SIMULATIONS USING DIMENSIONLESS KEY FIGURES FOR THE DESIGN AND OPTIMIZATION OF COMPACT, HYBRID MGT-SOFC SYSTEMS OF THE "TURBO FUEL CELL" TYPE FOR HIGH EFFICIENCY

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ABSTRACT

The "Turbo Fuel Cell" represents a highly integrated and highly compact technology system of a micro gas turbine fuel cell cycle (MGT-SOFC). It provides the solution for a highly efficient reverse electricity generation with an electrical efficiency of at least 68% (status 2020-21) to approx. 75-80% (in the future). In the context of industrial research on such a hybrid process, there should be used adapted, dimensionless parameters in the design and optimization of the overall system. As an example, simulations of thermally optimized solutions to improve the energy yield using various dimensionless key figures are presented.

Above all, heat integration measures enable an increase in system efficiency and a reduction in primary energy input. On the basis of exergetic analyses by use of a modified Heat Balance Factor \( X \), as presented at ETC12, and the consideration of the SOFC enthalpy spread \( \delta \bar{H} \), as well as a highly integrative use of the High Temperature Heat Exchanger Function \( \varepsilon_{\text{min}} \), it is shown how the hybrid cycle process efficiency can be optimised through innovative coupling of the individual heat flows.

Measures to change the hybrid process can be used to deliberately shift the useful energy from the predominant heat yield to optimize electrical efficiency. A developed system enables primary energy to be used with the highest possible efficiency. The primary fuel used here is gaseous primary energy in the form of methane (natural gas) and hydrogen from renewable sources. Treatment mechanisms such as the reforming of the methane used and the targeted use of modern heat insulation and recovery mechanisms also have been considered. For the optimised hybrid system, total electrical efficiencies of more than 68% could be shown, and additional thermal energy for heating purposes could be extracted. Ultimately, overall efficiencies for the utilisation of the energy content of the primary energy of up to 97% can be achieved.

Energy converters with a maximum system output of around 200-300kW were examined. In the near future, such plants can replace existing fossil power plants being part of decentralized network systems. By their variability, they can guarantee the necessary security of power supply.

KEYWORDS

CHP MICROGASTURBINE, SOFC FUEL CELL, MGT-SOFC, TURBO MACHINERY, THERMODYNAMICS, TURBOFUELCELL

NOMENCLATURE

\( F \) Faraday constant
\( I \) current
\( \bar{\omega} \) heat ratio Anode to overall SOFC
\( \bar{M}_{F-\text{Steam}} \) fuel to synthesis gas ratio

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INTRODUCTION

The "turbo fuel cell" represents a highly integrated and highly compact technology system of a micro gas turbine fuel cell cycle (MGT-SOFC). It offers the solution for highly efficient combined
heat and power generation with an electrical efficiency of at least 68% (2020-21) to about 75-80% (in the future). Within the framework of industrial research on such a hybrid process, there should be used adapted, dimensionless parameters in the design and optimisation of the overall system. As an example, simulations of thermally optimised solutions for improving energy yield are presented using various dimensionless parameters [Berg 2017b, Berg 2020, Calisea 2006, Mueller 2008].

For the assessment of such conversions and measures for heat integration, key figures are suitable which evaluate the heat flows and classify the effort required to achieve the optimum energy flow. Furthermore, the dimensioning of the modules to be interconnected to form an overall system is to be simplified with the support of such figures. With such methods, hybrid systems consisting of SOFC high-temperature fuel cells and micro gas turbines, for example, can be freely scaled and adapted to the respective process requirements. It is also conceivable to use and integrate external process heat, which can specifically support conversion processes in the system. Pinch analyses can be improved and optimised for optimum heat integration using suitable key figures.

In this context, the "Turbo-FuelCell 1.0" is currently being developed at BTU Cottbus-Senftenberg, LS VFA [Berg 2020]. It is a hybrid, highly integrated and highly compact energy converter consisting of a micro gas turbine and fuel cells (MGT-SOFC). The aim of the energy conversion is the optimal utilisation of the primary energy input for the generation of electrical energy. For example, gas systems generated from renewable energies are to be used for electricity generation with a high electrical efficiency.

Within the framework of university and industrial research into such a hybrid process, adapted, dimensionless parameters are used in the design and optimisation of the overall system and are used for the dimensioning of sub-modules. This includes in particular the analysis of the heat released in the fuel cell in relation to the heat required to achieve the process conditions.

