MICRO TURBO-FUEL-CELL-TECHNOLOGY

Hybrid compact turbo machinery technology and thermodynamic aspects regarding design parameters of a high efficient MGT-SOFC-system

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ABSTRACT

The improvement of decentralised energy supply systems has received an important role in the recent years. One option is the combination of SOFC with recuperated MGT. Here, a new strategy for selecting the system parameters, such as the operating temperature of the SOFC, turbine inlet temperature and the pressure ratio of the hybrid system, is presented. By introducing the heat ratio between the heat required to increase the process gas to the SOFC operating temperature and the heat required to raise the SOCF exhaust gas to the TIT, it was found that high efficiency (approx. 68%) is realisable in a compact hybrid system today. Analysis also shows that the HEX-technology is needed to improve the system effectiveness. Also, high recirculation rates with lower TIT can be considered as the future development direction. In addition, a sample configuration of an oil-free MGT rotor unit with high speed foil bearings is presented.

KEYWORDS

TURBO MACHINERY, SOFC, THERMODYNAMIC, CHP, FOIL BEARINGS

NOMENCLATURE

I	current	G	generator
P	power	HeatEx	heat exchanger
Q	heat	I	current
T	temperature	Sys	system
U	voltage	U	voltage
X	heat ratio	conv	converted
c	specific heat capacity	el	electric
e	elementary charge	g	gaseous
h	specific enthalpy	in	inlet
k	quality	max	maximum
n	polytrophic exponent	min	minimum
p	pressure	out	outlet
s	second	p	isobaric
s	specific entropy	real	real process

Φ	replacement function
γ	adiabatic exponent
η	efficiency
θ	temperature ratio
ξ	exergetic efficiency
π	pressure ratio
$\Delta^R G$	Gibbs potential
$\Delta^R H$	formation enthalpy
$\Delta^R S$	formation entropy
Indices	
After-B	afterburner
C	conversion
F	fuel

rev	reversible
th	theoretically
tot	total
ε	recuperator
Acronyms	
AFC	Alkaline Fuel cell
CHP	combined heat and power (plant)
HEX	high temperature heat exchanger
MCFC	molten carbonate fuel cells
MGT	micro gas turbine
PEFC	polymer electrolyte fuel cell
SOFC	solid oxide fuel cell
TIT	turbine inlet temperature

INTRODUCTION

Stationary gas turbines with a capacity up to 250 kW_{el} are called micro turbines. These possess radial compressors and turbines as well as recuperators to increase efficiency (Wiedermann, 2010). Due to their operating mode, micro turbines provide a comparatively large amount of thermal energy at high temperatures. This circumstance and the fact that CHP are normally operated heat out, are limiting the economically feasible application field of small micro turbines to industrial or (Business) district areas (Klausmann, 2000).

In contrast to micro-gas turbines, fuel cells do not burn fuel with a flame phenomenon. The fuel is converted into electricity through electrochemical processes directly without going through heat. The development of fuel cells dates back to the 19th century. Meanwhile, there are many different types of fuel cells. These are fundamentally divided into two types; the low temperature fuel cells (e.g. AFC, PEFC) and the high temperature fuel cells (e.g. MCFC, SOFC) (Kurzweil, 2013).

Like micro turbines, solid oxide fuel cells (SOFC) also operate at high temperatures ($T \geq 700°C$). Oxygen ion-conducting ceramics of yttrium-stabilised zirconium oxide ($ZrO_2 + Y_2O_3$) are used as electrolyte in these high temperature fuel cells. However, fuel cells are not thermal machines, unlike micro turbines. They operate on the galvanic principle, which is based on a spatially separated redox reaction. At the cathode, oxygen is reduced to O^{2-}. These oxygen ions diffuse through the ceramic to the anode and oxidise there with the fuel. Unlike other fuel cell types, carbon monoxide and hydrocarbons can be used in addition to hydrogen, directly as a fuel in SOFC, by means of internal reforming at high temperatures. Hereinafter, the reaction equations and the functionality of SOFC are shown again (Kurzweil, 2013; Singhal, 2013).

Anode: $$2\,H_2 + 2\,O^{2\ominus} \rightleftharpoons 2\,H_2O(g) + 4\,e^{\ominus}$$
$$\left(CO + O^{2\ominus} \rightleftharpoons CO_2 + 2\,e^{\ominus}\right)$$

Cathode: $$O_2 + 4\,e^{\ominus} \rightleftharpoons 2\,O^{2\ominus}$$

$$2\,H_2 + O_2 \rightleftharpoons 2\,H_2O$$

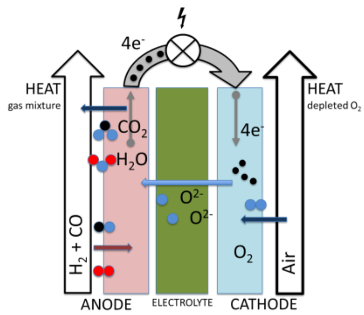

Figure 1: Operating principle of a solid oxide fuel cell

SOFC are available in two different designs, which have mutually different advantages and disadvantages. The specific differences of the tubular and planar structure are adequately described in the literature and are not considered at this point (Sammes, et al., 2005; Stiller, et al., 2005; Singhal, 2013; Zhou, et al., 2008). The present work is based on the combination of small MGT and planar SOFC.

