Heat balancing of direct reforming fuel cells in MGT-SOFC hybrid systems

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Abstract. Solid oxide fuel cells convert chemical energy in electrical energy and are highly suitable for the conversion of hydrocarbon based fuels and products from PowerToGas conversions. Embedded in a micro gas turbine-cycle instead of the combustion chamber the heat energy of the injected fuel, released in the SOFC-Stack, can additionally converted into work and by a turbine-generator into electricity. In a compact system, SOFC stacks are designed to realize a direct steam-reforming process inside. In such direct-reforming fuel cell systems the SOFC operating temperature due to the heat demand for reforming, can be reduced to a value in the range of the outlet temperature of the downstream flow (650°C). If the cycle uses a recuperating system, the operating conditions of the SOFC can be realized without additional high-temperature heat exchanger systems. The system with an uncooled turbine, described in [1], just can reach the operating temperature with an additional high-temperature heat exchange. The system described in this publication does not require an additional high-temperature heat exchanger, because the X-value, as the ratio between the exchanged heat quantity and the required amount of heat to complete the MGT-cycle [2] due to the referring process, is nearly zero and can be realized via the inner container wall (of the MLC). The cycle is completed (between the SOFC and the turbine entry) by the heat input of an afterburner. Here the unreacted fuel of the SOFC fuel-stream is used to provide the necessary heat energy for the downstream turbo-generator-system.

1. Introduction
A MGT-SOFC hybrid system has been described in [1] and [2] in the planned "Turbo-Fuel-Cell (TFC)" design. A marketable system (developed by the B+K GmbH) [3] in cooperation with the BTU Cottbus-Senftenberg, LS VFA [4]) is scheduled to go into service in 2027. The TFC system [1] consists of a recuperated micro gas turbine process (MGT process) with an embedded SOFC subsystem ("Solid Oxide Fuel Cell"). This technology uses planar SOFC stacks because they are more economical and more compact than SOFC cylindrical cell stacks (SOFC-CCS) [19]. CCS technology is currently considered to be stronger and better suited for integration into gas turbine processes, as possible differential pressures between the anode and cathode sides (e.g. under load changes) may be higher due to the cylindrical shape [5]. Targeted control of a low differential pressure means that new generations of planar SOFC stacks now can achieve service life cycles of more than 30,000 hours [14], [20], [22].

The BTU-CS [4] MAXEFF research program investigates the suitability of planar SOFC stacks for the hybrid pressure-charged hybrid application with respect to a cluster design (SOFC Stack Grape Technology / SOFC-SGT) [1]. A recent Mitsubishi-Hitachi Power Systems, LTD (MHPS) project demonstrates SOFC-CCS technology in a hybrid combination with gas turbines [5]. By contrast, the
TFC 1.0 strategy relies on the available market for planar SOFC stacks and follows the SOFC-SGT strategy. The tubular SOFC stacks of the MHPS technology show a high differential pressure resistance compared to planar systems. This article is based on a MGT-SOFC system architecture (type TFC 1.0) for the study with planar stack systems.

A research and development-oriented collaboration between industrial companies and research institutes will establish the most suitable SOFC technology for hybrid systems in the future. Figure 1 visualizes the 270kW TFC1.0 system. In this case, the SOFC stacks are connected to grapes and the already industrialized micro turbine is shown. [1]

**Figure 1. Visualization of a MGT-SOFC System with SOFC-SGT [1]**

The System architecture examined in this article is based on the TFC 1.0 type [1]. The complexity of the high-temperature heat exchanger fixes the temperature difference between the SOFC inlet temperature and the recuperator outlet temperature. The complexity of the high temperature heat exchanger determines the temperature differential between the SOFC inlet temperature and the recuperator outlet temperature. For this reason, SOFC technology with reduced temperature and internal reforming is examined in this study.