Measures for heat integration, which result in an increase in system efficiency and a reduction in the use of primary energy, are discussed with dimensionless parameter approaches and corresponding module solutions are discussed. An example based on exergetic analyses using a modified heat balance factor, as presented at ETC12 [Berg 2017], shows how such a parameter can be used. Under the consideration of the SOFC enthalpy spread as well as a highly integrative use of the high-temperature heat exchanger function, it is shown how the process efficiency of the hybrid circuit can be optimised by innovative coupling of the individual heat flows.

**THERMODYNAMIC ASPECTS**

The efficiency of the overall process of an MGT SOFC system is increased to a value which is significantly higher than the efficiency value of the individual systems by integrating the efficiency of an SOFC high-temperature fuel cell into an MGT system. Such a design enables efficiencies that are in the maximum range of what is physically possible. For example, the pilot plant planned in Cottbus should already be able to achieve an electrical efficiency of 65% over a period of 25000h. [Berg 2017a, Berg 2017b, Berg 2015]

The electrochemical conversion of the chemical into electrical energy takes place via the fuel cell module with the maximum usable potential of exergy. This manifests itself, among other things, in the maximum process temperature permitted for the fuel cell type at the outlet of the fuel cell cluster. The exergy potential that cannot be converted by the fuel cell (resulting from the heat effect at high temperature and the unconverted fuel) is used to generate mechanical work by embedding the high temperature cell with subsequent post-oxidation (in an afterburning process) of the unconverted fuel in an MGT process.

The combustion chamber of a recuperated MGT is effectively replaced by a highly integrated system consisting of SOFC fuel cell module, afterburner, reforming reactor design and high temperature heat exchanger as shown by Figure 1. Furthermore, this system is housed in a pressure...
vessel, the contents of which are charged according to the pressure ratio of the MGT's compressor. This is best possible thermally insulated to the outside by a stratification of the flow guidance corresponding to a rising process temperature. To simplify the pressure vessel construction, it is equipped with a water jacket which limits the temperature of the pressure-loaded outer shell to 80°C.

**Description of the hybrid process**

As shown in Figure 1 the process air is first sucked into the plant system by the compressor. The air compressed to the pressure ratio continues to flow through a recuperator, which preheats the compressed air with heat from the exhaust gas. The compressed air is then heated to the SOFC stack inlet temperature by a high temperature heat exchanger. In the case of the Fraunhofer IKTS Dresden SOFC stacks [Fraunhofer 2020] used in the projected plant, a temperature of 700°C has been determined as the optimum inlet temperature for this purpose. The high-temperature heat exchange is necessary because the exhaust gas heat at the turbine outlet is not enough at most operating points to preheat the air in the recuperator up to the operating temperature of the high-temperature fuel cells.

![Figure 1: Schematic SOFC-MGT-Process TurboFuelCell 1.0 – T-Cell](image-url)

The fresh air flows to the cathode inlet side of the SOFC fuel cells, as shown in Figure 2. In addition, the pressurised synthesis gas, to which natural gas has been added, is introduced on the anode side. The conversion reaction now takes place in the SOFC cells. The chemical energy of the fuel is converted directly into electricity by electrochemical processes ("cold combustion"). For this purpose, such fuel cells use hydrogen and carbon monoxide as fuel, which is supplied either directly or as a fossil precursor. For oxidant, the cell uses the oxygen of the cathode supply air, which flows to a solid oxide membrane side. At high temperatures, this oxygen can diffuse through the membrane ionised as O\(^2^-\). On the anode side, these ions then react with the hydrogen and carbon monoxide, releasing electrons and heat to form water. The migration of electrons can be used as electric current via the connected electrodes [Kurzweil 2016].
Anode: \[ 2H_2 + 2O^2\ominus \rightleftharpoons 2H_2O(g) + 4e^\ominus \] \[ (CO + O^2\ominus \rightleftharpoons CO_2 + 2e^\ominus) \quad E_0 = 0\ V \]

Cathode: \[ O_2 + 4e^\ominus \rightleftharpoons 2 O^2\ominus \quad E_0 = 1.23\ V \]

\[ 2H_2 + O_2 \rightleftharpoons 2H_2O \]

