Influence on the Electrical Efficiency of a Hybrid MGT-SOFC-System by μ-fogging in a-Two-Staged Compressor System

R Dückershoff¹*, H P Berg², A Himmelberg², M Lehmann² and M Kleissl²

¹University of Applied Sciences Mittelhessen (THM), Friedberg, Department of Mechanical Engineering, Mechatronics and Material Technology, Wilhelm-Leuschner-Str. 13, 61169 Friedberg, Germany
²Brandenburg University of Technology Cottbus-Senftenberg, Chair of Combustion Engines and Flight Propulsion, Siemens-Halske-Ring 14, 03046 Cottbus, Germany

* Corresponding Author: roland.dueckershoff@m.thm.de

Abstract

Hybrid combinations of solid oxide fuel cell and recuperated micro gas turbines can convert the chemical energy of hydrocarbon-based fuels in electrical energy with high electrical efficiency. With an integrated and improved cycle management, more than 70% of the energy content of the fuel could be converted. Therefore, the systems are highly suitable for the Power-To-Gas conversion. In particular, a pressure charging of the SOFC fuel cell leads to an increase in stack performance. By a downstream turbo set, after residual fuels are intentionally oxidized with an afterburner, additional electrical energy can be gained from the expansion of the hot exhaust gas stream and the overall efficiency can be increased. In order to increase the electrical efficiency of the system, it is proposed, to ensure the required compression of the process air in particular by a-two-staged turbo compressor with an intermediate cooling system. By thus achievable reduction of the dissipation of the compressor and by targeted condensation of finest drops in front of the second compressor stage affected by intermediate cooling, an increase in efficiency of the system is possible. This is achieved by targeted cooling of the process air behind a low pressure compression, so that it is saturated over 100% relative air humidity. As a result, a slightly supersaturated airflow is available for the second compressor stage, which enters the compressor after heat removal via an intermediate cooling having a small number of microdroplets. Therefore, the condensed water evaporates again by the heat of compression in the second stage and the compressed flow ultimately enters the recuperation at a lower temperature than during normal compression. Thus, more heat can be recovered within the recuperation system. Therefore, the electrical energy of the system can be produced having higher efficiency, because the heat dissipation of the overall system decreases. In this article it is presented, how such a process is thermodynamically modelled and how a technical realization can be built after optimization by simulations. Finally, in this study, the process-influencing factors are analyzed to show the highest possible electrical yield of such a system.
1. Introduction
The hybrid power plants from Micro Gas Turbines (MGT) and high-temperature fuel cells (Solid Oxid Fuel Cells / SOFC) promise high electrical efficiency in energetic recovering Power-To-Gas fuels from renewable energy systems [1], [2], [7], [7]. The residual fuel released by an incomplete fuel conversion in the SOFC is treated by an afterburning. So, it provides additional energy in the gas turbine component.
In particular, the efficiency of the micro gas turbine can be increased by using the so-called Fogging and thus, its specific output of system performance can be raised [3], [4], [5]. The investigation is intended to show that the intermediate appearance of liquid water in the compression system leads to an increase in the efficiency of the MGT part and thereby to an increase in the overall efficiency of the system [10].
For this purpose, the development of a-two-staged compression system with intermediate cooling down to the entrance temperature is being presented. By taking out heat after the first stage, it is expected that microdroplets will be generated in the airflow by condensation. Then, the adiabatic cooling by the evaporation effect helps to run the second compression stage more efficient. Now, the air has been compressed to the operating pressure but having a lower temperature than without intermediate cooling. The air is led through a recuperator, wherein, regarding the lower entrance temperature, more heat within the system can be recovered. Thereafter, additional heat required will be supplied in one case by a combustion chamber system and in the other case using a hybrid system of SOFC fuel cell and the afterburner.
As a result, it will obtain an increase in the performance of the overall machine. It also requires less energy during the compression process. The heat rate shows a significant increase. Inlet fogging also reduces emissions of oxides of nitrogen (NOx) because the additional water vapour quenches hot spots in the combustors of the gas turbine [10].
All tasks that concern the mechanical stress regarding the thermal impact on blading, rotor and casing of the compressor have to be kept in mind. Therefore, we have to avoid large drops and agglomerations of water and still ensure a sufficient evaporation rate should be established. Furthermore, in a hybrid system with SOFC fuel cells, the operating temperature must be ensured via recuperator and a high-temperature heat exchanger. Through a targeted recovery of combustion heat and waste heat of the SOFC fuel cells, the overall process can be made highly efficient. In this study, the processes MGT and MGT-SOFC are presented with a thermodynamic comparison, both with and without intermediate cooling within the compressor. It will be shown that an increase in efficiency is possible having the appropriate use of micro-fogging by condensation.
The reduction in heating during compression shows an energetic advantage of the procedure.