2. **Fundamentals and heat balancing in the cycle with the TFC-1.0 technology**

A realization of the TFC-1.0 is planned with the industrialized SOFC components available today. In future, however, an internal reforming process (exothermal) can reduce the operating temperature of the SOFC cell, under the condition that sufficient electrolyte conductivity is possible. At present, electrolyte membranes of yttrium-stabilized zirconia (YSZ) are used [16]. Above 750°C, this material is a useful oxide ion conductor, which is the reason for the currently high SOFC operating temperature (700°C to 900°C). At this temperature range, the technology generates sufficient performance and achieves a very high efficiency. The fuel cell heat loss and the heat from the afterburner (burning the non-converted fuel) is the equivalent to the traditional combustion chamber in the MGT process [2]. Part of this heat energy is needed for the reforming process or pre-reforming process (with a complete implementation inside the SOFC-Stack). To complete the MGT-Process the heat quantity ΔQ_{Input} is necessary. It is determined using the SOFC efficiency chain (\eta_{SOFC-rev} \cdot \eta_U \cdot \eta_I \cdot \eta_C). The heat quantity is the not in electricity converted chemical energy described with the formation enthalpy of the fuel as follows [2]:

\[ \Delta Q_{Input} = \Delta H \cdot (1 - \eta_{SOFC-rev} \cdot \eta_U \cdot \eta_I \cdot \eta_C) \]  \hspace{1cm} (1)

This technology is equipped with an innovative multi-layer pressure vessel [21]. The housing temperature of less than 80°C is possible due to the multilayer insulation, while the operating temperature of the SOFC in the first application, with a reforming process outside the SOFC, is 860°C.
Figure 2. Visualization of a TFC-1.0 System in a vertical MGT Axis-Architecture and the main components of the process. The MLC technology allows minimal heat losses.

Figure 2 illustrates the architecture of the actual system. In this design, the entire system is thermal-optimized, because all heat losses through the ducting of the MLC (multi-layer container) are low and returned into the process. In the latest design, the inner MLC-wall is used for the high-temperature heat exchange to obtain the required SOFC inlet temperature (heat balancing in the cycle).

For general understanding of the MGT-SOFC process, Figure 3 shows the basic structure of the fundamental equations.

Figure 3. Sketch of the MGT-SOFC process (left) and the fundamental equations (right) [2]

3. The X-value (for the quantification of heat balancing in the cycle) and the extended definition taking the SOFC inlet- and outlet temperature into account

To estimate the design effort of a MGT-SOFC-process, the heat ratio X was introduced in [2] as the ratio between the exchanged heat quantity $\Delta Q_{\text{HeatEx}}$ and the required amount of heat $\Delta Q_{\text{Input}} = \Delta R Q + \Delta Q H + \Delta FC Q - \Delta Q_{\text{Reformer}}$ to complete the MGT-cycle.

$$X = \left( \frac{\Delta Q_{\text{HeatEx}}}{\Delta Q_{\text{Input}}} \right)$$  \hspace{1cm} (3)

To be on the safe side for the system design, the maximum amount of heat that the high-temperature heat exchanger supplies was determined from the temperature difference between the mean SOFC temperature and the recuperator outlet temperature (Figure 4 left).
Further, to clarify the heat balance on the SOFC stack, the definition of [1] was extended to the dimensionless temperature spread ratio across the cell. The dimensionless temperature spread of the SOFC cell is defined as follows:

$$\theta_{\text{Spread}} = \frac{T_{\text{SOFC Outlet}} - T_{\text{SOFC Inlet}}}{T_{\text{SOFC M}}^{\text{Nominal}}}$$

(4)

