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Design studies of mobile applications with SOFC–heat engine modules

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Abstract

The recent development of thin tubular solid oxide fuel cells (SOFCs), microturbines and Stirling engines has inspired design studies of the integration of a SOFC–heat engine (HE) system within a car. The total power system consists of a SOFC–HE power generation unit, a power storage (battery) system, a power management system and electric motors at the wheels. The sizes of the HE and the SOFC stack are to be matched by the start-up requirements. The use of micro tubes allows a very high power density of the stack. The thermodynamic calculation of the cycle gives the actual design values for the study and indicates further steps for system optimisation. The first SOFC–GT layout lead to an electric efficiency of 45% for the cycle used as a base for a design study [The Design of Stationary and Mobile SOFC–GT Systems, UECT, 2001]. The design study shows that the space available in a mid-class car allows the integration of such a system including space reserves. A further improvement of the system might allow an electric efficiency of more than 55%. The integration of a Stirling engine instead of the microturbine is a second possibility and the object of an ongoing study. This was motivated by interesting results from the development of solar powered Stirling engines. Generally, the analyses show that the optimal match of the SOFC and the HE will be a key issue for any engineering solution. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Mobile SOFC (solid oxide fuel cell); Stirling engine; Microturbine; SOFC–GT (solid oxide fuel cell–gas turbine); All electric car; Design studies

1. Background and former works

As shown in [1], the integration of a solid oxide fuel cell (SOFC)–GT power system in an all electric car concept seems to be possible. The power output of the mobile SOFC–GT system was set to 75 kW for the design study, Fig. 1. The result of the design study showed a still available space at the mid-class automotive platform. Thus the failure tolerance of the concept is fairly high.

The most important demands of mobile propulsion systems have been taken into account here. Especially the demands of a short start-up time, of an existing and thus a cheap fuel logistic and of low values of weight and volume can be met by the proposal. Interesting results of solar Stirling systems motivated us to extend this study.

In general there are two possibilities to approach the reference cycle of an isothermal operated fuel cell [2] with a direct heat extraction by a connected heat engine (HE). The SOFC stack can be cooled by an integrated cooling loop and the coolant is the working fluid of the connected heat cycle. Alternatively, the SOFC stack can be divided into sub-stacks and the oxygen rich flue gas of any sub-stack is cooled by a connected HE and is fed to the cathode of the next sub-stack. The mobile application and its demand for simplicity and small volumes excludes the second proposal and leads to the SOFC–HE cycle with an external cooling. A SOFC–GT cycle is shown in Fig. 2 [3,4]. The incoming air and the incoming fuel are heated by the flue gas of the SOFC and a gas turbine (GT) cycle is the connected heat cycle in this example. The cooled flue gas is reheated by the integrated coolers of the SOFC and expanded in the GT. The integrated reformer is used as additional cell cooling and the depleted anode gas flow can be recycled as a steam source for the reforming.

The use of total pressurised heat exchanger surfaces with comparable high heat transfer coefficients and the inevitable high integration of reforming and cell cooling allow a very compact system design. The cooling of the cell stack can be realised, e.g. by a radiation cooler. This leads to the demand of a high integration of the cooler in the stack. The heater of a Stirling engine can be built as a radiation cooler of the SOFC as well. The principle design of a SOFC–Stirling engine cycle is shown in Fig. 3.

In this case, the cooling loop and the reaction loop are divided and the working fluid of the Stirling engine is used as a coolant. Mostly helium is used as the working fluid of the