Figure 2: Operating principle of a solid oxide fuel cell

Since enthalpy of the reaction of \( \Delta G_0 = 237,13\, \text{kJ/mol} \) and an enthalpy under standard conditions of \( \Delta H = 285,83\, \text{kJ/mol} \) can be determined for the free Gibbs reaction, a theoretical efficiency can be calculated as follows

\[ \eta_{SOFC}^{rev} = \frac{\Delta G_0}{\Delta H} = \frac{237,13\, \text{kJ/mol}}{285,83\, \text{kJ/mol}} = 82.96\% \] (1)

In a real SOFC, an efficiency of 50% can be realised. As an additional anode reaction, the oxidation of carbon monoxide to carbon dioxide takes place. Electrons are also released during this reaction and can be dissipated as voltage and fed to the cathode.

\[ \text{Anode 2:} \quad CO + O^2\ominus \rightarrow CO_2 + 2e^- \] (2)

A part of this energy released by the reaction can be dissipated and used as electrical energy. In addition, when an additional CH\(_4\) current is reformed internally, further heat released is now used to implement the reformation reaction. In this way, more energy can be converted overall, and the efficiency of the cell system can be increased. This reaction receives an additional boost from the higher operating pressure in the system. After leaving the system, the temperature of the cathode exhaust air stream and the anode residual gas stream has risen to the cell boundary temperature of, in this case, 830°C. This enthalpy flow is now used in the high temperature heat exchanger to preheat the cathode supply air to fuel cell inlet temperature. Subsequently, anode exhaust air and cathode exhaust air with a residual content of combustible H\(_2\) and CO are conducted to the afterburner where they are completely converted with further release of heat [Hau 2008, Heddrich 2012].

The heat is partly used in the integrated reformer system for partial reformation of the CH\(_4\) fuel gas flow. In the process, CH\(_4\) is converted into synthesis gas (3H\(_2\) + CO). SOFC fuel cells have the advantage that they can also convert CO by emitting electrons and use it as fuel. The steam reforming used is carried out with heat input and the addition of steam with an S/C ratio (steam/carbon) under an endothermic reaction according to the following equation:

\[ \text{Reformer:} \quad CH_4 + H_2O \rightleftharpoons CO + 3H_2 \quad \Delta H_{Ref} = + 206.2\, \text{kJ/mol} \] (3)

A large part of the carbon monoxide reacts further in an exothermic reaction in the so-called shift reaction to form carbon dioxide.
Shift-Reaction: 

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \Delta H_{\text{Shift}} = -41.2 \text{kJ/mol}$$ (4)

The last shown reaction should be reduced if possible, by specifying appropriate reaction conditions so that the associated energy loss can also be used in the SOFC. However, it cannot be completely avoided.

The complete reacted exhaust gas flow is conducted to the micro gas turbine and used there to generate mechanical energy. This is used to drive the compressor and for supplementary power generation. The expanded exhaust gas flow is further conducted to the recuperator where it gives off its heat to the fresh air flow. Subsequently, residual heat is used to evaporate the ultrapure water required for the CH$_4$ reformation. Figure 1 shows the plant diagram of the MGT-SOFC process with an el. efficiency of at least 65%. The main losses are caused by the incomplete conversion of the fuel in the fuel cell, heat losses due to the outflow of the hot exhaust gas and internal voltage losses due to the incomplete electrocatalysis, electrolyte and cell structure. In the projected hybrid system, the SOFC fuel cell contributes about 87% of the electrical energy yield, while the microturbine contributes the remaining 13%. It must be pointed out, that this efficiency is reduced by degradation of the SOFC cell stacks in continuous operation. The planned TurboFuelCell 1.0 system (see Figure 3) is designed to ensure an electrical efficiency of 65% under full load at an output of 270kW over an operating time of 25000h [Berg 2017b, Berg 2020].

Component systems are currently being further developed from known technologies for such a system, so that from 2023 a corresponding prototype can be built up which can represent the specified performance. Figure 3 shows the construction of such a prototype, which can electrically supply a total output of up to 270 kW with planar SOFC cells and can flexibly represent partial loads of down to 10 % of the total output at high load change rates. The ratio of the electrical output between the fuel cell stack and the micro gas turbine generator is 5.5:1. It should be moved towards the fuel cell stack, as this has a higher inherent efficiency than the micro gas turbine. This ultimately results in a higher system efficiency. However, it must be ensured that the MGT supplies enough process air at the optimum pressure level.