2. Thermodynamic comparison of the processes MGT, SOFC-MGT with or without intermediate cooling
A micro gas turbine process with double compression and intermediate cooling will be presented, in this section. Initially, air with a defined humidity, e.g. moistened by a wetted packed bed, is sucked in by a supercharger, which is used to be the first stage and thereby is precompressed to an intermediate pressure. Then an intermediate cooling by an intercooler follows. Since the airflow is now cooled down to the level of ambient temperature, its vapour pressure is lowered to the level of the ambient conditions, while the pressure is increased to the intermediate pressure level. Depending on the inlet conditions, the airflow is now supersaturated with moisture. As a result, microdroplets condense. Then, in a second stage, the actual compression to the operating pressure of the micro gas turbine system is performed. Due to the lower inlet temperature and the evaporation of the microdroplets during compression within the second stage, the airflow from the compressor occurs at a lower temperature compared to the normal process. In addition, having a lower level of temperature, the compression done in the second stage can be done with less workload. Now, the airflow is going to be heated in a recuperator system up to the combustion chamber inlet temperature, resp. the supply temperature of the SOFC stacks. Due to the lower inlet temperature of compressed air in the recuperator, more heat can be recuperated from the flue gas from turbine exhaust.
In the combustion chamber, the heat is generated by gas combustion at a working pressure of around 5 bars. This is followed by the expansion of the working gas in a high-pressure turbine to almost the pre-pressure of the low-pressure turbine. Further, on, the exhaust gas is passed through the recuperator and is used for preheating the combustion air. As a final step, the exhaust gas is driving the supercharger by passing its low-pressure turbine.

In the modified hybrid process, the combustion chamber is replaced by a combination of a SOFC fuel cell cluster and an afterburner system, as shown in Fig. 1. It is accepted that the compressed air flow on the airside into the SOFC stack system is with higher moisture content, but sub saturated.

An airflow with a higher vapour content has a higher heat capacity. As a result, smaller mass flow can dissipate the same amount of heat produced during the fuel cell conversion. However, the partial pressure of the water vapour is so low on the airside that only a marginal change can be expected there.

The heat diagram (Fig. 2) shows the MGT-Process and the advantage of micro-fogging in the second stage. The micro-fogging causes a shift of the point D (to D’) by adiabatic cooling and thus, a shift of

![Figure 1: Connection scheme of MGT-SOFC-Process with intermediate cooling and μ-fogging installation between the first and the second stage.](image1)

![Figure 2: TS-Heat diagram of the MGT-Process with intermediate cooling and μ-fogging](image2)

The point E (to E’). Thus, more heat energy is recuperated and as a result, exergy losses are lower. The outlet temperature from the compressor is reduced and the process step needs less energy.
The efficiency of the overall process can be determined from the recovered and usable energy. It is to be distinguished between the electrical efficiency and the overall efficiency, which includes subsequent waste heat utilization. Since both the fuel cell and a micro gas turbine jointly supply electrical energy, more electrical energy can be obtained from the energy content of the gas than is possible with the individual components. The prerequisite for an increase in efficiency is that heat integration can be successfully achieved.

The energetic behaviour of the humid air depends on its thermal and caloric state equation variables. Density and specific heat capacity depend directly on the relative humidity resp. its degree of saturation, as shown e.g. in [9], 0. The air mass flow is directly related to the density of air and the flow of volume at the entrance of the system.

\[ \dot{m} = \rho \cdot \dot{V} \]

The density of the air depends on the relative humidity, pressure and temperature. See also [10]:

\[ \rho_{\text{humid air}} = \frac{p_d}{R_d \cdot T} + \frac{p_v}{R_v \cdot T} = \frac{p_d \cdot M_d + p_v \cdot M_v}{R \cdot T} \]

with index d for dry air, v for water vapour and R as Universal Gas Constant.