With a fictitious heat capacity $C_p$, the relationship can be rewritten as follows:

$$T_{\text{SOFC M}} = \frac{1}{\theta_{\text{Spread}}^{\text{Nominal}}_p} \cdot \left\{ \left[ \dot{m}_{\text{LowSyn}} \cdot \Delta H_{\text{LowSyn}} \right]^{\text{catode outlet\rightarrow\text{HEX}}} + \left[ \dot{m}_{\text{Air}02} \cdot \Delta H_{\text{Air}02} \right] \right\}_{\text{SOFC\rightarrow\text{Outlet}}} - \left[ \dot{m}_{\text{High}} \cdot \Delta H_{\text{High}} \right]^{\text{inlet\rightarrow\text{ref. outlet}}} +$$

including formation enthalpy of the: \(\Rightarrow\)High Syngas from the pre reformer or reformer \(\Rightarrow\) SOFC,

$$\dot{m}_{\text{overall}} = \dot{m}_{\text{Air}} + \dot{m}_{\text{H2O}} + \dot{m}_{\text{Fuel}} + \dot{m}_{\text{ref. outlet}} = \dot{m}_{\text{High}} + \dot{m}_{\text{Air}} + \dot{m}_{\text{LowSyn}} + \dot{m}_{\text{Air}02} = (1 - \beta) \cdot \dot{m}_{\text{Air}} + \dot{m}_{\text{H2O}}$$

(6)

4. MGT-SOFC map extension by introducing a SOFC stack internal reforming

Internal reforming is a possible method for increasing the efficiency of a SOFC System. No separate reforming apparatus is needed, a more even hydrogen formation and a higher methane conversion ratio are possible. But, for the reforming, catalyst deactivation reactions are possible and the combination of the electrochemical reaction and the reforming in one cell can reduce the flexibility in the operation of the fuel cell [9], [10], [17], [18]. With a combination of pre- and direct reforming systems, the requirement of a higher and even hydrogen production should be solved. However, the balancing of such a system needs more time and is a task of future development.

In [1], this mean temperature was given to allow a representation in a map (Figure 4 right). Here, the dimensionless power

$$\frac{P_{\text{Total}}}{P_{\text{Nominal}}} = \frac{(P_{\text{MGT}} + P_{\text{el.SOFC}})_{\text{Total}}}{(P_{\text{MGT}} + P_{\text{el.SOFC}})_{\text{Nominal}}} \approx \frac{\dot{m}_{\text{Total}} \cdot \left( \frac{\text{real}}{\text{real}} \cdot \frac{\text{real}}{\text{real}} \right)}{\dot{m}_{\text{overall}} \cdot \left( \frac{\text{real}}{\text{real}} \cdot \frac{\text{real}}{\text{real}} \right) \cdot \eta_{\text{sys,T}}} \cdot \eta_{\text{sys,N}}$$

(7)

is plotted against the overall efficiency as a function of the mean SOFC temperature and the turbine inlet temperature.

The map shows that for an uncooled micro turbine (max. $T_{\text{Turbine\rightarrow\text{in}}}$, the green limit curve) the x-value is in a range of 0.9 in the MGT-SOFC design point. The boundary line $x = 0$ is shown also. In the
area below this curve, the MGT-SOFC process can perform without a high-temperature heat exchanger. Above this curve, a high temperature heat exchange is required [2], [19].

For the practical SOFC application of the planned TFC 1.0, a steam reforming process has been established [9], [15]. Therefore, this boundary condition was also selected in the work plan. It is mentioned that, in principle, the partial oxidation and the autothermic reforming can also be used for the generation of synthesis gas (HighSyn Gas).

If the SOFC stack allows a high temperature spread $\theta_{\text{spread}}$ or if the average operating temperature $T_{\text{SOFC}_{\text{IM}}}$ is lower, less heat has to be exchanged at high temperature.

However, a high spread-ratio means higher thermal stresses in the stack, which is negative for the lifetime. A low SOFC operating temperature $T_{\text{SOFC}_{\text{IM}}}$ would be very good. However, here the problem, that the oxide ions conductivity decreases (border temperature 650°C), can occur. An inner reforming can help to lower the thermal load. Since less cathode air is required for internal stack cooling, system performance increases as more stacks are used (higher power density of the TFC1.0).

5. Heat balance through a coordinated distribution between the reforming process inside and outside the SOFC stack

From the field of possible MGT-SOFC processes (by taking into account the practical engineering conditions) the presented TFC architecture is favoured and further optimized. In addition to the realization of a very high efficiency, in particular the service life, the costs and a high power density are in focus.