Regarding the real efficiency of the hybrid system, $\eta_{\text{MGT-SOFC}}^{\text{real}}$ it must be pointed out, that beside the thermodynamic efficiency $\eta_{\text{SOFC}}^{\text{real}}$ of the SOFC part the efficiency of the MGT $\eta_{\text{MGT}}^{\text{real}}$ and the global system $\eta_{\text{Sys}}$ has to be taken into account [Berg 2017a].

$$\eta_{\text{MGT-SOFC}}^{\text{real}} = \left( \eta_{\text{MGT}}^{\text{real}} + \eta_{\text{SOFC}}^{\text{rev}} \cdot \eta_U \cdot \eta_I \cdot \eta_C \cdot (1 - \eta_{\text{MGT}}^{\text{real}}) \right) \cdot \eta_{\text{Sys}}$$ (5)

The other relevant efficiencies are the voltage efficiency ($\eta_U$) is used to represent the internal losses due to electrocatalysis, electrolyte and cell structure. This can be calculated via the ratio of terminal voltage to open-circuit voltage [Kurzweil 2016]:

$$\eta_U = \frac{U_{\text{cell}}}{E_0}$$ (6)

With the relation between the theoretically possible current to the actual current efficiency, there is the current efficiency $\eta_I$ [Kurzweil 2016]:

$$\eta_I = \frac{I}{I_{\text{theo}}} = \frac{I}{z \cdot F \cdot \dot{n}_{\text{Sym.Gas}}}$$ (7)

The fuel conversion efficiency $\eta_C$ is finally needed. This indicates how high the amount of hydrogen used in electricity generation is compared to the amount of synthesis gas supplied and is expressed as the ratio of the hydrogen used to the hydrogen supplied [Kurzweil 2016]:

$$\eta_C = \frac{U_F}{\dot{n}_{\text{Fuel,used}}} = \frac{\dot{n}_{\text{Fuel,used}}}{\dot{n}_{\text{Fuel,in}}}$$ (8)
The following study keeps care for the optimisation of the thermodynamic efficiency $\eta_{SOFC}^{\text{real}}$ of the SOFC part in combination with the high temperature heat exchanger of the hybrid machine.

**Heat analysis for the high temperature heat exchange**

The thermal cycle of the MGT-SOFC process based on the TFC design concept is shown schematically by Figure 1. The basic principle is sufficiently known from the literature and has already been described in numerous publications [Berg 2017a, Berg 2017b, Berg 2018]. A brief description of the thermodynamic modelling of the MLC (multi-layer containment for a thermal heat loss recuperation and the interconnection of the thermal components, see figure 3) is given below. 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

$$\Delta Q_{\text{Input}} = \Delta^R Q + \Delta'^I Q + \Delta^F Q - \Delta Q_{\text{Reformer}}$$

(9)

to complete the MGT-cycle.

$$X = \frac{\Delta Q_{\text{HeatEx}}}{\Delta Q_{\text{Input}}}$$

(10)

The importance of the X-value could be shown in earlier publications [Berg 2017a]. However, in these publications the X-value was formed at a constant SOFC temperature. By the present model, an extension to the real situation is shown (temperature increase by the SOFC stack). The X-value is very important for assessing the cost of the high-temperature heat exchanger.

With an X-value of zero, no additional high-temperature heat exchanger is required. For TFC designs with an uncooled turbine, the X-value was described in [Berg 2017a]. To be able to make a more precise assessment for engineering practice, the enthalpy spread (or temperature spread) via the SOFC should be included in the consideration. This is important because the amount of heat generated in the $\Delta Q_{SOFC-I-O}$ represents a large proportion. The balance equation known from [Berg 2017a] has therefore been extended:

$$\Delta Q_{\text{Input}} = \Delta Q_{\text{HeatEx}} + \Delta Q_{SOFC-I-O} + \Delta Q_{\text{HEX\rightarrow Turbine}}$$

(11)

In this Equation $\Delta Q_{\text{Input}}$ is the heat, which is necessary to close the cycle. $\Delta Q_{\text{HeatEx}}$ is the amount of heat, which increases the temperature of the air from the recuperator in the HEX to the fuel cell input temperature. $\Delta Q_{\text{SOFC-I-O}}$ is the additional heat coming from the fuel cell conversion and $\Delta Q_{\text{HEX\rightarrow Turbine}}$ an additional heat to reach turbine inlet temperatur in the afterburner. The respective heat quantity and heat output are defined as follows:

$$\Delta Q_i = m_i \cdot \Delta q_i$$

(12)

