel utilization and the air utilization, this must be validated in practice.

The cell voltage depends on the cell temperature. Part of it is modeled in the Nernst equation [2] and the cell voltage equation [1]. The effective cell resistance, \( R_{\text{eff}} \), also depends on the operating temperature. This dependency is modeled using:

\[
R_{\text{eff}}(T_{\text{cell}}) = R_0 \times e^{(R_t \times T_0 / R_0) \times (1 - T_0 / T_{\text{cell}})}
\]

[3]

Where:
- \( T_0 \) = reference temperature of 1273.15 K (1000 °C)
- \( R_0 \) = the effective cell resistance at \( T_0 \) (Ω)
- \( R_t \) = the temperature coefficient of \( R_{\text{eff}} \) at \( T_0 \) (Ω/K)

The value of \( R_t \) is determined by a correlation method. Assuming equation [3] gives the correct relation, the correlation between the calculated effective cell resistance \( R_{\text{eff}} \) and the average cell temperature \( T_{\text{cell}} \) should be zero for normal operation. During the first 1700 hours of operation of the Field Unit, this correlation is minimized by varying the value of \( R_t \). Figure 5 shows that there is a single value for \( R_t \) that minimizes this correlation. This procedure assures that the effects of alterations in the stack temperature distribution are incorporated in the value of \( R_t \). A disadvantage of this approach is that sudden alterations in the stack temperature distribution will affect the effective cell
resistance until a steady state (on which the value of $R_t$ is based) is reached again.

\[ R_t = -0.00323 \text{ m}$\Omega$/K \]

**Figure 5:** Correlation between the calculated effective cell resistance, $R_{eff}$, and the average cell temperature, $T_{cell}$, as a function of parameter $R_t$.

Figure 6 shows the results of a sensitivity analysis of the calculated cell voltage according to equation [1] with respect to a 5% variation in the model parameters. This is done for typical operation conditions of the Field Unit. It shows that the cell voltage will be most sensitive to the fuel utilization, the average cell resistance and the cell temperature.

**Figure 6:** Sensitivity of the cell voltage to a 5% variation in the model parameters for typical operating conditions of the Field Unit. The black bar to the left indicates a negative correlation; the black bar to the right indicates a positive correlation.

**Average Cell Voltage (V)**

| parameter                  | 0.63 | 0.64 | 0.65 | 0.66 |
|----------------------------|------|------|------|------|
| fuel utilization           |      |      |      |      |
| effective cell resistance  |      |      |      |      |
| cell temperature           |      |      |      |      |
| cell voltage weighting factor |    |      |      |      |
| O to C ratio               |      |      |      |      |
| cell limiting current      |      |      |      |      |
| cell pressure              |      |      |      |      |
| temp. dependency resistance |    |      |      |      |
| air utilization            |      |      |      |      |

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SOFC MODULE PERFORMANCE FACTOR

The SOFC module performance factor is calculated as follows:
- The condition-monitoring model is used to calculate the effective cell resistance at 1000 °C, \( R_0 \).
- A flow sheet model is used to calculate the cell voltage at nominal conditions, given the previously calculated value of \( R_0 \).
- The module performance factor is determined by dividing the calculated nominal cell voltage by the design cell voltage at nominal conditions.

Figure 7 presents the result of this procedure. This figure indicates that initially the performance is increasing with approximately 0.8% per 1000 hours. Then a small drop in performance occurred. It is not sure yet what caused this sudden performance decrease and whether it is a real effect or a modeling effect. However, the performance decrease due to sulfur breakthrough is clearly visible. It is also clear that the module recovered from the breakthrough completely showing an exponential course. After that, an inverter stop caused a sudden decrease in module performance. Again, the module seems to recover from it in an exponential course. However, this time it does not seem to recover completely. After a second replacement of the sulfur absorbent, the module performance decreased gradually until operation of the Field Unit was stopped at the end of June 1998.

![Figure 7: The SOFC module performance factor during the 1998 operating period of the SOFC Field Unit.](image)

CONCLUSIONS

The condition-monitoring model is able to translate a significant amount of operating data for the 1998 operating period to a single performance factor for the SOFC module.
This single performance parameter has a lot of advantages. It can be used on-line to detect any abnormal change in stack performance at an early stage (for instance as a result of sulfur breakthrough). It can also be used to analyze performance data afterwards.

The 1998 operating period included some alterations in the stack current that did not influence the SOFC module performance factor. This indicates that the condition-monitoring model is correct in relation to changes in the stack current. However, full validation of the model is only possible with real performance data for a wider variety of operating conditions (especially the fuel utilization).

Currently, the condition-monitoring model assumes a fixed temperature distribution in the stack. Alterations in the stack temperature profile affect the performance factor. A more detailed model, incorporating the effects of the temperature distribution in the stack, might solve this problem.

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