DIFFERENCES AND SYNERGIES BETWEEN MOBILE AND STATIONARY SOFC-GT DESIGNS

Wolfgang Winkler, Hagen Lorenz
University of Applied Sciences Hamburg
Fuel cells and rational use of energy
Faculty of Mechanical Engineering
Berliner Tor 21
D 20099 Hamburg, Germany

ABSTRACT

Simple combined SOFC-GT cycles show an efficiency between 60 and 72%. Combinations of SOFC-GT cycles and a steam injection achieve an efficiency of more than 75%. The use of a reheat gas turbine process in a (RH) SOFC-GT cycle can be improved by a steam turbine (ST) cycle. A study of such a RH-SOFC-GT-ST cycle indicates that a cycle design with an efficiency of more than 80% is possible and confirm the predictions by an earlier theoretical thermodynamic model. The design principles of such SOFC-GT cycles were already shown in a design study in 1994 on the example of a 50 MW plant. The extreme short heat-up time of a thin tubular SOFC and the market entrance of the microturbines give the option of using these SOFC-GT designs for mobile applications. The possible use of hydrocarbons as Diesel oil is an important benefit of the SOFC. The microturbine and the SOFC stack will be matched depending on the start-up requirements of the mobile system. The minimisation of the needed volume is a key issue. But the volume reduction of the components decrease the system's efficiency. A design study shows that the space available in a mid class car allows the placement of such a system including space reserves. A further improvement of the system might allow an electric efficiency of about 55%. The production technology of thin tubes is a key issue.

INTRODUCTION

The engineering base of the development of stationary and mobile SOFC-GT is similar, as shown in fig.1. The demand for and the cost of any design of an energy converter are determined by the market and together they deliver the R&D target. The process design mainly based on the thermodynamics is the next important step. The following design study finally results in a specification and an identification of the critical components. The specification allows the decision to stop or to proceed the project and delivers the target for the next step. The identification of the critical components and the modified specification initiate further activities. The feedback allows a reengineering of the process or the design or starts R&D activities of certain components. Finally the result of the last step should be a basic engineering of the system including an engineering package of the "critical components". The delivering of the necessary design tools is a
task of technical faculties and research institutions in this Product Orientated REsearch (POR) to support the product development in the industry.

**Figure 1**
The Product Orientated REsearch process POR

Fig. 2 gives an impression of the demand profile of a stationary and of a mobile application of a SOFC-GT system. Any customer expects the lowest possible cost, the lowest possible pollution and the highest reliability in both cases. The power related volume, the power related weight and the start-up time of the system are key issues of any mobile application. These figures influence the usable space and the performance of the vehicle, as acceleration and fuel consumption etc. But these figures do not strongly influence the performance of a stationary power generation unit. The logistic of the fuel supply is important in both cases. But a power generation unit can be designed for a defined fuel that is locally available and the fuel of a mobile system must be available anywhere. Thus the possible use of a Diesel fuel or of any other commercially available fuel is an important design benefit. The energy density of the used fuel influences the size of the fuel storage or the range of the vehicle. The efficiency, the utilisation and the lifetime of the system are essential for any stationary or any commercial mobile application. But a private user may have other priorities e.g. design, luxury etc. as far as these properties don't impair the user's mobility.