In practice, it is very likely that the amount of heat generated by the SOFC $\Delta Q_{SOFC-I-O}$ is higher than the required amount of heat $\Delta Q_{\text{HeatEx}}$. The internal reformation in the SOFC stack is below a reformation ratio of 62%, otherwise the carbon formation limit may be exceeded, due to the reformer heat no longer being sufficient for this purpose. Here, the reformation ratio is described by a heat ratio

$$\Gamma = \frac{\Delta Q_{\text{SOFC\rightarrow Reformer}}}{\Delta Q_{\text{AB\rightarrow Reformer}} + \Delta Q_{\text{SOFC\rightarrow Reformer}}}$$

(13)

Theoretically, the reforming ratio for the evaluation of the internal reformation can be increased until the amount of heat generated in the SOFC and the temperature spread becomes zero. But if all the heat is used for internal reformation, a high-temperature heat exchange is then no longer possible.
only through the inner MLC wall (Figure 4, Type 1) which is used as a high temperature heat exchanger HEX. The different possibilities of high-temperature heat exchange are shown in Figure 4.

**Figure 4: possibilities of high-temperature heat exchange**

Type 1 = the MLC inner wall is the high-temperature heat exchanger HEX
Type 2 = the high-temperature heat exchanger is located on the MLC wall and in the afterburner reformer
Type 3 = the high-temperature heat exchanger is integrated in the afterburner reformer or is located behind it

If the same SOFC mean temperature is used for all machine sizes, the following statement can be made: The size increases from Type 1 to Type 3. Type 1 is the most compact one, because the heat exchange at the inner MLC is very well possible with high temperature spread and the construction costs of the afterburner reformer are lowest due to the high temperature spread. A reduction of the temperature spread by increasing the reforming degree ratio reduces the size of the afterburner-reformer disproportionately less, so that this statement is generally true.

In this publication the thermodynamic model is described for Type 1 only. It is the basis for the Turbo Fuel Cell 1.0 machine. The reforming ratio for this type of machine is in the range of up to approx. 62%. An increase of the ratio leads to a further increase in efficiency of the overall process. However, this will only be possible with the realisation of the next SOFC stack generation.

For the Type 1 design, the relative enthalpy spread as a thermal load index is defined as follows:

\[
\tilde{S}H = \frac{\Delta Q_{SOFC-1-o}}{\Delta h_F \cdot m_F \cdot (1 - \eta_{SOFC}^{real})} = \frac{\Delta Q_{SOFC-1-o}}{\Delta Q_{Input}}
\]

\[
\begin{align*}
\tilde{S}H &= \frac{\Delta Q_{SOFC-1-o}}{\Delta h_{SYN \ GAS} \cdot m_{SYN \ GAS} \cdot (1 - \eta_{SOFC}^{real})} \\
\end{align*}
\]

Hereby, the enthalpies of formation of the fuel and the synthesis gas are in the following relation to the efficiencies:

\[
\tilde{M}_{F-\text{Steam}} = \frac{\dot{m}_F}{\dot{m}_F + \dot{m}_{\text{Steam}}} = \frac{\dot{m}_F}{\dot{m}_{\text{SYN GAS}}}
\]

\[
\tilde{H} = \frac{\Delta R_{\text{SYN GAS}}}{\Delta R_F}
\]

\[
\tilde{H} = \frac{\eta_{SOFC}^{real}}{\eta_{SOFC}^{real}} = \bar{\Theta}
\]
The efficiency $\eta_{\text{SOFC}}$ here is the ratio of the electrical work produced by the SOFC in relation to the enthalpy of formation of the fuel. Meanwhile, the efficiency $\hat{\eta}_{\text{SOFC}}$ is the ratio of the electrical work produced by the SOFC in relation to the enthalpy of formation of the synthesis gas. For the efficiency $\hat{\eta}_{\text{SOFC}}$ there applies:

$$\hat{\eta}_{\text{SOFC}} = \hat{\eta}_{\text{rev}} \cdot \hat{\eta}_{\text{i}} \cdot U_F = \frac{\Delta R G}{\Delta R_{\text{SYN GAS}}} \cdot \hat{\eta}_{\text{i}} \cdot U_F \quad (18)$$

Here $\hat{\eta}_{\text{i}}$ is the internal efficiency and $U_F$ the fuel conversion efficiency of the SOFC stack. $\Delta R G$ is the Gibbs enthalpy of the synthesis gas. The heat energy generated in the SOFC stack is the balance of the heat produced minus the heat for internal reformation. It can be described as follows:

$$\Delta Q_{\text{SOFC-1-o}} = \Delta R_{\text{SYN GAS}} \cdot (1 - \hat{\eta}_{\text{SOFC}}) - \Delta Q_{\text{AB-Reformer}} = \Delta H \cdot \Delta Q_{\text{Input}} \quad (19)$$