A thermally adapted reforming process in the SOFC stack reduces the temperature increase on the anode side by heat removal. Decrease in the temperature distribution across the stack reduces the thermal stresses. As a result, the reformer is mutating into an adapted pre-reformer. This balancing process has to be adjusted carefully, so the temperature cycle profile is exectically well balanced and the operating temperature of the SOFC does not fall below the limit temperature.

Due to the internal reforming, the mass flow on the cathode side can be reduced because the required stack cooling is lowered. The resulting effect leads to a shift of the generated energy between the SOFC and MGT in favour of the SOFC. This means getting a higher relative system performance because of the lower excess air. With the same turbo-set the overall performance becomes better. Studies, calculated with the simulation system Ebsilon [12], also show that the system is experiencing a further increase in efficiency.

It has been determined by calculations that in a MGT-SOFC process, the amount of energy generated by the SOFC, with identical MGT, can be doubled. In addition, internal reforming reduces the energy required for the reformer. With the same MGT, the required reformer performance is almost identical and this with almost twice the output power of the entire process. In Figure 5 and Figure 6, both processes are presented as an example with an indication of the energy flows relative to the generated electrical energy (EP).

In the pictures, the dimensionless component power is shown in blue and the dimensionless cycle process temperatures are shown in green. The dimensionless power is built by the total power of the TFC and the dimensionless temperature is formed with the turbine inlet temperature. The following definitions apply:

$$\Psi = \frac{|P_{\text{Component}}|}{P_{\text{System}}} = \frac{|P_{\text{Component}}|}{(P_{\text{MG1}} + P_{\text{el,SOFC}})_{\text{System}}} \equiv \text{Blue numbers}$$ (8)

$$\vartheta_{L,\text{cycle}} = \left(\frac{T_{\text{L, cycle}} - T_0}{T_{\text{Turbine, in}} - T_0}\right) \equiv \text{Green numbers} \text{, with } T_0 = 273.16 \text{ K}$$ (9)
The bypass in Figure 6 is used to regulate the hydrogen concentration in the anode inlet for CH₄ / H₂ gas mixtures at the primary inlet, since the pre-reformer otherwise reformed too much of the CH₄.

6. Heat situation and heat balancing in a SOFC stack with external and internal reforming

Heat Transfer problems can be described by dimensionless number models [11]. In SOFC-cells, oxygen ions flow through the membrane and affect the heat transfer processes in the interfaces of the cathode and the anode. On the cathode side, the heat transfer compared to a channel without membrane is larger (depending on the oxygen-ion flux). At the anode, the reverse case occurred (the heat transfer decreases with increasing oxygen-ion flux). This influence on the heat transfer can be described by the Graetz-Number. It is the reciprocal of the known Fourier-Number. It expresses the ratio of the convective heat transferred  \( \dot{Q} \) to the heat dissipated  \( \dot{Q} \) and can be described by the Peclet-Number and the dimensionless channel length as follows [11]:

\[
\beta = \frac{\dot{m}_{\text{Fuel}}}{\dot{m}_{\text{Air}}}
\]

\[
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\]

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\]

\[
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\]
The estimate for the anode density between the educts and the products on the anode side, one must estimate this influence, since the effect is much smaller. Hence, the anode density in the channel is written for the anode

\[
GZ = \frac{q}{q_0} = 1/F_0 = Pe \cdot \frac{1}{x}
\]

(10)

with \( \bar{x} = \frac{xS_E}{4A} = \frac{x}{d_E} \) (S_E=scope, A = area, x= channel coordinate, d_E= equivalent diameter)

A description can be done by modifying the Pe-Number in such a way that there is a simplified modification via the Re-Number with a Pr-Number dependent only on the flow material properties as a function of x/l_c (l_c = channel length). The result is approximately the following relationship:

\[
P_e(x) = \frac{Re(x)}{Correction} \approx Re \left( \frac{x}{l_c} \right) \cdot \left( \frac{4k_E}{\rho E_k-5} \left( 1 - \frac{x}{l_c} \right) + \frac{4k_O}{\rho E_O-5} \cdot \frac{x}{l_c} \right)
\]

(11)

For the Reynolds number, a correction term is used on the membrane wall side.