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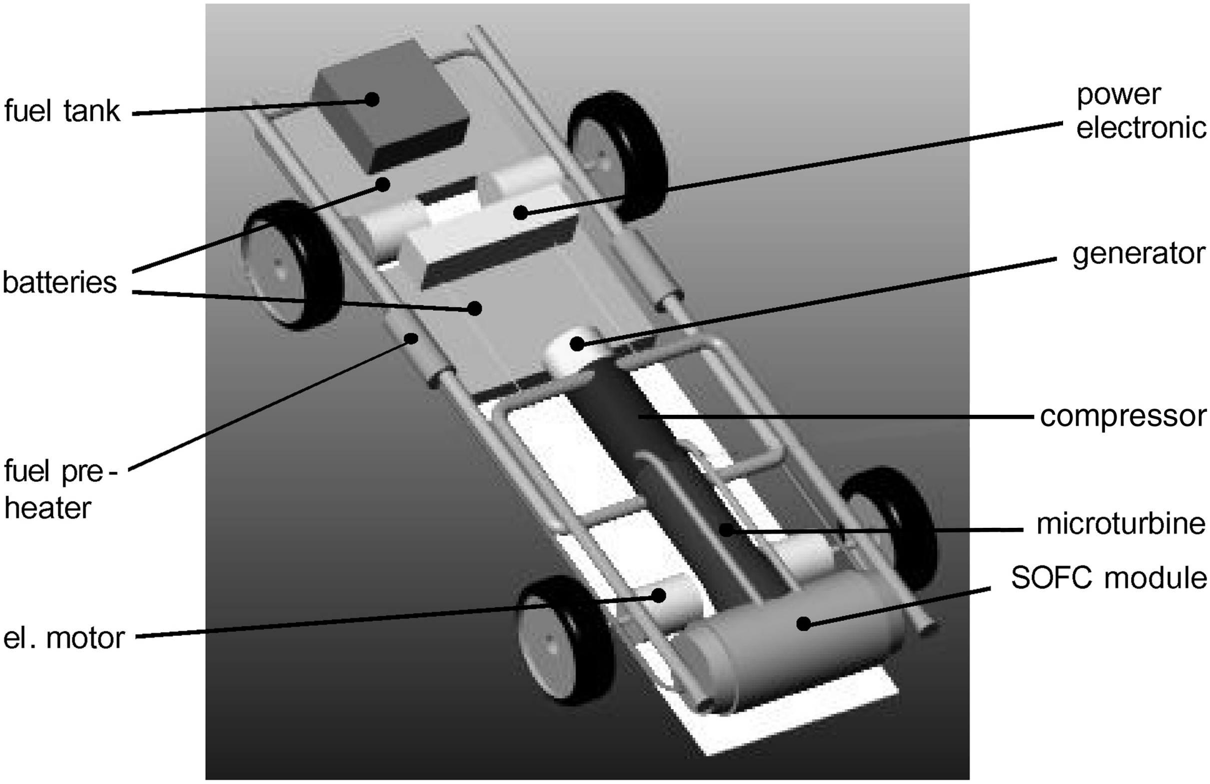


Fig. 1. Design study of a mobile 75 kW SOFC–GT power train system.

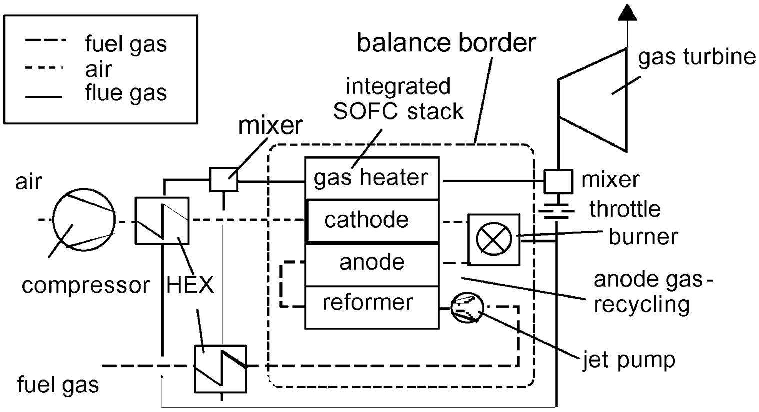


Fig. 2. The SOFC–GT cycle with an external cooling.

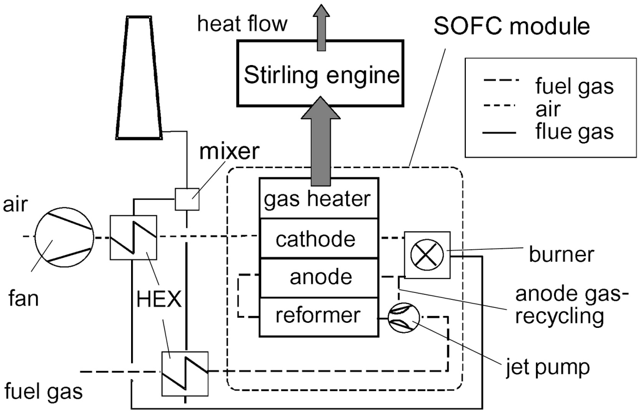


Fig. 3. The SOFC–Stirling cycle.

Stirling cycle. The heat recovery of the air and fuel supply system is similar to that of the SOFC–GT cycle. The fan is supplying the combustion air. This design was used for a first evaluation only. But it seems to be useful to use a turbocharger system for the air supply and to pressurise the stack.

2. New components for combined automotive systems

The realisation of these combined SOFC–HE systems for transportation depends on still ongoing developments in the cell design itself and on available small HEs. Temperature gradients of 200 K/min have been realised with thin tubular SOFC, as shown by Kendall et al. [5]. The cells with outer diameters of about 2 mm meet two main targets of the SOFC to be used in automotive applications. The first one is a relatively short start-up time and the second one is a high power density needed for weight and volume reduction of the stack. With the above mentioned temperature gradient the start-up time of the stack may reach a figure in the order of 5 min and the power density exceeds 1 kW/l when using the thin tubes [6].