Here $T_{\text{FCM}}$ is the thermodynamic middle temperature of the SOFC fuel cell, $\Delta s$ is the entropy increase over the SOFC stack and $\Delta T_{\text{SOFC}}$ is the temperature spread. With

$$T_{\text{FCM}} \cdot \Delta s \approx c_{\text{pm}} \cdot \Delta T_{\text{SOFC}} \quad (20)$$

and the increase in entropy under approximate isobaric conditions (pressure loss negligible)

$$\Delta s = (s_{\text{SOFC-out}} - s_{\text{SOFC-in}}) = c_{\text{pm}} \ln \frac{T_{\text{SOFC-out}}}{T_{\text{SOFC-in}}} - R_m \ln \left( \frac{p_{\text{SOFC-in}}}{p_{\text{SOFC-in}}} \right) \quad (21)$$

is obtained for the thermodynamic middle temperature

$$T_{\text{FCM}} \approx \frac{T_{\text{SOFC-out}} - T_{\text{SOFC-in}}}{\ln \frac{T_{\text{SOFC-out}}}{T_{\text{SOFC-in}}} \quad (22)}$$

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**Figure 5: Visualisation of the heat conditions in the TS diagram [Cerbe 2017], [Berg 2020]**

Here the heat energies of a Type 1 machine as shown in figure 1 are represented by the following areas:

a) Area 1-6-f-a = $\Delta Q_{\text{Input}}$

b) Area 1-2-b-a = $\Delta Q_{\text{HeatEx}}$

c) Area 2-4-d-b = $\Delta Q_{\text{SOFC-1-o}} = \Delta R Q + \Delta' Q - \Delta Q_{\text{AB-Reformer}}$

d) Area 5-6-f-e = $\Delta F Q - \Delta Q_{\text{AB-Reformer}}$
and for the relative temperature spread across the SOFC stack
\[
\Delta \tau = \frac{\Delta T_{SOFC}}{T_{FCM}} = \ln \frac{T_{SOFC-OUT}}{T_{SOFC-IN}} = \ln \frac{T^*_4}{T_{T3}}
\]  

(23)

With \(T_{T3}\) and \(T^*_4\) as temperatures shown in the thermodynamic Ts-Diagram in figure 5. The temperatures are always to be regarded as total temperatures, which would result from a mixture calculation of the energies in anode and cathode fluid streams. A heat exchanger characteristic describes the amount of heat required to heat up the cathode supply air. Hereby, the level of the total temperature \(T^*_4\) at the exit of the SOFC stack, the exit temperature of the recuperation \(T_R\) and the entry temperature \(T^*_3\) into the SOFC is the main driver. The quality of the required heat exchange is described by the heat exchanger characteristics. The heat quantities can be visualised in good approximation by the areas in the TS-diagram (see Figure 5).

The right part of Figure 5 shows the condition in a heat exchanger along the heat exchange area. A counter current heat exchanger is shown here for example. If the heat exchange curves lay on top of each other, a relative temperature spread of zero could be realised with a Type 1 machine in borderline cases. In practice, however, this is not possible. For evaluation purposes, the heat exchanger characteristics are therefore described as follows:

\[
\epsilon_{\text{min}} = \frac{\Delta Q_{\text{HeatEx}}}{\Delta Q_{\text{HeatEx}} + \Delta Q_{SOFC-1-0}} \leq 1
\]  

(24)

\[
\epsilon_{\text{min}}' = \frac{\Delta Q_{\text{HeatEx}}}{\Delta Q_{\text{HeatEx}} + \Delta Q_{SOFC-1-0} (1 - \tilde{\omega})} \leq 1
\]  

(25)

\[
\tilde{\omega} = \frac{\Delta Q_{\text{Anode}}}{\Delta Q_{SOFC-1-0}}
\]  

(26)

\(\epsilon_{\text{min}}'\) is a correction of the value \(\epsilon_{\text{min}}\) by the dissipated anode heat, which cannot be available for high-temperature heat exchange for technical reasons. The value is determined from the process conditions for a Type 1 machine and represents the minimum required value. The more heat energy is now removed by the internal reformation, the better the heat exchanger must be, as the temperature spread becomes smaller. In the limiting case with a temperature spread of zero the value tends towards 1. In typical technical systems, \(\tilde{\omega}\) lies in a range from 0.21 to 0.54, because of the higher amount of steam in the anode flow. For the known X - ratio the detailed result is

\[
X = \frac{\Delta Q_{\text{HeatEx}}}{\Delta Q_{\text{Input}}}
\]  