However, it is to be noted that not all of the supplied fuel is converted. The height of the degree of conversion depends on operating parameters (such as temperature and pressure) and of the fuel cells itself. It is clear, therefore, that on the exhaust side of the fuel cell next to $H_2O_{(g)}$ and CO_2 unused fuel is also present. This unused fuel has to be be utilised further, to obtain maximum efficiency (Zhu, 2006; Hau Y., 2008; Berg & Krienke, 2015; Gandiglio, 2013).

Because micro gas turbines (MGT) and SOFC are operating in a similar temperature range and the pressure-charging of high-temperature fuel cells have a positive impact on the SOFC-effectiveness, the combination of micro gas turbines and SOFC offers to obtain the highest possible efficiencies (Berg & Krienke, 2015; Gandiglio, 2013). Therefore, it is appropriate to combine a micro gas turbine and a SOFC in scheme as shown in Figure 2 and in several studies since the early 1990s (Kurzweil, 2013).

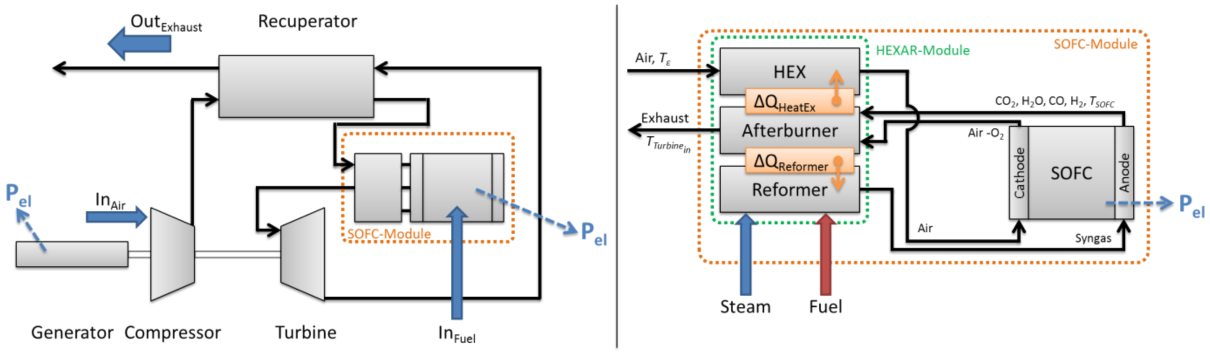

Figure 2: Scheme of MGT-SOFC hybrid system (reforming and water-steam cycle not shown) [left] and Scheme of the SOFC-module with reformer, afterburner and HEX (without the overlaid water-steam cycle) [right]

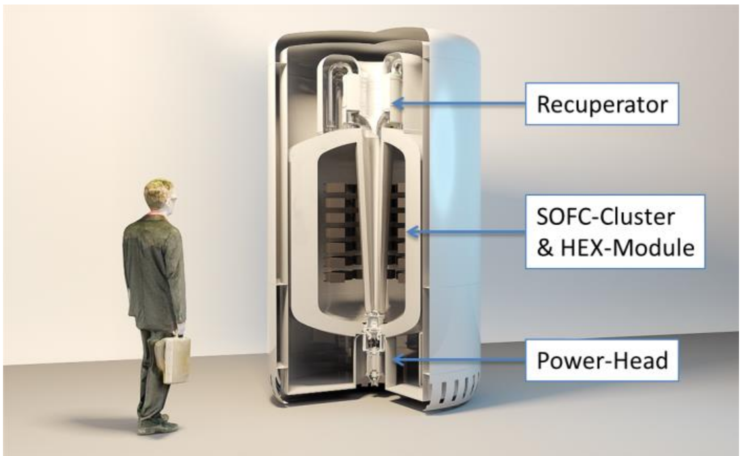

Figure 3: Model of a future technical realisation (270 kW$_{el}$)

Due to the integration of fuel cells in micro turbine systems, there are various requirements for MGT as a result to the requirements of SOFC. The electrochemical process within the fuel cell provides basic conditions to the materials and working gases. The cathode material has a high electronic conductivity with simultaneous chemical and dimensional stability (Singhal, 2013). Floating and other (chemical) foreign substances in the combustion air would adversely affect those properties. Therefore it is very important to keep the intake air stream as clean as possible. This goal and the requirement of high life time of the turbomachinery can be reached by using air bearings. These are further illustrated lateron. However, the generation of oil-free process air is the most decisive characteristic, which advertised the use of aerodynamic bearings in the hybrid system described herein.

It has often been shown in the literature (e. g. Zhou, et al., 2008; Stiller, et al., 2005; Calisea, et al., 2006; Sadegh Motahar, 2009) that MGT-SOFC systems have a great potential for a highly effective process. Particularly interesting are the remarks by Mueller et al. (2008). He was able to prove theoretically that in MGT-SOFC systems it is also possible to achieve a high response (100 kW/s) in addition to the high efficiency levels of the overall system. This response is positively reflected in today's power grids by a high peak load support. Own theoretical and constructive investigations have shown that it is possible to realise small compact MGT-SOFC systems (example see Figure 3) with known technology. Further details of the shown technological implementation cannot be presented at this point for patent reasons. Based on self-developed air bearing micro turbine technology and industrialised stacks (MK 200 by Fraunhofer), thermodynamic analyses developed characteristics for the design (Berg & Krienke, 2015). These are the basis of this publication. As the design parameters pressure ratio, turbine inlet temperature, the speed and the size of the high-temperature heat exchanger are very important for engineers, the required characteristics have been expanded.