Typically, thermodynamic relationships of humid air are given by its relative humidity \( \varphi \) and its water content \( x \).

\[ \varphi = \frac{p_v}{p_s} \quad \text{and} \quad x = \frac{m_v}{m_d} \]

The relation between both is given by:

\[ x = \frac{R_d \cdot p_s \cdot \varphi - p_s}{R_v \cdot \varphi} \]

Thereby, \( p_s \) is the pressure of saturation, which is mainly depending on the temperature as long as the overall pressure of the humid air is less than 10 bars. Exceeds the vapour pressure \( p_v \) the pressure of saturation \( p_s \), the relative humidity \( \varphi \) is above 100% and water will start to condense.

The overall pressure is to be calculated by the partial pressures:

\[ p = p_d + p_v \]

By pressurizing the humid air, its partial pressures will increase by the same ratio as the overall pressure does:

\[ \frac{p_{\text{out}}}{p_{\text{in}}} = \frac{p_{\text{d,out}}}{p_{\text{d,in}}} = \frac{p_{\text{v,out}}}{p_{\text{v,in}}} \]

Therefore, the relative humidity \( \varphi \) will increase at a higher pressure having the same temperature. Caloric state variables of the humid air are to be calculated by its water content \( x \), as in the example shown for the specific heat \( c_p \).

\[ c_p = \frac{c_{p,d} + x \cdot c_{p,v}}{1 + x} \]

The needed chemical energy flow of the fuel can be determined by its mass flow and the lower calorific value:

\[ E_{\text{chem}} = \dot{m}_{\text{Fuel}} \cdot H_{0,\text{Fuel}} \]

In a micro gas turbine system, the electrical efficiency can be determined by the ratio of the electric energy yield to the chemical energy flow:

\[ \eta_{\text{el}} = \frac{E_{\text{el,MGT}}}{E_{\text{chem}}} \]

To determine the electrical efficiency, the electrical energy yields of fuel cell fraction and micro gas turbine fraction in a hybrid system have to be taken into account. In order to consider the compression
work of the fuel gas and the steam, needed by the internal steam reformer, the energy expenditure for these sub-processes have to be subtracted from the total energy yield:

$$\eta_{el} = \frac{E_{el,SOFC} + E_{el,MGT} - E_{comp,fuel} - E_{comp,steam}}{E_{chem}}.$$

The energy effort for the evaporation of the water of the reformer system and the gas heating up to working temperature is available internally by heat exchanger systems and other heat integration methods. In addition, if, heat energy is to be used via an exhaust gas heat exchanger, the overall efficiency will be higher and can be calculated as:

$$\eta_{ges} = \frac{E_{el,SOFC} + E_{el,MGT} - E_{comp,gas} - E_{comp,steam} + E_{therm}}{E_{chem}}.$$

By use of humid air and an inter-cooling system, an increase in efficiency can be achieved in a two-staged compressor system. The lower intermediate inlet temperature in the compressor requires less energy to compress an equal mass flow. By cooling the airflow after a first compression stage in a heat exchanger to ambient temperature, the inlet temperature of the second stage is reduced. In this case, the cooling process must be controlled so that only microdroplets condense, which then evaporate during the second compression stage. This action reduces the expected outlet temperature. The entire airflow can be compressed to the working pressure of the combustion chamber or fuel cell system with less energy expenditure. Next, after expansion in the turbine, the system can recover more energy in the recuperator from the exhaust stream. This is mainly possible due to the lower inlet temperature of the recuperator rear of the compressor exit side.

![Simulation scheme for MGT-SOFC-Process with intermediate cooling and μ-fogging with EBSILON Professional](image)

**Figure 3.** Simulation scheme for MGT-SOFC-Process with intermediate cooling and μ-fogging with EBSILON Professional.
In hybrid power plants made of MGT and SOFC systems, an increase in the efficiency of the MGT fraction also leads to an increase in the efficiency of the complete system. Moreover, the higher water content due to the increased air humidity at systems entry can improve the conditions for the SOFC conversion on its airside, since here the heat capacity increases slightly.

The simulation is done with the program system Epsilon 0. There, a 1D model of the considered processes was mapped. Fig. 3 shows a simulation schema for the MGT-SOFC-Process. First, the system simulation has been running with MGT fogging, therein variations of the air humidity at the inlet of the first compressor stage have been done. Subsequently, the simulation of MGT-SOFC hybrid system has been conducted. The fogging took place in both systems in front of the first compressor stage. Therefore, the heat of compression has been used to vaporize the mist so that the temperature rise is less than in no fogging systems. At lower temperatures, the required compression energy is also less.