(27)

\[
= \frac{\epsilon_{\text{min}}' (\Delta Q_{\text{HeatEx}} + \Delta Q_{SOFC-1-0})}{\Delta R_H^{\text{Fuel}} (1 - \bar{n}_{\text{SOFC}}) + \Delta H_{\text{H}_2O,\text{Reformer}} + \Delta Q_{\text{Heating}} + \Delta Q_{\text{Ext.Ref.}}}
\]  

and under the condition of 100% burnout in the afterburner reformer with

\[
\Delta Q_{\text{HeatEx}} + \Delta Q_{SOFC-1-0} = \Delta Q_{\text{HeatEx}} + \Delta R_H^{\text{SYN GAS}} (1 - \bar{n}_{\text{SOFC}}) - \Delta R_H^{\text{Anode Out}}
\]  

(28)

**RESULTS**

The simulations to determine and analyse the key figures were created with EBSILON Professional [STEAG 2018]. As a key parameter the degree of internal reformation was varied. It should be noted that with a mole fraction of less than 10%, more energy must be introduced into the pre-reforming. The process temperature is increased, and the inlet gas must be cooled to keep the normalised inlet temperature in the stack in the optimum range. The X-factor decreases in this case because more energy is exchanged in the high temperature heat exchange, because more water is
carried in the system due to the higher external reforming and more energy is required for the reformer. This is shown by the increased factor, the heating value ratio of the anode air to the heating value of the reformer gas. The same applies to $\tilde{\mathcal{H}}$, the heating value ratio of the synthesis gas to the heating value of the fuel introduced.

Figure 6: a) X-Factor depending on CH4-Mole-Fraction at entrance SOFC-Stack, b) $\tilde{\mathcal{H}}$ Heat-Value-Ratio Reformer gas to original Fuel gas

The left diagram (a) of Figure 6 shows the X-factor for estimating the heat requirement for high-temperature heat exchange. It becomes clear that a higher proportion of internal reformation requires less heat to be transferred. But also, less exhaust gas heat is available for the heating of the inflows. The X-factor also shows the amount of effort required to dimension the high-temperature heat exchanger. Based on the experience of this assembly, it can be estimated there which size should be chosen for a combined system. The diagram also shows that with increased heat input in the reformer, the heat output will drop again, because more heat must be supplied in the external reformer. An optimum must be found, because with the current technology carbon formation can be expected from a mole fraction of about 38% CH$_4$ in the stack supply the needed reformer heat decreases the temperature in the cell under the limit of carbon formation.

Figure 7: a) $\bar{\omega}$ shows the CH$_4$-amount for intern reforming, b) $\varepsilon_{\text{min}}$ and $\varepsilon'_{\text{min}}$ correlated to the mole fraction CH$_4$ of the mass flow inflated into the stack

$\bar{\omega}$ (Equation 20/Figure 7a) shows the heat that is transferred from the heat emitted by a stack to the anode off-gas and is no longer available for high temperature heat exchange. Again, the marking shows how the adaptation of the simulation for lower mole fractions, which was carried out to maintain the process temperatures of the stack systems, changes the dependency. The proportion of heat dissipated via the anode current decreases. With a high proportion of internal reforming, on the other hand, these proportion increases, which means that although relatively less heat is available for the high-temperature heat exchange, no statement can be made as to how much is actually available.

$\varepsilon_{\text{min}}$ and $\varepsilon'_{\text{min}}$ (Figure 7b) show which heat is actually exchanged in the high temperature heat exchanger. $\varepsilon_{\text{min}}$ (equation 19) indicates how much energy can be exchanged in relation to the total
amount of heat emitted by the SOFC fuel cell (T₁ to T₄*). This value remains at a constant level in the relevant concentration range and shows that sufficient heat is always available in the process at hand. \( \varepsilon'_{\text{min}} \) (equation 20) shows the ratio of the high-temperature heat exchange compared to the heat released by the SOFC fuel cell without the anode current. The higher the value, the more efficient this heat exchange should be, but it also shows that even with high internal reformation there is always sufficient energy available for the heat exchange. A maximum value of up to \( \hat{\eta}_{\text{SOFC}}^{\text{real}} = 70\% \) can be expected. This results in an el. efficiency for the 270kW MGT-SOFC-System with an pressure ratio of 4.8 and a turbine inlet temperature of 850°C (\( \eta_{\text{is,turbine}} = 80\% \)) of approximately \( \eta_{\text{MGT-SOFC}}^{\text{real}} = 80\% \) can be reached.