DESCRIPTION OF THE HYBRID SYSTEM

The efficiency of the overall process is enhanced by the integration of the high-temperature fuel cell in a MGT system to a value significantly higher than the efficiency value of the individual systems.

This design provides efficiencies which are in the maximum range of the physically possible (theoretically up to 80%, first pilot plant estimated 65%). Here an exergetic useful conversion of the chemical energy of the fuel into electrical energy takes place. First, an electrochemical conversion into electrical energy via the fuel cell module takes place, with the maximum possible exergy. The by the fuel cell non-convertible exergy potential (resulting from the heat apparition at high temperature and of the unconverted fuel) is used by embedding the high-temperature cell with a subsequent post-oxidation (in an afterburner) of unconverted fuel in the MGT process for the generation of mechanical work. The fuel cell module (SOFC, afterburner, reactor, reformer and heat exchanger, Figure 2 [right]) effectively replaces the combustion chamber of a recuperated MGT and is installed in a pressure vessel (pressure depending on the pressure ratio of the compressor of the MGT).

The air is sucked in by the compressor. The compressed air flows through the recuperator into a further high temperature heat exchanger, which is required because the exhaust heat after the turbine is not sufficient in most operating points to preheat the air in the recuperator up to the operating temperature of the high-temperature fuel cells. This air flows to the cathode of the SOFC (Figure 2). On the anode side the pressurised synthesis gas is supplied.

In case of the use of an integrated ‚steam reforming process‘, the process-water is brought to a pressure above the operating pressure, preheated and vaporised in a steam generator utilising exhaust heat, then superheated and fed to the methane stream for the steam reforming process. The reformed synthesis gas flows at operating temperature to the anode.

In the SOFC the oxygen reacts at the anode with the carbon monoxide and hydrogen of the fuel gas (synthesis gas from the reformer) to water and carbon dioxide. The heated air is fed to the SOFC stack at the cathode side. There, oxygen molecules are split with the aid of four electrons in two O^{2-}ions. These diffuse through the electrolyte to the anode to oxidise there with syngas as descripted in Figure 1. In the SOFC stack no complete reaction takes place. In order to use the remaining portion of the combustible ingredients in the anode exhaust gas energetically, a post-oxidation (in the “afterburner”) is supplied. The residual oxygen in the cathode exhaust gas serves as oxidation partner. The resulting heat is used for the reforming process and the high temperature heat exchange to increase the temperature T_ε of the air (coming from the recuperator) to the operating temperature T_{SOFC} of the SOFC. Subsequently, the exhaust gases flow to the turbine. Here, the expansion takes place. The turbine drives a common shaft to the generator and the compressor. The turbine exhaust gas gives off heat energy in the recuperator to the compressed air (Figure 2). The remaining heat energy is used in heat exchangers for preheating the steam (for the steam reforming process), the fuel gas and for heating purposes.

In addition to the combination of pressurised SOFC shown here and the Joule-cycle, which is a direct thermal coupling, there are many other strategies for the integration of SOFC into hybrid energy generation plants. These schemes can be divided into four groups: direct thermal coupling, indirect thermal coupling, fuel coupling and the advanced integration cycles for improved power generation (Zhang, et al., 2010). There are also possibilities to couple more than just the MGT and the SOFC into one machine. For example, according to the MGT-SOFC process described here, it is also possible to integrate the so-called Cheng-cycle. In this system, the exhaust gas heat is used to generate additional steam, which is fed to the system for the turbine process part after the fuel cell (Yoshizumi, et al., 2005; Zhang, et al., 2010).

THERMODYNAMIC ASPECTS

The real efficiency of a SOFC module can be described by the voltage efficiency η_U (ratio of actual terminal voltage to the reversible cell voltage), the current efficiency η_I (the ratio of real cell current to the theoretically achievable cell current) and the fuel gas degree of conversion η_C together with the thermodynamic efficiency of an ideal SOFC (Kurzweil, 2013),

$$\eta_{SOFC}^{real} = \eta_{SOFC}^{rev} \cdot \eta_U \cdot \eta_I \cdot \eta_C \tag{1}$$

where the reversible efficiency of the SOFC η_{SOFC}^{rev} is determined by the Gibbs potential $\Delta^R G$ proportional to the formation enthalpy$\Delta^R H$

$$\eta_{SOFC}^{rev} = \frac{\Delta^R G}{\Delta^R H} = 1 - T_{SOFC} \cdot \frac{\Delta^R S}{\Delta^R H} \tag{2}$$

and

$$\eta_U = \frac{U_{real}}{U_{rev}}, \eta_I = \frac{I_{real}}{I_{th}}, \eta_C = \frac{\dot{m}_{F,conv}}{\dot{m}_{F,in}} \tag{3}$$

For a micro gas turbine process the real efficiency can be described by the exergetic efficiency ξ and the generator electrical efficiency η_G.

$$\eta_{MGT}^{real} = \xi \left(1 - \frac{T_{min}}{T_{max}}\right) \cdot \eta_G = \xi \left(1 - \frac{T_{Ambient}}{T_{Turbine_{in}}}\right) \cdot \eta_G \tag{4}$$

The ambient temperature $T_{Ambient}$ (compressor inlet temperature) is in this case the minimum temperature and the turbine inlet temperature $T_{Turbine_{in}}$ is the maximum temperature of the gas turbine process.