Here, the cumulative oxygen ion mass (proportional to the current flow) per channel region is introduced in relation to the channel mass flow and as a function of the running length.

\[
Re = Re \left( 1 + \bar{C} \right) = \frac{4k_E}{\rho E_k-5} \left( 1 + \bar{C} \right)
\]

(12)

\[
\bar{C} = \frac{\Sigma n_{e-}}{m_{Channel}/l_c} \cdot x \quad \text{with} \quad \bar{C} = \bar{C}_{Anode}, \quad \bar{C} = -\bar{C}_{Cathode} \quad \text{and} \quad \bar{C} = 1
\]

It applies to Graetz number for the anode side, the cathode side and the other channel walls:

(a) Membrane side (anode and cathode *)): 

\[
GZ = 1/F_0 = \frac{d_E}{x} \cdot Re \left( 1 + \bar{C} \right) \cdot \left( \frac{4k_E}{\rho E_k-5} \left( 1 - \frac{x}{l_c} \right) + \frac{4k_O}{\rho E_O-5} \cdot \frac{x}{l_c} \right)
\]

(13)

(b) The other channel walls:

\[
GZ = 1/F_0 = \frac{d_E}{x} \cdot \left( \frac{4k_E}{\rho E_k-5} \left( 1 - \frac{x}{l_c} \right) + \frac{4k_O}{\rho E_O-5} \cdot \frac{x}{l_c} \right)
\]

(14)

The heat transfer through the membrane and the interconnectors can be calculated as a simple heat conduction process [11], [13]. For the heat transfer calculations well known relationships for the laminar pipe flow can be used. In this case, a relationship of Churchill and Oze [8], experimentally and numerically validated by Berg [7] is recommended.

Because the Re-Numbers of the flow channels in planar SOFC-Stacks are very low (Re = 1 to 50; Pr = 0,7), the x*-value

\[
x^* = \frac{x}{D_re}
\]

(15)

is already in the area of the formed flow, so that approximately the Nu-Number is 3,65 and the heat transfer coefficient \( \alpha \) only depends on the thermal conductivity as a function of the gas composition (anode or cathode site) which is in the channel a function of x [11]. With known gas composition at the inlet and outlet it can be written for the anode (A) and cathode (C) channel:

\[
\alpha(x) \approx 3,65 \cdot \frac{1}{d_E} \cdot \lambda(x) = 3,65 \cdot \frac{1}{d_E} \left( \frac{\lambda_{A,C}}{A,C} \left( 1 - \frac{x}{l_c} \right) + \frac{x}{l_c} \right)
\]

(16)

with \( \lambda = \text{thermal conductivity at the entrance} \) and \( \bar{l} = \text{thermal conductivity at the outlet} \)

Whether the buoyancy effect and the layer position of a SOFC stack must be taken into account can be estimated using the known Gr-number (Grashof-number) of the SOFC-channels [11]. Here, it was found that the buoyancy effect caused by the temperature difference on the cathode side and the anode side causes no effect, since the Gr-number is negligible. Forming the Gr number with the difference in density between the educts and the products on the anode side, one must estimate this influence, since the Gr-number has a slightly negligible value. There is no significant effect on the cathode side.

The estimate for the anode side is for the vertical SOFC layers alignment. When horizontally aligned, the effect is much smaller.