**Figure 2**
Specification of demands on stationary and mobile power systems

THE SOFC-GT DESIGN AND ITS STATIONARY APPLICATION

The principal process engineering of a stationary or a mobile SOFC-GT system is very similar. The potential efficiency of any combined fuel cell - heat engine system has been estimated with about 80 % by a generalised thermodynamic model already in 1993 (1). This model can be used to understand the principles. The fuel cell is a "power producing burner" only defined by the ratio of delivered power and heat in the area of thermal engineering. The resulting engineering tasks are listed in fig. 3. The thermal integration of the fuel processing is necessary to avoid entropy losses by an extra combustion that can lead to efficiency losses in the order of 10 % as already shown in (2), (3). The ideal generalised cycle shows that the heat recovery process for the air heating and the fuel
heating is independent of the heat engine cycle. But we have a real process and we get a matching between the heat engine and the air heating, if we use a common gas turbine (GT) as the heat engine. Here the air flow of the fuel cell becomes a part of the GT process as well. The design process of such a GT cycle is now directly determined by the restrictions of the thermal stresses of the SOFC. The maximal allowable temperature difference $\Delta \theta_{\text{max}}$ between the inlet and the outlet temperature of the cathode e.g. 150 K delivers a very high air flow for the SOFC cooling only by air. If we allow this, the waste gas loss drastically increases and the system (or electric) efficiency can become lower than the cell efficiency itself. Thus any successful cooling strategy of a SOFC integrated in the SOFC-GT system must avoid a high excess air at the outlet of the total system.

Figure 3
The generalised fuel cell - heat engine cycle and the tasks of the thermal engineering

Fig. 4 shows an example of a SOFC - GT cycle with an external cooling (EXCO) to avoid a high excess air. The incoming air and the incoming fuel are heated by the flue gas of the SOFC as shown by the reference cycle in fig. 3. The cooled flue gas is reheated by the integrated coolers of the SOFC and is expanded in the gas turbine. The integrated reformer is used as an additional cell cooling. A combination with a steam turbine cycle is a further possible improvement for stationary applications. Here the waste heat of the gas turbine is used to produce steam to be injected before the gas heater integrated in the SOFC stack (steam injected GT). A part of the steam can be injected in the fuel pipe before the reformer. This process delivers an efficiency of 76% as published e.g. in (2). The depleted anode gas flow can be recycled as a steam source for the reforming as well and we obtain here without any steam generation and with a high waste gas temperature an efficiency of about 70%.

Figure 4
The EXCO cycle with steam injection

An efficiency of about 80% is possible in combination with a reheat gas turbine process as recent studies showed (4). The EXCO cycle as shown in fig. 4 is expanded now by a second low pressure SOFC-GT module instead of the waste heat boiler and the flue gas condenser, see fig. 5. The EXCO design is the first stage of the Reheat SOFC-GT steam turbine (RH SOFC-GT-ST) cycle. The
first GT, after the high pressure section (HP-SOFC module) as the first stage, is named as "waste air turbine" to show that the waste air is used as the combustion air of the second stage. The second stage, the low pressure (LP) section, doesn't need any external gas cooler because the comparable small LP-SOFC module is cooled by a comparable high waste air flow coming from the HP-SOFC module. The waste gas boiler of the ST cycle is supplied with the flue gas of the last GT - the "flue gas turbine" - to use the waste heat of the SOFC-GT modules in a most efficient way. The size of the components show that this type of cycle is interesting for a capacity > 10 MW. A similar cycle without a steam cycle is interesting for a smaller capacity and the efficiency is between 70 and 75 %.

**Figure 5**
The RH SOFC-GT-ST cycle

The necessary design study for this type of cycles has been already done in 1994 for the ECXO cycle as shown in fig. 4. In the centre of the main floor we can see the axis generator - gas turbine - waste heat boiler - flue gas condenser - stack. The new technology of the SOFC leads to a four pass design of all components directly connected with the SOFC. The four pressure vessels containing the SOFC are arranged around the mentioned axis generator to stack. Each vessel can be supplied with air and fuel separately via the heat exchanger systems. The four compressors are electrically powered. The compressors and the heat exchangers are on the ground flour. The

**Figure 6**
Design study of a 50 MW SOFC-GT plant

design of the 50 MW unit showed that the SOFC technology can be pretty good integrated in the existing technology (2). Only the SOFC module and the interfaces are the completely new designs. The study already showed that the size of these plants is equal to actual CCGT plants. But a new development of system components as microturbines and new stack designs as well will generate the new applications with very small capacities as discussed below.