Under the reasonable assumption that the fuel conversion rate of the entire hybrid MGT-SOFC system including post oxidation is 100% and the loss of peripheral devices (converters, control engineering, gas supply, safety equipment, etc.) are recognised as the global system efficiency η_{Sys}, the real efficiency of the hybrid system can be written as

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

referring to the scheme of a SOFC module with an integrated HEXAR module which consists of a heat exchanger, an after-burner and a reformer depicted in Figure 2. The operating temperature of SOFC T_{SOFC} usually lies between 700°C to 900°C, which os generally higher than the recuperator exit temperature T_ε of a recuperated micro gas turbine process. In order to raise the temperature of the compressed air before being fed into the SOFC stacks, an amount of heat ΔQ_{HeatEx} is added into the air stream by using a higher temperature gas from the after-burner through a high-temperature heat exchanger (HEX). If $\Delta Q_{SOFC-Turbine}$ is the amount of heat required to increase the operating temperature of the fuel cell T_{SOFC} to the turbine inlet temperature $T_{Turbine\_in}$, the heat input which required to close the MGT-SOFC combine process ΔQ_{Input} can be described as follow

$$\Delta Q_{Input} = \Delta Q_{HeatEx} + \Delta Q_{SOFC-Turbine} \tag{6}$$

The heat input which ΔQ_{Input} can also be written with energy balance in the SOFC-Module as

$$\Delta Q_{Input} = \Delta Q_{HeatEx} + \Delta Q_{SOFC-Turbine} = \Delta^R Q + \Delta^I Q + \Delta^F Q - \Delta Q_{Reformer} \tag{7}$$

This heat input consists of the reversible heat $\Delta^R Q$, the irreversible heat $\Delta^I Q$, the amount of heat from the post-oxidation $\Delta^F Q$, minus the amount of heat $\Delta Q_{Reformer}$ for the reforming process (if integrated in this process part).

In order to estimate the cost of the high-temperature heat exchange, the heat ratio X is introduced as the ratio between the exchanged heat quantity ΔQ_{HeatEx} and the required amount of heat input ΔQ_{Input}, which is required to close the cycle.

$$X = \frac{\Delta Q_{HeatEx}}{\Delta Q_{Input}} \tag{8}$$

Assuming the process gas is an ideal gas and the SOFC process is an isobaric process $c_p \cong \left(\frac{\partial h}{\partial T}\right)_p = T\left(\frac{\partial s}{\partial T}\right)_p$. Let k_ϵ be the coefficient of the recuperator which is less than unity, equation (8) can be written as

$$X = \left(\frac{h_{SOFC} - h_\varepsilon}{h_{max} - h_\varepsilon}\right)_p = \left(\frac{T_{SOFC} - T_\varepsilon}{T_{Turbine_{in}} - T_\varepsilon}\right)_p = \left(\frac{T_{SOFC} - k_\varepsilon \cdot T_{Turbine_{out}}}{T_{Turbine_{in}} - k_\varepsilon \cdot T_{Turbine_{out}}}\right)_p \tag{9}$$

The relationship between the maximum turbine inlet temperature $T_{Turbine_{in}}$ and the outlet temperature of the turbine $T_{Turbine_{out}}$ allows the introduction of the pressure ratio of the gas turbine process $\pi_{Turbine}$, which can be used as a good approximation for the ratio π_{SOFC} between the operating pressure of the SOFC and the ambient pressure.

$$\pi_{SOFC} = \frac{p_{SOFC}}{p_{Ambient}} \cong \pi \cong \frac{p_{Turbine_{in}}}{p_{Turbine_{out}}} = \pi_{Turbine} \tag{10}$$

For an adiabatic process the ratio of the turbine outlet temperature and turbine inlet temperature can be written using the polytrophic efficiency of the turbine η_T and the adiabatic exponent γ as

$$\frac{T_{Turbine_{out}}}{T_{Turbine_{in}}} = \pi^\phi \; ; \; \phi = \frac{1-\gamma}{\gamma} \eta_T \tag{11}$$

with the ratio θ of the SOFC operating temperature T_{SOFC} to the turbine inlet temperature $T_{Turbine_{in}}$

$$\theta = \frac{T_{SOFC}}{T_{Turbine_{in}}} \tag{12}$$

the heat ratio X can be written as

$$X = \frac{\theta - k_\varepsilon \pi^\phi}{1 - k_\varepsilon \pi^\phi} \tag{13}$$

An additional heat exchanger will be unnecessary in the case of $\theta = k_{\varepsilon}\pi^{\phi}$ whereby the heat ratio becomes zero ($X = 0$). If the operating temperature T_{SOFC} is equal to the turbine inlet temperature $T_{Turbine_{in}}$, the heat ratio becomes one ($X = 1$). Theoretically, the operating temperature of the SOFC T_{SOFC} might also be above the turbine inlet temperature ($X > 1$). In this case, however, a heat consumer has to be placed to take the heat from the exhaust gas after the SOFC to match the turbine inlet temperature $T_{Turbine_{in}}$. A value of ($X < 0$) is also conceivable, for example, if the temperature behind the recuperator T_{ε} is lowered by a heat consumer ($T_{SOFC} < T_{\varepsilon}$). However, the targeted operating temperatures T_{SOFC} are in generally below the turbine inlet temperature $T_{Turbine_{in}}$ and above the recuperator outlet temperature T_{ε}. Thus, the heat ratio X is in the range of $0 \leq X \leq 1$.