In order to make the different simulations comparable, the same inlet mass flow into the high-pressure turbine was defined as the boundary condition. For this purpose, compression pressure and temperature level for the combustion chamber area resp. of the SOFC fuel cells area were specified as further fixed boundary conditions. The variation parameter used has been the specific water input using the fogging at the system entrance. Therefore, humidity at entry into the second compressor stage as well as regarding the overall process has been increased.

However, by the simulation program, only a limited water content, which exceeds a saturated atmosphere, could be simulated. Thus, the maximum relative humidity at ambient temperature and under pressure conditions has been limited to 120%. Required for comparison, the constant mass flow has been assumed.

3. Efficiency Analysis
A comparison of the thermodynamic efficiencies has been carried out in particular for a one-stage and an intercooler two-stage compressor MGT system. Therefore, the relative humidity at the entrance of each system has been used for the variation parameter. A sensitivity study regarding performance and efficiency has been done. Fig. 4 shows the impact of the relative humidity on the electrical efficiency in both cases.

In all simulations, it has been found that an increase in air humidity leads to an increase in the overall efficiency of the MGT system. In the case of having a single-stage compressor within the MGT system, it has been found that the system’s electric efficiency does not increase if the air at the entrance of the system is supersaturated. Furthermore, it can be shown that the efficiency of the investigated MGT system can reach 32.7% at maximum level.

In contrast, the electric efficiency of the MGT system having an intercooled two-staged compressor is a much higher, at least 36.5%. Moreover, is shown, using fogging for increasing the relative humidity at the system’s entrance increases the overall efficiency. A special point of inflexion is shown. There the air humidity reaches 70%. From here, the overall system’s efficiency increases sharply regarding the air humidity at the system’s entrance. At this point, the relative humidity at the entrance of the second compressor stage has reached 100% and water will start to condense. Here the micro-fogging process within the compressor has taken place. The simulations have been done up to a relative humidity of 120% based on ambient pressure and temperature at the inlet of the system. At higher water content level, convergence problems occurred in the simulation system, which did not allow for overall results of the calculation.

At a relative humidity of the entrance airflow by 120% in the simulations regarding the two-stage process, the maximum electrical efficiency of approximately 40% has been achieved for the MGT process. Thus, this variant offers a good opportunity to increase the overall efficiency of the MGT system. If by exhaust heat exchanger systems, additional usage of heat could be done, e.g. regarding heating purposes, the overall efficiency can be increased up to over 99%, based on the lower heating value.
Moreover, placing instead of the combustion chamber a combination of SOFC and afterburner, as shown by Fig. 1, the so-called hybrid MGT-SOFC system has been simulated. The comparative simulation by Ebsilon 0, even much more complex, as shown by Fig. 3, shows that the electrical efficiency of 74% can increase by 2% using an intercooled compressor having micro-fogging internally. At least, the simulation shows an electrical efficiency of around 76% (see Fig. 3).

4. Discussion

In this publication, a two-stage compression system with a fog system in front of the first compressor stage in combination with an intercooler was presented. Overall, the simulations show that with such a system, the electrical efficiency of a MGT system can be significantly increased. A benefit in electric efficiency of 8% seems to be possible. Regarding the MGT-SOFC system the benefit in electric efficiency seems to be lower, being 2%. However, this is not surprising, since the electric efficiency of the MGT-SOFC process already is at a high level having more than 70% and the MGT part of this system, which has the gain by intercooling and micro-fogging, has a minor share of around 1 to 7 regarding its overall performance [1].

On one hand, such an increase in efficiency can be explained by the reduction of the workload required for compression. Intercooling generates lower inlet temperatures into the second compression stage, as well as supersaturation of the inlet air with microdroplets. This reduces the energy expenditure for the compression and reduces the outlet temperature from this subsystem. On the other hand, it is achieved by the lower inlet temperature into the recuperator, that from the hot gas side after the first turbine stage more energy can be taken out. This allows remaining more exhaust heat in the process. Regarding the MGT-SOFC system, it has to be pointed out that an increase in water content, due to higher heat capacity of the water vapour, may increase slightly the heat capacity of the air at the entrance of the SOFC stack. A positive effect can be here, that heat conduction within the SOFC fuel cells will be improved. However, this has to be investigated more in detail. However, higher water vapour content in the overall system ultimately may entail risks concerning the risk of fuel cell de-integration.

