THE EFFECT OF MASS FLOW DISTRIBUTION ON THE CHARACTERISTICS OF A SOLID OXIDE FUEL CELL SYSTEM

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ABSTRACT

In a solid oxide fuel cell (SOFC) stack the fuel and the air have to be uniformly distributed to a system of parallel channels. This is a difficult task, particularly when the total pressure loss of the stack should be kept as low as possible. In this paper a simulation program is described treating the problem of branching channels with a particular view to fast convergence for application as a subroutine to the main SOFC code. The simulation is experimentally verified and then applied to a planar SOFC cell and stack as well. The calculations show that a mass flow variation by a factor of 3 to 4 occurs along the stack. The effect on the integral operation quantities, i.e. cell voltage and performance is smaller than 1%, the local temperatures, however, increase by 20 K. Additional results of a sensitivity study are presented, particularly the effect of the manifold size on the mass-flow distribution.

INTRODUCTION

The calculation of SOFC-systems is predominantly performed by assuming a uniform mass flow distribution across the fuel cells. This is for a first step a suitable approximation. Planar fuel cells, however, consist of an arrangement of multiple parallel channels. It is well known that for such configurations a uniform mass flow distribution cannot easily be achieved unless a considerable pressure drop is admitted. Therefore it is necessary to make the situation predictable by means of an appropriate simulation. Thus it is possible to improve the design or to estimate the flow effect on the operation conditions of the stack.

The aim of the present work is to integrate a flow model as a subroutine of the main SOFC-program (1, 2). Commercial codes are available; they don’t meet, however, the requirements of low time usage, which is necessary for a subroutine used in iterations. The idea of the present code is to combine numerical integration with analytical solutions.

The principles of the flow model and the verification by experimental data are presented. Then the code is applied to single cells and to stacks as well to make the flow effects evident. Finally some design parameters are considered which affect the flow field and thus the operation of the stack.
FLOW MODEL

The flow distribution problem occurs in a SOFC-stack for four times (3,4). Within the cell itself the air and the fuel must separately be distributed to the particular channels. Furthermore, each of the cells of the stack must be provided with air and fuel by means of stack manifolds. All applications are of the same type: inlet manifold, a system of parallel channels and outlet manifold. Figure 1 shows a sketch of the arrangement to be treated.

The mass flow in each of the channels depends on the local static pressure difference across the two manifolds. Therefore the static pressure along the manifolds must be calculated. For this reason the manifold is subdivided in elements each containing one branching channel. The pressure drop along the element i is the sum of the acceleration, friction and impact loss terms:

\[
\Delta p_i = (\Delta p_{acc} + \Delta p_f + \Delta p_m)_i \tag{1}
\]

where

\[
\Delta p_{acc} = \frac{1}{2} (\rho/2) (\frac{w_{i-1}^2}{w_i^2} - \frac{w_i^2}{w_i^2}) \tag{2}
\]

\[
\Delta p_f = (\lambda z) / (d_b (\rho/2) w_{i-1}^2) \tag{3}
\]

\[
\Delta p_m = -\zeta_m (\rho/2) (\frac{w_{i-1}^2}{w_i^2} - \frac{w_i^2}{w_i^2}) \tag{4}
\]

and

\[
\lambda = [ (\phi 64/Re)^4 + 0.3164^4/Re ]^{0.25} \tag{5}
\]
Eqn.[5] holds for the friction coefficient of channels where $\varphi$ means a geometry factor depending on the channel geometry. The impact coefficient $\zeta_m$ of Eqn.[4] is different for the inlet and outlet manifold, and from experimental data is found to be 0.2 and 0.95, respectively. The flow in the fuel cell channels is affected by mass and molar changes due to the electrochemical and reforming reactions and by temperature variations associated with changes of the gas properties. As an approximation, a linear change of mass flow $m(x)$, molar flow $n(x)$ and temperature $T(x)$ along the channel is assumed. It can be described by introducing the following coefficients:

$$f_m = \frac{m_{in}}{m_{out}}, \quad f_n = \frac{n_{in}}{n_{out}}, \quad f_T = \frac{T_{in}}{T_{out}}, \quad f_v = \frac{\rho_{in}}{\rho_{out}} \text{(spec. vol. before/after reforming)}$$