Three example systems A, B, and C, where the operating temperature of SOFC is identical, are illustrated in Figure 4. In the example C, the turbine inlet temperature $T_{Turbine_{in}}$ is that high, that the operating temperature T_{SOFC} matches the recuperator outlet temperature T_{ε}. In this example, no high-temperature heat exchanger is required ($X \rightarrow 0$). In the examples A and B, the operating temperature T_{SOFC} is very close to the turbine inlet temperature $T_{Turbine_{in}}$. Via a high-temperature heat exchanger, nearly the total amount of heat $\Delta Q_{Input} \approx \Delta Q_{HeatEx}$ between the state points (recuperator outlet - fuel cell inlet) has to be exchanged. Figure 4 also shows that the total amount of heat ΔQ_{Input} in the example C (i.e. at a higher turbine inlet temperature $T_{Turbine_{in}}$) and in the example A (at a higher pressure ratio π) is larger compared to the example B (represented by the distance $T_{Turbine_{in}} - T_{\varepsilon}$). Because of this the range of the turbine inlet temperature and the pressure ratio has to be coordinated carefully.

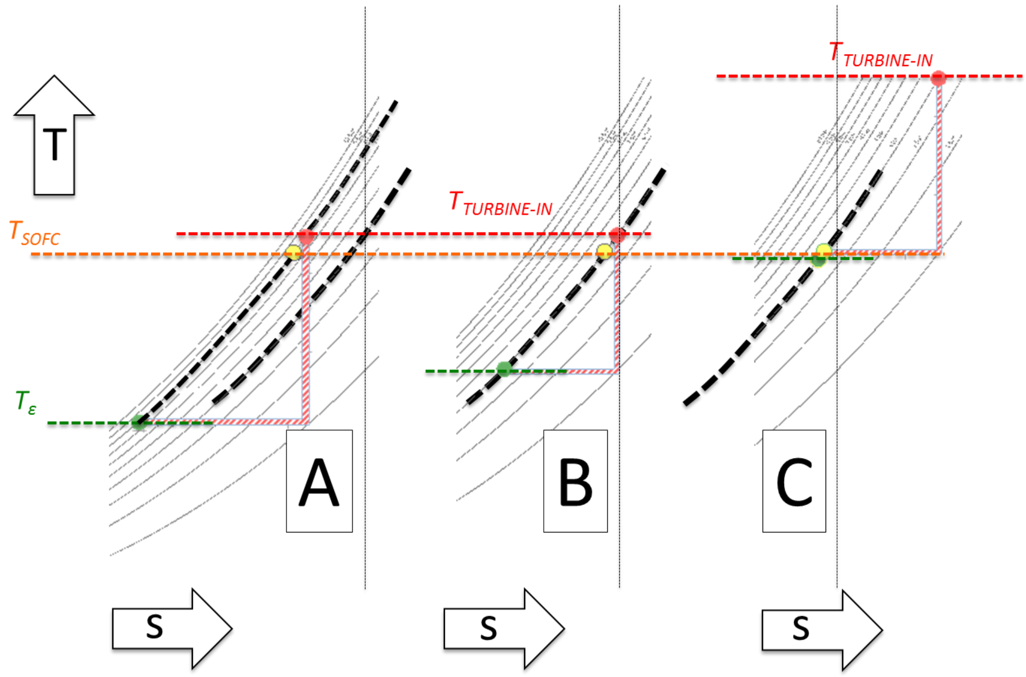

Figure 4: Simplified examples for explanation (Boundary conditions: $T_{SOFC} = const.$, $\pi_A > \pi_B = \pi_C$, $T^C_{Turbine_{in}} > T^A_{Turbine_{in}} = T^B_{Turbine_{in}}$)

TURBOMACHINERY DESIGN CONSIDERATION

In Berg & Krienke (2015), a simulation of a MGT-SOFC hybrid system has been demonstrated, where methane CH_4 is used for fuel by mean of a steam reforming process. The results of the system performance operated at pressure ratio of $\pi = 4.5$ including the constant heat ratio lines are shown in Figure 5. It can be seen that the overall efficiency $\eta^{real}_{MGT-SOFC}$ increases with increasing turbine inlet temperature $T_{Turbine_{in}}$, while the SOFC operating temperature T_{SOFC} is constant. In this case, X decreases. For realising this, a higher technological effort is needed referring turbine cooling and material. This area is to the right of the green dotted line. This confirms that the heat ratio within the limits $0 \leq X \leq 1$ are reasonable.