The estimation is made with a further correction of the Gz-number for the anode side. An equivalent Re-number with the correction term \( C_{Gr} \) with the Gr-number is used.

\[
GZ = 1/F_0 = \frac{d_E}{x} \cdot \sqrt{Re_{equivalent}} \cdot \left( \frac{\Sigma n_{e-}}{m_{Channel}/l_c} \cdot x \right) \cdot \left( \frac{4k_E}{\rho E_k-5} \left( 1 - \frac{x}{l_c} \right) + \frac{4k_O}{\rho E_O-5} \cdot \frac{x}{l_c} \right)
\]

(17)
with the correction term \( C_{GR} \approx 0.4 \cdot Gr \) and with

\[
E = +, \text{for the condition “anode entrance up” and } O = -, \text{for the condition “anode outlet up” ,}
\]
because the products on the membrane side have a higher density than the educts

For the heat transfer calculations, known relationships for laminar pipe flow can be used again (see above).

Because the equivalent Re-Numbers of the flow channels are in a range of \( \sim 180 \), the Nu value of 3.65 can be assumed after a length of about 2.4\% (in the case of the examined own SOFC stacks, Figure 7) and the above \( \alpha(x) \) relationship can be combined.

As proven, the determination of the temperature distribution and thus the stress distribution is essentially dependent on the unique heat transfer coefficient, the heat conduction processes and the amount of heat released in the cell. This amount of heat is released on the anode surface. In a first approximation, it is dependent on the oxygen-ion flux, since a uniform distribution of the educts is assumed. In a realistic simulation, however, the exact composition of the gases have to be known. As a first approximation, however, the simplified approach is sufficient. If a reformation process takes place within the cell, the amount of heat required for this purpose must be deducted. For the heat production and the consumption (with Reformer) applies:

\[
\Delta R_H \cdot (1 - \eta_{\text{SOFC}} \cdot \eta_U \cdot \eta_I) - \Delta Q_{\text{innerRef}} = \Delta Q_{\text{SOFC inside}} = \frac{\Delta R_H Q + \Delta^I Q}{\eta_{\text{reversible}}} - \Delta Q_{\text{innerRef}}.
\]

In the case of SOFC-Stack internal reforming, the anode side can be provided with a permeable porous catalyst material or it can also be done for the reasons of stability in a SOFC cell without internal reforming or on the cathode side. This would result in heat transfer conditions, which differ from the conditions in a simple channel. The heat flows in the porous layer can be relatively easily interconnected with the heat transfer processes in the fluid. This is dependent on porosity-value \( \psi \). The same applies to the cathode channel, if e.g. higher mechanical stabilities and better heat transfer by means of a porous layer would be required in future cell constructions.

Channel-side porosities are an obstruction. Assuming the channel without porosity, at the same gas mass flow, the Graetz-number will increase depending on the equivalent diameter of the remaining flow area of the porosity. Since the Reynolds number is very low in this case, the Nusselt number after a short channel length has the value 3.65 [11, 13]. In a simplified model, the heat transfer processes can be imaged via a parallel-serial heat conductor circuit with the porosity material. For the solid material and the fluid in a porous reformer structure, a total thermal conductivity can be formed to a first approximation. This depends on the porosity \( \psi \) and for such a structure can be written in general.

\[
\lambda_{\text{total}} \approx \mathcal{B} \cdot \lambda_{\text{serial}} + (1 - \mathcal{B}) \cdot \lambda_{\text{parallel}} = \mathcal{B} \cdot \lambda_{\text{serial}} + (1 - \mathcal{B}) \cdot \lambda_{\text{parallel}}
\]

For \( \lambda_{\text{Solid}} \)-value of the solid material and the \( \lambda(x) \)-value of the fluid are determined \( \lambda_{xp} \)-values for the parallel and serial interconnection. Inserted into the relationship, the adaptation factor \( \mathcal{B} \) gives the value of the porous fissile material of the reformer. For a sponge-like structure the adaption factor is about 0.54 [6]. With this relationship and with the above heat transfer relationship, with a modified equivalent diameter, the heat transfer problem in a porous layer (e.g. reformer) can be easily described. The modified equivalent diameter is determined by the porosity of the layer. For the dimensionless channel length thus applies:

\[
\tilde{x} = \frac{x \lambda_{xp}}{4d_e} = \frac{x}{d_e} \cdot \frac{\delta_{\text{porosity}}}{\psi}
\]

For the determination of the specific surface, models of the literature can be taken. [6]

In the heat balancing procedure, after the mean temperature of the SOFC has been determined, a heat balancing is carried out within the stack in such a way that the temperature gradient is low. Thereafter, the adjustment is made with the heat balancing of the cycle. This involves the coordination of the pre-reformer/internal reformer distribution and the adjustment of the HEX-function of the inner MLC wall.
7. Outlook

This publication gives an insight view into a research and development area of cycle process fuel cell tuning and optimization. This area is currently in its infancy and is part of the TFC 1.0 development strategy.