Thus the local fluid density and channel velocity

$$\rho(x) = \rho_{in} \frac{[(f_m - 1)(x/L) + 1]/[(f_T - 1)(x/L) + 1]( (f_n - 1)(x/L) + 1)]}{[(f_T - 1)(x/L) + 1)( (f_n - 1)(x/L) + 1)]}$$

$$u(x) = \frac{m_{in}}{A_{ch} \rho_{in}} \frac{[(f_T - 1)(x/L) + 1)( (f_n - 1)(x/L) + 1)]}{[(f_T - 1)(x/L) + 1)( (f_n - 1)(x/L) + 1)]}$$

help to express the pressure loss along the channels depending on the flow entrance conditions. The pressure drop is affected by friction, impact loss and acceleration terms:

$$\Delta p_{ch} = \Delta p_{f,ch} + \Delta p_{m,ch} + \Delta p_{ac,ch}$$

The contribution of friction is obtained by integrating the local friction loss

$$d p_{f,ch} (x) = -(\lambda \frac{dx}{du_{ch}}) \frac{(\rho(x)/2)}{u(x)^2}$$

along the channel. The impact loss at the entrance region is accounted for by an empirical equation

$$\Delta p_{m,ch} = - \zeta_{ch} \frac{(\rho/2)}{u_{in}^2}$$

The momentum equation yields the acceleration term $\Delta p_{ac,ch}$

$$\Delta p_{ac,ch} = \frac{( \rho_{in} u_{in} )}{A_{ch} (1 - f_m f_v f_T f_n)}$$

Finally, Eqn.[8] yields together with Eqns. [6], [7], [9], [10] and [11] the channel entrance velocity depending on the pressure difference across the inlet and outlet manifold:
The system to be solved depends on three coupled nonlinear one-dimensional equations. For isothermal conditions without chemical reactions the coefficients \( f_m \), \( f_n \), \( f_r \), and \( f_v \) are equal to unity. In the case of applying the code to fuel cell operation, these coefficients have to be recalculated after each iteration.

The calculation starts by setting an estimated pressure distribution in the two manifolds. From that the new channel velocities \( u_{\text{new}}(i) \) are determined and corrected by means of a relaxation procedure:

\[
u(i) = u_{\text{prev}}(i) + F_{\text{rel}} (u_{\text{new}}(i) - u_{\text{prev}}(i))
\]

By means of the new velocity distribution the local pressure in the manifolds can be calculated from which the next channel velocity is determined. The calculation is terminated, when the velocities of two succeeding iterations do not exceed a given threshold. In general the computed mass flow does not meet the given one. Therefore the procedure has to be repeated until agreement occurs within a given threshold. Best convergence is obtained by setting the relaxation coefficient \( F_{\text{rel}} = 0.1 \ldots 0.15 \).

RESULTS

Flow Distribution in a Stack

In order to verify the flow simulation, a test has been applied which represents the situation occurring in a stack of 86 cells. Each cell was a plate 11 mm thick, 200 by 280 mm large containing 10 channels 200 mm long, 20 mm wide and 4 mm deep. Inlet and outlet manifolds provided the stack with air from a blower. The static pressure distribution could be measured along the manifolds in three lateral positions of the cells.

Figure 2 illustrates the comparison between experimental and theoretical results for the case of counter flow in the manifolds. The static pressure increases in the inlet section due to the deceleration of the flow. This effect increases with increasing Reynolds number. In the outlet manifold the flow is accelerated which causes a pressure decrease (flow direction in the Figure from right to left). The local difference between both sides is the driving pressure difference for the local channel flow. It is obvious that this quantity is pretty well predicted.