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The interesting developments of the last years that made a mobile SOFC-GT application to an realistic option are collected in fig. 7. The temperature gradients that can be realised by a thin tubular SOFC, as shown by K. Kendall et. al. (5), gives the impression that thin tubes could solve the start-up problem of the SOFC in mobile applications. The temperature gradient is now 200 K/min in stead of 200 K/h. The second benefit of thin tubes in general is the high power density > 1 kW/l. The development and the market introduction of the microturbines shows the availability of small sized turbines down to 25 kW capacity (6). These developments initiated the own study about the feasibility of a mobile SOFC-GT system however a mobile SOFC was already described (7). The results show that a further consideration of the possible realisation seems to be useful (8).

Figure 7
The basic innovations for a mobile SOFC-GT system

The high efficiency of SOFC-GT cycles, the comparable simple use of Diesel oil and other hydrocarbons and the long lifetime of the SOFC were very motivating to start investigations of such designs with students (9). The main purpose of the reported work was to find out, what restrictions could occur by integrating such a system in a car. Thus a principle design study was necessary. The general thermodynamic theory is the same as for the stationary system. But the process design is strongly influenced by the demand on a very short start-up time.

Figure 8
Start up and design target formulated in 1998

The total energy system on board of a vehicle driven by a SOFC-GT system consists of three sources of electric power : the SOFC, the gas turbine and the battery. Two of them, the battery and the gas turbine will be immediately available for the propulsion. There are two principle extreme possibilities to assure the power supply of the car during the heating-up time of the SOFC module. The capacity of
the batteries can be extended to deliver the required power during the start-up time or the capacity of the microturbine can be increased to deliver the needed power during the heat-up phase of the SOFC. If the batteries are extended the dead load of the car increases and this will reduce the total efficiency of the automotive system. The electric efficiency of the SOFC-GT system decreases with a decreasing SOFC capacity share too because an increasing part of the used fuel is burnt in the burner of the microturbine and not in the SOFC. Both influences should be deeper analysed and optimised. The minimum available microturbine of today has a capacity of 25 kW. The size of the microturbine was thus fixed to 25 kW for the above mentioned design study. This is one third of the total system capacity of 75 kW. Fig. 8 shows the principles of the chosen start-up procedure.

The difference between a stationary and a mobile SOFC-GT lead to the following restrictions for a mobile system design. The required space of the system is a key issue. Thus the higher pressure losses must be accepted to decrease the required volume of the SOFC module including the heat exchangers. The influence of the leakage within the stages of gas turbines increases with a decreasing size of the gas turbine. Thus the compressor and the turbine of a microturbine have a smaller isentropic efficiency as a gas turbine in a power plant and the pressure ratio is smaller than in a large gas turbine. A cycle model was used to calculate the basic design data. The calculations of the mobile SOFC-GT system showed the connections between the electric efficiency and the above mentioned restrictions of the mobile system. Fig. 9 shows the results.

**Figure 9**
The influences on the efficiency of mobile SOFC-GT systems at 900 °C SOFC module temperature

The decrease of the isentropic efficiency of the compressor and the turbine is illustrated by an efficiency curve for an isentropic efficiency of 88 % of the compressor and an isentropic efficiency of 92 % of the turbine as known from big power plant gas turbines and the reduced values 80 % and 85 % of a microturbine. The relation of the sizes of the SOFC and the gas turbine is the ideal relation for a maximum efficiency at any pressure level. The influence of the isentropic efficiency increases with the SOFC module pressure. The fixed combination of the capacities, 1/3 gas turbine and 2/3 SOFC, as chosen for the study delivers always a lower efficiency than the ideal relation. But the influence on the efficiency decreases with an increasing SOFC module pressure. Finally the demand of reducing the volume leads to an increase of the pressure loss of the heat exchangers to increase the heat transfer coefficient. It is important to choose a microturbine with a SOFC module pressure of 4 bar or higher to reduce the negative influences of the pressure loss. It is necessary to consider the fixed capacity relation of
microturbine and SOFC module in combination with the battery as mentioned above in a later stage and an efficiency of about 55% may be obtained.