Not at least, increasing the operating pressure of the SOFC fuel cells by use of a two-stage compressor will have a positive effect. An increase of the output by the SOFC system can certainly be expected up to a system pressure of 8 bar [6]. Future investigations have to be done in particular to determine an optimal setting of the pressure level between the first and second compressor stage. Overall, the balancing by optimization tasks has to be done, so that a maximum in efficiency gain can be achieved.

Appropriate technical process management should also prevent problems regarding agglomeration of water or too large droplets, e.g. to protect the second stage of the compressor against damage by erosion and thermal stress. Thus, the generation of fine microdroplet formation by water condenses in the intercooler, the so-called micro-fogging, is required as a control variable.

Figure 4. Electrical efficiency of the simulated MGT systems with a one-stage and a cooled two-stage compressor process in relation to the relative humidity at the system entrance
However, significant is the risk that, due to the lower process temperature and the higher vapour content at the exhaust gas side of the recuperator water droplets due to condensation will occur and will reach the second turbine stage. In the waste heat recovery system, a sufficient distance must be maintained.

5. Conclusion
The concept and simulations regarding the determination of efficiency for a two-staged system using humid air for compression within MGT and hybrid MGT-SOFC processes have been presented in this study. Through the simulations and analysis, efficiency advantages have been proven useful for both systems. The MGT system will be able to increase electrical efficiency up to 40% having a two-staged compressor with intercooler and a fogging system at the entrance of the compressor. In a hybrid MGT-SOFC system, this may result in an increase of the electrical efficiency by up to 2% and therefore up to an electrical efficiency of about 76%.

Further investigations will be carried out. To study process variants with a relative humidity more than 120% at the entry into the main compression stage, an adaptation of the thermodynamic calculation models handling a higher water content are required. A realization of the intercooled two-stage compression having micro-fogging on a laboratory scale and further investigations, e.g. regarding the problem of erosion, corrosion and material stress, are planned.

In an update to the hybrid system, Turbo-Fuel-Cell intercooling which has micro-fogging within the system should have to be taken into account. For this purpose, assembly capability and handling the heat management of the overall system are to be optimized. However, as a first step, the technical system should be implemented as MGT-SOFC Turbo-Fuel-Cell 1.0 without micro-fogging, enhancements to do this process to increase efficiency by micro-fogging systems are conceivable following their implementation phase (to be in service in 2026).

References
[1] Berg H P Himmelberg A Lehmann M Dückershoff R Neumann M 2018 IOP Conf. Series: Materials Science and Engineering 297 012004
[2] Berg H P Kleissl M Himmelberg A Lehmann M Prechavut N Vorpahl M 2019 IOP Conf. Series: Materials Science and Engineering 501 012007
[3] Bracco S Pierfederici A Trucco A 2007 Applied Thermal Engineering 27 699-704
[4] El-Shazly A A Elhelw M Sorour M M El-Maghlany W M 2016 Alexandria Engineering Journal 55 1903
[5] Tahani M Masdari M Salehi M Ahmadi N 2018 Applied Thermal Engineering 143 955
[6] Henke M Willich C Westner C Leucht F Leibinger R Kollo J Friedrich K A 2012 Electrochimica Acta 66 158-163
[7] Berg H P Krienke C 2015 Magdeburger Maschinenbautage CD-ROM, UB Magdeburg 12
[8] Berg H P Dückershoff R Lehmann M Prechavut N 2017 Proc. 12th European Conference on Turbomachinery Fluid dynamics & Thermodynamics (Stockholms:Sweden)
[9] Baehr H D Kabelac S 2016 Thermodynamik (Springer)
[10] Marek R Nitzsche K 2015 Praxis der Wärmeübertragung (München:Hanser)
[11] STEAG System Technologies 2018 EBSILON®Professional-User Manual (Zwingenberg, STEAG Energy Services GmbH)
[12] Sanjeev Jolly, https://www.powermag.com/inlet-air-cooling-systems-improve-gas-turbine-performance/, accessed 30 Apr 2017.