Same effects as described for the stack also occur in the particular cells. As an example Figure 3 shows the relative velocity distribution along the channels of the three types of fuel cell design: cross-flow, counter-flow and co-flow. The local velocity is related to the mean velocity. For cross-flow, deviations of less than 2% occur due to temperature effects since a cell manifold is not necessary. Counter-flow and co-flow results collapse both
for the air and the fuel side. It is evident that velocity variations by a factor of about 3 are predicted.

Figure 2: Experimental and theoretical pressure distribution along a fuel cell stack. Cross symbols experimental, lines theoretical data: + inlet manif.; x outlet manif.; * ΔP_{ch}

Figure 3: Relative channel velocity in a single cell

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Figure 4: Solid temperature of a fuel cell at co-flow, without (a) and with (b) flow simulation

Figure 5: Solid temperature of a fuel cell at counter-flow, without (a) and with (b) flow simulation

The Effect of Non-uniform Flow Distribution on Cell Operation

It is expected that the non-uniform flow distribution has an effect on the local and integral parameters of the fuel cell. In order to quantify those effects a reference fuel cell is defined operating under uniform mass flow distribution on the fuel and air side. Main parameters of that cell are: active area: 100 x 100 mm², pressure 1 bar, inlet temperature 900 °C, water/methane ratio 2.5, pre-reforming 30%, utilization 70%, stoichiometry factor 7.
For cross-flow only minor effects are expected for the single cell. Co-flow and counter-flow, however, are significantly affected as shown in the Figures 4 and 5. Here the solid temperature distribution is represented in comparison to the reference cell.

In both cases the symmetrical pattern changes such as the hot spots are displaced to the lower frame. As a whole the temperature variations across the cell increase and also the local internal reforming rates and the current density. Details can be read from Table 1.

| flow | simulation | U [V] | P [W] | Tmax [K] | Tmin [K] | dT/ds [K/mm] | Δjmax [mA/cm²] |
|------|------------|-------|-------|----------|----------|--------------|----------------|
| cross | with       | 0.732 | 21.96 | 982.1    | 903.2    | 1.72         | 196.0          |
| cross | without    | 0.732 | 21.96 | 983.2    | 903.7    | 1.69         | 203.7          |
| co   | with       | 0.719 | 21.56 | 979.8    | 899.2    | 1.52         | 328.6          |
| co   | without    | 0.723 | 21.71 | 966.0    | 896.6    | 1.19         | 129.6          |
| counter | with     | 0.743 | 22.29 | 990.3    | 935.1    | 1.71         | 421.3          |
| counter | without  | 0.746 | 22.38 | 983.4    | 942.0    | 1.45         | 304.5          |

**Table 1**: Comparison of the operation data of a single cell

It is obvious from Table 1 that the integral quantities such as cell voltage and cell performance are little influenced by non-uniform flow distribution. It is the material, however, which is additionally stressed. Counter-flow produces the highest temperatures, temperature gradients and current density variations, but also the highest performance.

![Figure 6: Effect of manifold width on the relative velocity distribution](image)

The simulation program allows for sensitivity studies with respect to design data of the cell. As an example the effect of cell-manifold size is illustrated in Figure 6.

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The ratio of maximum to minimum channel velocity decreases with increasing manifold width, here represented relative to the reference cell. The reason is that for both the inlet and the outlet manifold the friction forces prevail compared to the acceleration forces and therefore the static pressure along the manifolds does not vary significantly. The effect is most important for width ratios smaller than 1.5.

The Effect of Non-uniform Flow Distribution on Stack Operation

In a stack the flow distribution problem occurs twice on each of the fuel and air side. Therefore effects are expected not only in each of the cells, but also along the stack height. In order to quantify these effects a reference stack of 50 cells is considered. It was seen that after the start under isothermal conditions four flow iterations were sufficient to reach convergence.