As shown in chapter 5, the entire cycle is treated in a multidisciplinary way and the calculation programs are coordinated. At the moment, this design process is not yet completed. The SOFC stack calculation module is in development. First results of the thermal simulation part can already be shown.

In the first approach, the SOFC cell is assembled with different material in thin layers which have different mechanical and thermal properties. Therefore, the temperature distribution of the SOFC in cell level and also in stack level are essential for stack design and implementation in each system.

The prediction of temperature distribution of the SOFC relates to complicated mass and heat transport phenomena in the cell level, which can be done using FSI technique (Fluid–structure interaction). However, these methods are very complicated and time consuming and focused only on the cell level. To avoid the mechanical error due to thermal deformation, the simulation must cover the SOFC stack level. Therefore, a simplified FEM model of the thermal analysis stack has been developed specifically for this publication as an example. Parallel to this, various test stacks under charged conditions are examined in the MAXEFF test facility (Fig. 7). Thus, a wide model validation can take place. As a case example, a stack of multiple cells is replicated for a steady state thermal FEM analysis using ANSYS. The stack is placed in the middle of a chamber surrounded with air with the Temperature $T_{\text{Chamber}}$. The dimensionless temperatures are defined as follows.

$$\theta_i = \frac{T_i - T_{\text{Chamber}}}{T_{\text{Chamber}} - T_{\text{SOFC\,Inlet}}}$$  \hspace{1cm} (21)

On the cell level, heat transfer and heat generation is assumed, modelled in a similar way to a test stack (Fig. 7). Convective transfer in the channels of cathode and anode sides are modelled using the coefficients in previous chapters. Thermal-Fluid-Elements simulate the gas flow in the channel and they are coupled to the channel wall surface to provide the gas temperature for the convection calculation in the channel. Specific heat generation on the anode surfaces is defined using the simplification of chapter 6. All thermal contacts are initially considered as ideal and the gas manifolds are neglected for the sake of brevity.

The development of a detailed model of the fuel cell stack used is underway. Refinements in this simulation technique can be further improved with a feasible effort. Heat generation can be defined locally on the anode surface using external computation data. The thermal contact can be specified more precisely to enhance the simulation accuracy. Thermal radiation, which could have a significant impact,
can also be implemented. By using a thermal fluid element model, the design of the flow channel orientation and flow parameters can be optimized to reduce stack deformation. This will lead to the next steps to precisely optimize the heat balance of a direct reforming fuel cell.

8. Conclusion

In this paper, the dependencies for the realization of a future MGT-SOFC system were shown and possibilities for further performance enhancement are presented. For this increase in efficiency, the heat balancing is an important aspect. For a preliminary design, a careful heat balancing of the cycle must be made. This has already been shown in [1], [2], [20]. In this case, the heat balancing between the reforming outside and inside the SOFC-Stack plays a role. It could be shown that with a good tuning a significant increase in performance with the same turbo set is possible. In addition, the overall efficiency of the hybrid process increases. Since a good matching is only possible with a further heat balancing of the SOFC stack, this process was also shown. The heat conditions in the stack were explained and first calculation results were shown. Furthermore, it has been proven that the Nu-numbers for the small Re numbers within the stack can be clearly defined. This provides further confidence in modelling to optimize the heat-balancing situation. The research and development activities are part of the realization strategy of the energy converter of the future (the Turbo-Fuel-Cell 1.0) [1].

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