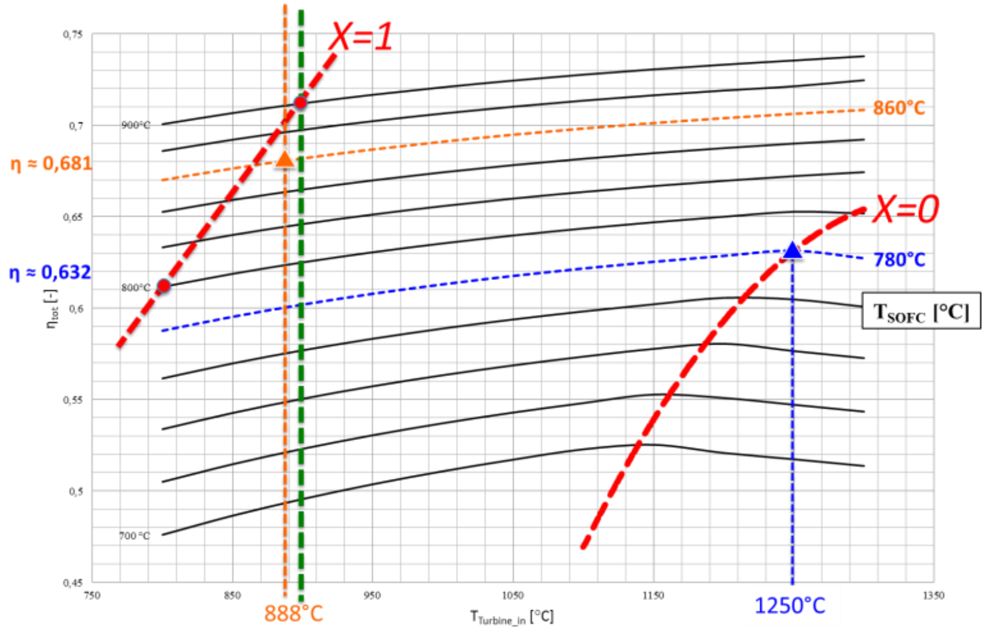

Figure 5: Performance maps of a calculated MGT-SOFC-System at $\pi = 4.5$

The configuration where no additional heat exchange is necessary $X = 0$ is presented by the blue line in Figure 5. An overall efficiency $\eta^{real}_{MGT-SOFC}$ of about 63% with an SOFC operating temperature T_{SOFC} of 780°C and with a turbine inlet temperature $T_{Turbine_{in}}$ of 1250°C is possible. However, due to the limit of the material, the turbine has to be cooled. Therefore, a complex development program is needed regarding the small radial turbine technology.

Likewise, the configuration where $X = 1$ is the approach unity, is presented by the cross point of the orange lines in Figure 5. The total efficiency $\eta^{real}_{MGT-SOFC}$ of 68% with a SOFC operating temperature T_{SOFC} of 860°C and a turbine inlet temperature $T_{Turbine_{in}}$ of 888°C is possible. However, this means that an increased technological effort is required in the high-temperature heat exchanger technology $\left(X = \left(\Delta Q_{HeatEx}/\Delta Q_{Input}\right)_p\right)$. In own research projects, this development is sought in connection with the post-combustion and the reforming process. The following practical range can be considered: $a \leq X \leq 1$ with $a \approx 0.6$ to 0.9.

Figure 6 shows a representation of the performance map at the pressure ratio $\pi = 4.5$. The green dotted line represents the practical limit with the technology available. It runs close to the 900°C line. It can be seen that overall efficiency values above 65% are possible with a SOFC operating temperature of about 860°C and a turbine inlet temperature of about 880-890°C. Figure 7 shows the same operating point in a map with pressure variation. It is seen that in principle the efficiency can be increased to values just over 70% with an increase in pressure (e.g. $\pi \approx 5$). However, the situation in Figure 4 made it clear that the entire heat demand ΔQ_{Input} in example B is the lowest. I.e. there are still existing certain "reserves" at the turbine inlet temperature of 888°C at a pressure ratio of $\pi = 4.5$, so that the cycle still can be close at SOFC operating temperature of 860°C. This was chosen that way, because the potential of recirculation has not yet been considered.

The potential of recirculation has the strongest impact, as it directly affects the efficiency $\eta^{real}_{SOFC} = \eta^{rev}_{SOFC} \cdot \eta_U \cdot \eta_I \cdot \eta_C$. An increase in the fuel gas recirculation leads to an increase of η_C. This increases the efficiency η^{real}_{SOFC} of the SOFC. Unfortunately, this results in a lower heat generation. At too low heat generation ΔQ_{Input}, there is the possibility that the MGT process cannot be closed. Figure 6 shows the influence of the recirculation ratio. One can clearly see the major impact on the overall efficiency. Furthermore, it can be seen that the line of development goes in the direction of lower turbine inlet temperature. Above the red dotted line the MGT cycle is no longer possible because the heat supply ΔQ_{Input} is too low. The choice of the range for the pressure ratio of $4 < \pi < 5$ and for the turbine inlet temperature of $800°C < T_{Turbine_{in}} < 900°C$, in the case of the micro gas turbine SOFC process for natural gas conversion (under the boundary condition of the selected SOFC with $T_{SOFC} \approx 860°C$), can be considered as logical.