Furthermore, this value shows that the projected outlet temperature of 830°C is necessary for an exchange, that lower outlet temperatures would supply too little heat for the high-temperature heat exchange. The difference between \( \varepsilon_{\text{min}} \) and \( \varepsilon'_{\text{min}} \) shows the importance of the temperature spread across the SOFC fuel cell, which only allows suitable high-temperature heat exchange in the hybrid system if it is sufficiently large in the range of 50K to 130K.

**Figure 8:** a) \( \hat{\eta}_{\text{SOFC}}^{\text{real}} \) of the system with increasing internal reforming, b) \( H_u \) of the exhaust anode gas at the outlet of the SOFC fuel cell stack.

Figure 8a shows the increase in efficiency of the SOFC fuel cell with the increase in internal reformation. This is mainly explained by the increase in fuel conversion (\( U_F \)). It is increased, more heat is produced in the stack. The aim is to keep the temperature as constant as possible and to ensure a quasi-isothermal heat dissipation in the stack. A better power yield is achieved, which starts approximately against a limit value of 70%, whereby the overall efficiency of the system is thus limited to a maximum of 80%. Further increases are no longer possible with conventional methods.

Figure 8b ultimately shows the development of the calorific value \( H_u \) in the exhaust gas with increasing internal reformation. A high proportion shows that more and more energy is converted in the fuel cell, but even with complete internal reforming, which cannot be carried out with conventional SOFC cells due to the risk of coking and lack of process heat, residual energy cannot be converted in the cell.

**CONCLUSIONS**

This study shows that the revised X-factor in particular offers a possibility to evaluate the high temperature heat exchange in the hybrid systems investigated. The X-factor helps to evaluate the fraction of used heat compared to the available heat. It indicates that a high-temperature heat exchanger is only necessary if a minimum heat supply through the fuel cell outlet flow is possible. This is the case when the heat generated in the fuel cell is not completely used for internal reforming. It can thus show the limits of internal reformation. The X-factor takes into account the temperature spread via the fuel cell, the heat above the temperature level of the external reformer and the turbine inlet temperature can be used and kept in the process. It shows the proportion of the calorific value
of the fuel gas that can be used in the high-temperature heat exchanger and retained in the process. It also indicates how much of the available waste heat is used. By using this factor, it can be shown that the MGT-SOFC combination by existing technologies with their aim of high-energy conversion has a high potential for heat recovery measures. In particular, this can compensate for disadvantages of the individual systems of a hybrid process. Above all, the microturbine SOFC systems presented here are particularly well suited for this purpose and, thanks to their excellent integration capability and system efficiency, offer great potential for reducing the use of primary energy.

It has been shown that the introduced heat ratio $X$ (within the limits of $0.25 \leq X \leq 0.33$ for this machine configuration), modified to the temperature increase in the stack gas flow, is a very good tool for the optimization of MGT-SOFC hybrid configurations. Compared to the publication [Berg 2017], the X-value is lower because there the consideration was carried out with a temperature spread of zero and also a very high operating temperature of the fuel cell. Here, the factor definition has been expanded to include the actual temperature spread along the SOFC fuel cell reaction. The influence of important system parameters such as the recuperator outlet temperature, the SOFC operating temperature, the turbine inlet temperature and the pressure ratio of the MGT-SOFC process are taken into account with their heat input in this dimensionless parameter.

By the knowledge of the X-factor a design of the system for high temperature heat exchange can be simplified and together with the knowledge of the usable heat exchanger technology a size estimation can be made. Further presented key figures illustrate the increase in efficiency of the implemented measures and show how such a coupled system can contribute to an increase in efficiency in electricity generation. Especially $\varepsilon_{min}$ und $\varepsilon'_{min}$ offer possibilities to evaluate the amount of heat available in the system. This makes it possible to assess whether the heat is sufficient for high-temperature heat exchange. Furthermore, it can be determined which influence the efficiency of the selected heat exchanger system has on the overall system. It became clear by the analysis that in the case of the machine under consideration, a heat exchanger having a lower degree of heat exchange can be used.

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