The calculations with and without flow effect indicate a displacement of the hot spot area in direction of the location opposite to the entrance and outlet. Here the cells are poorly provided with air which is responsible for removing the heat. Correspondingly the entrance-outlet region is well cooled which drops the minimum temperatures. Both effects are in the order of 10 degrees. Table 2 gives more details about temperature and other operation data.

|                   | flow | U [V] | ΔU [mV] | P [W]  | T_{max} [K] | T_{min} [K] | dT/ds [K/mm] | Δj_{max} [mA/cm²] |
|-------------------|------|-------|---------|--------|-------------|-------------|--------------|-------------------|
| cross with        | 0.732| 4.7   | 1099    | 982.2  | 904.5       | 1.51        | 220.2        |
| cross without     | 0.734| 0.1   | 1102    | 973.2  | 919.4       | 1.34        | 232.1        |
| co with           | 0.720| 1.7   | 1080    | 978.1  | 897.1       | 1.51        | 322.2        |
| co without        | 0.725| 0.3   | 1088    | 967.9  | 896.6       | 1.31        | 195.8        |
| counter with      | 0.744| 7.3   | 1116    | 988.0  | 934.2       | 1.67        | 410.8        |
| counter without   | 0.746| 0.4   | 1118    | 982.8  | 941.8       | 1.43        | 307.1        |

Table 2: Comparison of the operation data of a stack

The effect on the stack voltage is 5 mV or less similar to the voltage difference ΔU referred to the reference cell. For co- and counter-flow the variation of the current density is more unfavorable by more than 100 mA/cm².

The pressure distribution along the manifolds and the non-uniformity of the flow distribution depend on the ratio of acceleration to friction forces and it therefore depends on the Reynolds number. This is lower by one order of magnitude for the fuel side compared to the air side. A further effect is expected due to the fact that the friction and acceleration forces subtract in the inlet manifold whereas they add in the outlet manifold. Thus it is useful to have a larger cross section in the outlet manifold than for the inlet.

In Figure 7 the ratio of outlet to inlet area A_{o}/A_{i} has been varied for the fuel and the air side. Due to low Reynolds numbers on the fuel side the effect on the flow distribution is negligible. For the air side the curve exhibits a minimum for A_{o}/A_{i} = 2. Here the friction
and acceleration forces compensate each other in the inlet manifold which is no longer the case for $A_0/A_1 > 2$.

**Figure 7:** Effect of the inlet / outlet manifold cross section ratio on the relative velocity distribution

**CONCLUSIONS**

The uniform supply of fuel cell channels and stacks with fuel and air, respectively, has been recognized as a severe problem, particularly when space restrictions are prevailing and the total pressure loss of the system must be kept as low as possible. In this case the inlet manifold has to be designed such that the acceleration forces compensate the friction forces. Then the outlet manifold should have twice the cross section of the inlet manifold to result in a possibly constant static pressure spread between the manifolds.

In spite of those means mass flux non-uniformities by a factor of four may occur in a stack, particularly on the air side. The effect, however, on the integral quantities such as cell voltage and performance is unimportant whereas the variation of the temperature and current density across the fuel cell area increase by $\Delta T = 10$ to $20$ K and $\Delta j = 10$ to $126$ A/cm$^2$, respectively. The simulation results demonstrate that the effect of the flow on the fuel cell operation conditions is sufficiently accounted for by four flow iterations.
LIST OF SYMBOLS

| Symbol | Description                      | Greek Symbols                  |
|--------|----------------------------------|--------------------------------|
| A      | area, m²                         | η                              |
| d_h    | hydraulic diameter, m            | λ                              |
| F_rel  | relaxation factor                | ρ                              |
| j      | current density, A/cm²           | ζ                              |
| m      | mass flux, kg/s                  |                               |
| n      | molar flux, mol/s                |                               |
| p      | pressure, N/m²                   |                               |
| Re     | Reynolds number                  |                               |
| T      | temperature, K                   |                               |
| U      | voltage, V                       |                               |
| u      | velocity, m/s                    |                               |
| x,y,z  | coordinates, m                   |                               |
| new    | new                              |                               |
| out    | outlet                            |                               |
| prev   | previous                         |                               |
| ref    | reference cell                   |                               |

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