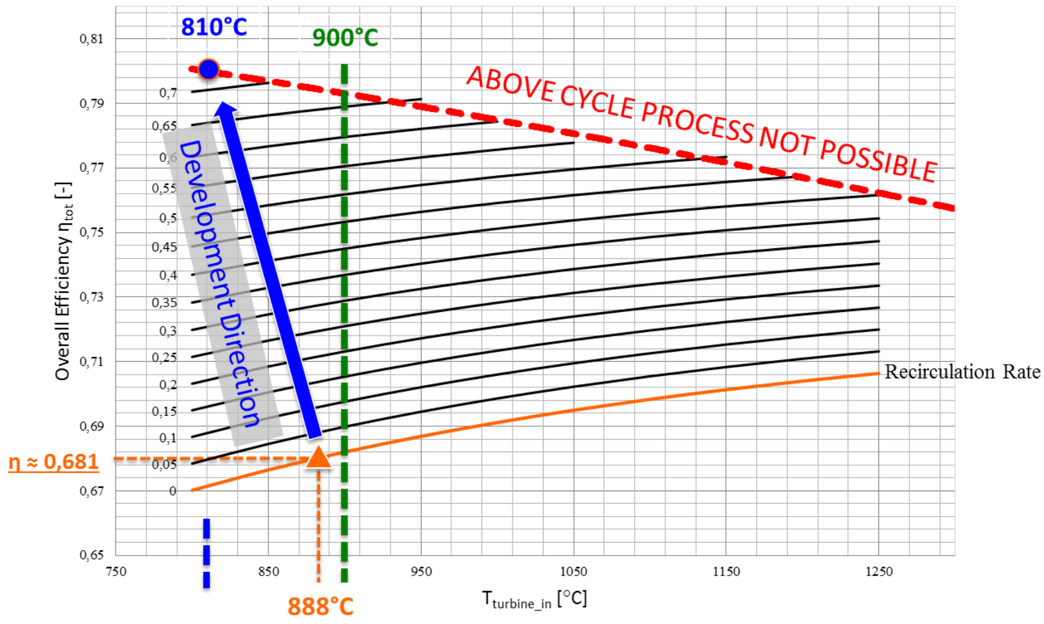

Figure 6: Performance map of a calculated MGT-SOFC system at $\pi = 4.5$ with the influence of the recirculation

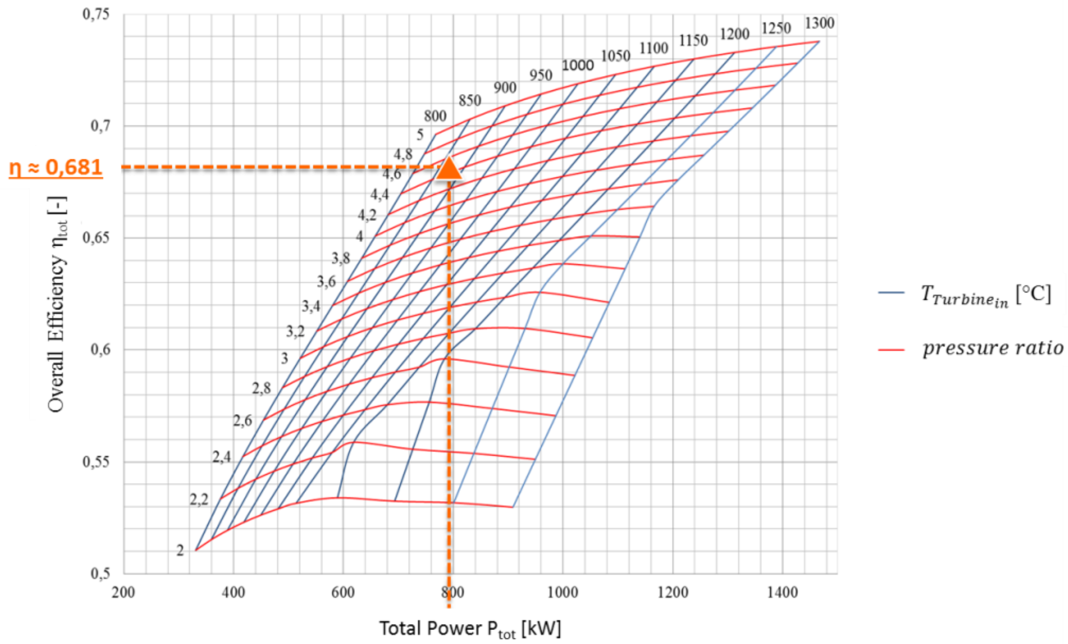

Figure 7: Performance map of a calculated MGT-SOFC system with the influence of the pressure ratio (mapping by use of a conventional MGT100 turbo set)

In order to deliver the process gas, that matches the temperature and pressure requirement, while maintaining a reasonable efficiency and the system robustness, a combination of small size single stage radial turbine and compressor pair which operate in a high speed range, are well-suited for the MGT in the SOFC hybrid system. Moreover, due to the fact that the ion exchange in the SOFC process is directly related to the surface area, oil contamination in the process medium will affect the effectiveness of the cathode surface in the stacks which leads to efficiency degradation. Thus, the MGT has to be completely oil-free for a hybrid system, to ensure the long term efficiency. Based on these requirements, together with a high-temperature operating condition, foil bearings are one of the promising solutions for the power unit in the MGT-SOFC system. Since decades, foil bearing has been proved in many turbo machinery applications, especially in commercialised oil free air cycle machines for cabin pressurization and cooling. The machine has shown a MTBF (mean time between failures) of over 100,000 hours in the field (Agrawal, 1997). The foil bearings technology has been improved continuously. Recently many research activities and demonstrations has been done worldwide in many branches of turbo machines, such as Turbochargers application (Heshmat, et al., 2006), Close Brayton's cycle turbine (Dellacorte, et al., 2005) and Rotorcraft Propulsion (Howard, et al., 2010). Once the air film is generated, the rotor is separated from the bearing surfaces which greatly reduce the power loss and ware of the bearings. Thus, the maintenance costs are minimised and the operating life is greatly extended. The wears, which take occur during start-stop cycle, can be reduced with tribological technology. Advance surface treatment in combination with solid lubricants for foil bearings has been developed and proved over 30,000 start-stop operation cycles (Dellacorte, et al., 2000) (Malcom, et al., 2004).