These results led to the conceptual design as shown in fig. 10. The necessary information about the dimensions of the car was taken from an actual compact mid-class car. The pressurised SOFC module including the air and the fuel heaters is under the hood of the car. The microturbine is flanged directly at the SOFC module. The batteries, the power electronic and the fuel tank are positioned in the mid and at the rear of the car. One interesting result of the design study is that the placement of the components left a still available space. Thus the failure tolerance of the system design is comparable high because there is still a reserve of space available that could be used for possible corrections if the further developments should show that some assumptions had been too optimistic.

**Figure 10**
Design study of a mobile 75 kW SOFC-GT power train system

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**FUTURE DEVELOPMENTS IN THE PRODUCTION TECHNOLOGY**

An important step to realise such designs is the development of stacks allowing the demanded short start-up times within a few minutes and the necessary power density. A key component will be the thin SOFC tube. The options to produce this key component are increasing. The extrusion process as reported in e.g. (5) with the results shown in fig. 7 and a tube production by the electrophoretic deposition technology (10) are already documented in the literature.

**Figure 11**
Micro-tube for a mobile SOFC application. Source: K. Rennebeck (11)

An other interesting emerging technology is the use of the spinning process to produce the needed thin tubes at comparable low cost. The simultaneous spinning of two layers is a further interesting
option of this production process (11). Fig. 11 shows a sample of the micro-tubes produced by a spinning process.

The increase of the power density with the decrease of the tube diameter shows the importance of matching the system design and the stack design as well to achieve the lowest possible unit cost. The connection between tube diameter and the insulation volume and the pressure vessel material volume and thus the cost has been already shown in (12). The high power density of small tubes leads to a smaller power related surface and thus to a smaller power related consumption of surrounding material.

The big changes in the production technology, that may be expected as mentioned above, can also strongly influence the infrastructure of the power industry operating gas or oil fired units. Generally the operation of automotive engines and power plants are following the same thermodynamic principles. But the manufacturing process, the actual load characteristics and the operational demands are completely different. The mass production of automobiles and the most mobile applications is governed by the laws of the economy of quantity, fig. 12. The economy of scale of power plants depends on the savings by the increasing size of the plant. This is one major reason of the different technical solutions and cultures of mobile and stationary applications. Only the ship engines are mobile applications that depend on the economy of scale like power plants. The use of automotive engines for stationary power applications did not really succeed yet. There is a high probability, that the stacking of fuel cells and the modularization of stacks will lead to an economy of quantity in the power industry similar to the automotive industry. The expected development to use fuel cells for a distributed generation with a high electric efficiency > 60 % will give an interesting option for an increase of the use of mass produced power generators in the future. Any fuel cell system with a similar or a higher efficiency as a conventional CCGT can be operated to supply the power demand only and has the benefit that the erection time is shorter and the size of the total installed capacity of the fuel cell systems can be closely matched with the power demand by the number of this small units.

Figure 12
Synergies between mobile and stationary applications

Thus the total capital needed of a decentralised park of high efficient fuel cell systems will be lower than that of one big CCGT unit if the power related investment cost are equal. A further but only additional benefit of a decentralised park of high efficient fuel cell systems is the possible use of the waste heat for heating purposes. It will be interesting to see the possible future interactions between the power industry and the automotive industry in that field. There is no doubt that the automotive application will be the driving force to develop cheap mass production technologies.
CONCLUSIONS

The small tubular SOFC will become a key component of the further development. The main benefits are the short start-up time and the high power density that allows automotive applications with a high number of produced units and that reduces the cost of the surrounding system at stationary applications too. The efficiency of the mobile and the stationary SOFC-GT application is clearly higher than any competing technology. The actual fuel logistic and any regenerative fuel as well can be used by such systems. But the measure for the cost are the competing technologies however there are a lot of benefits of SOFC-GT systems that are important for an economic and sustainable development. The results of the studies encourage a further and deeper consideration with the SOFC-GT technology at the different applications.

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