An example of a micro gas turbine unit for the hybrid system with foil bearings is shown in Figure 8. It consists of two main units which are the generator and the turbo group. Both are coupled together with flexible coupling. In the turbo group, the rotor is supported with two radial bearings and two axial bearings. Because no axial force exists on the inductor, only two radial bearings are implemented. As mentioned earlier, it can be seen that the rotor configuration is very simple and robust. The moving parts in the machine are only the inductor and the turbo group. Because foil bearings can operate at high temperature, the rotor group can be very compact and yet no external cooling is required. It is practically to cool the generator unit by using air which is sucked by the compressor through the generator casing. This can be done only when the generator unit is completely oil-free regarding the contamination problems of the SOFC unit.

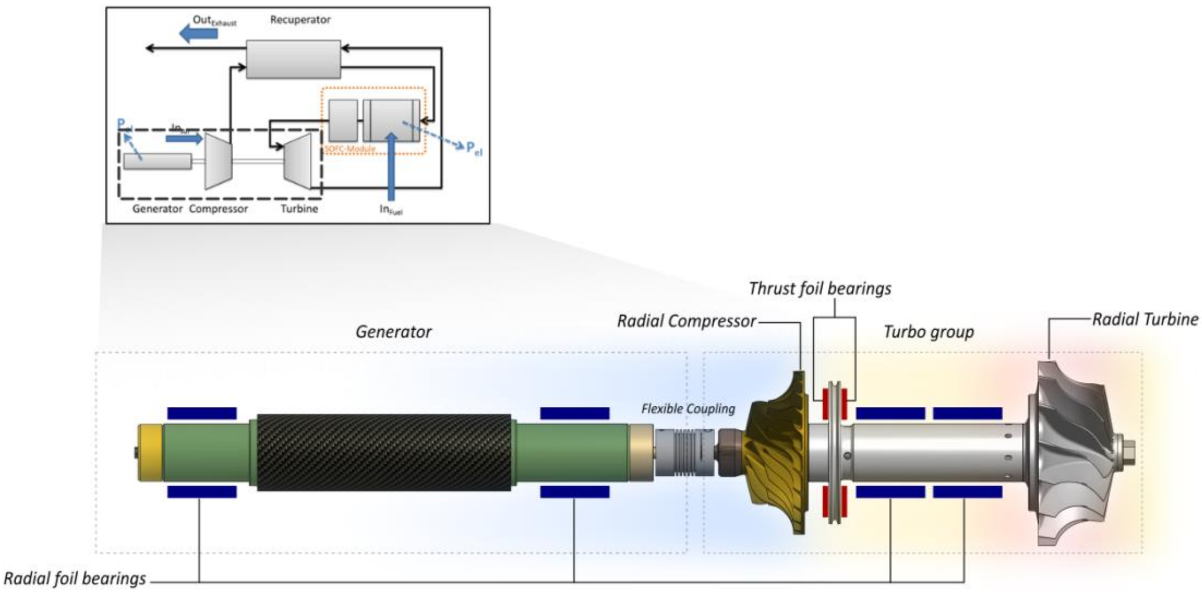

Figure 8: General configuration of the micro gas turbine unit with foil bearings

CONCLUSION AND PERSPECTIVE

Reducing the dependence from fossil fuels, the increasing use of renewable energy sources and the resulting need of storage (power to gas) requires the development of new and highly efficient energy conversion technologies. It has been shown that the MGT-SOFC combination, with existing technologies for this purpose, have high potentials. Through hybridising, the advantages of different energy conversion options can be combined and the respective disadvantages can be negated. It has been shown that micro turbine-SOFC-systems therefor are particularly well suited, because a combination allows high efficiency of energy conversion and the realising with today's existing and manageable technologies is possible.

To achieve the highest efficiencies ($\eta > 60\%$), merely comparatively moderate pressure ratios ($\pi \approx 4{,}5$) and operating temperatures $\left(T_{Turbine_{in}} \approx 800 - 900°C\right)$ are required, whereby material requirements on the turbomachinery drops and simultaneously the service life of the entire system increases by reducing stress on the machine.

It has been shown that the introduced heat ratio X (within the limits $0 \leq X \leq 1$) is a very good and innovative tool for the design of MGT-SOFC while including important system parameters like the recuperator exit temperature, the SOFC operating temperature, the turbine inlet temperature and the pressure ratio of the MGT-SOFC process in one dimensionless number. It has been shown that a practical range of $a \leq X \leq 1$ with $a \approx 0.6$ to 0.9 can be considered.

Also, the recirculation rate was detected as an important parameter for increasing the efficiency of a hybrid MGT-SOFC system. With a higher recirculation rate, less turbine inlet temperature is required. That is also an advantage for long term efficiency and a long service life.

Furthermore, the use of aerodynamic air bearing is essential for the implementation of the described hybrid energy converter. Oil-free process air is indispensable; otherwise the SOFC modules very quickly degenerate and become unusable. This technology is also already available, industrialised and will be continuously improved.

In addition to the already extensive occurred theoretical consideration and examination of the pressure charging of high temperature fuel cells, there are also several practical research projects with the goal of an application-oriented implementation of a hybrid MGT-SOFC power converter. Also here, the precise adjusting of the individual components and operating parameters of the entire system is indispensable. Generally, it can be said that hybrid energy converters based on micro turbines will play an important role in the future regarding the design of decentralised energy supply due to the large variety of fuels, the high efficiency potential and flexible technical refinement. Hence, it is very important to develop these technologies intensively.

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