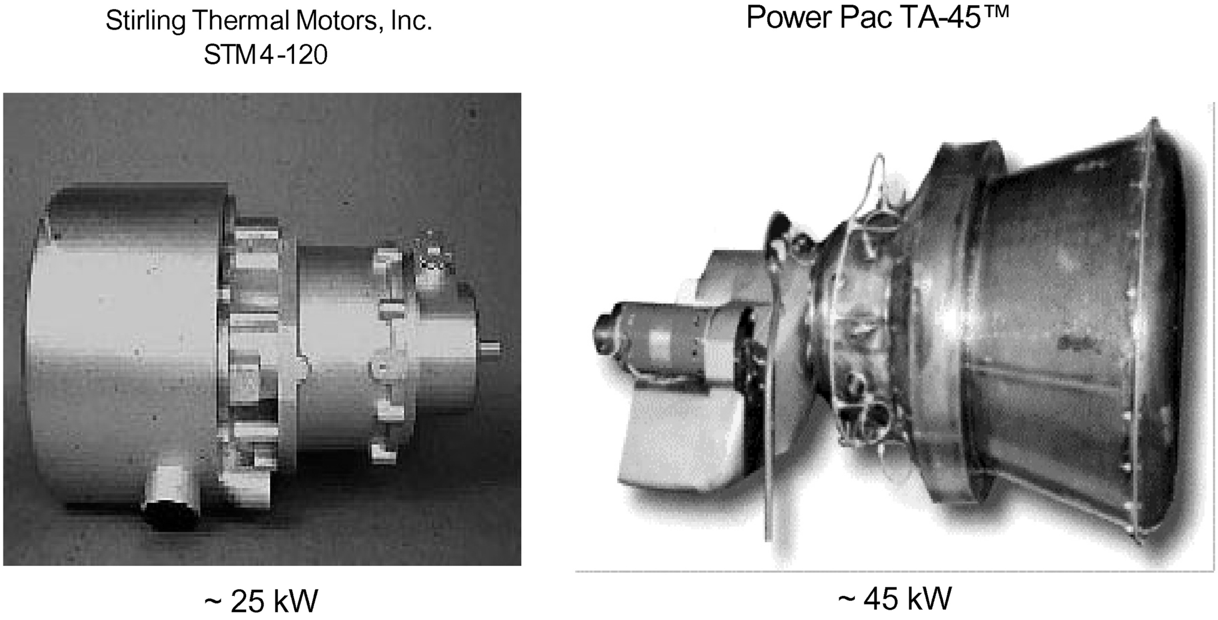
The integrated HE has to meet similar targets. But the demanded short start-up time is not a problem for a HE as proven in different applications. An oversized afterburner of the anode gas of the SOFC can be used as a start-up burner of the HE. The development and the market introduction of microturbines with capacities down to 25 kW were the necessary conditions of a first study in 1998. The recent developments of solar powered Stirling engines resulted in interesting ongoing approaches of Stirling engines as well. They promise at least two benefits, the first is a relative high electrical efficiency of up to 40%, the second is the low emission of noise. Built examples of both technologies can be seen in Fig. 4.

Both types of engines show a stage of development that might promise their use in automotive applications. Reciprocating engines are a well known automotive technology. The integration of turbo machines on board of motor cars is known from the common turbo-charger technology. Units with a power output as low as 25 kW are available in both designs. An important disadvantage of the microturbine is the decreasing efficiency with the decreasing size. The dynamic effects of larger units and the heat exchanger design are typical problems of the Stirling engine.

The availability of engines with a low power output is very important for an optimisation of the automotive system design. The interesting range of power output of the combined HE in an automotive application is between 10 and 30 kW. Fig. 5 gives an overview of the state of the art of existing microturbines and Stirling engines [7,8].

As a first impression the Stirling engine seems to show a better characteristic in all relevant parameters. But there are more detailed design studies necessary to evaluate both designs. Specially the integration of the heat exchanger in the stack and the HE cycle must be a topic of further studies. The specific volume of the microturbine and the Stirling engine as well may be decreased by integrating its heat exchanger system into the SOFC system. But the microturbine as a stand alone system has clearly the larger heat exchanger system. Because of the different ways of system integration a direct comparison of microturbine and Stirling engine is not possible yet.

Further necessary improvements are a higher integrated heat exchanger and reforming system and an electronic system for energy storage and power conversion to mechan-



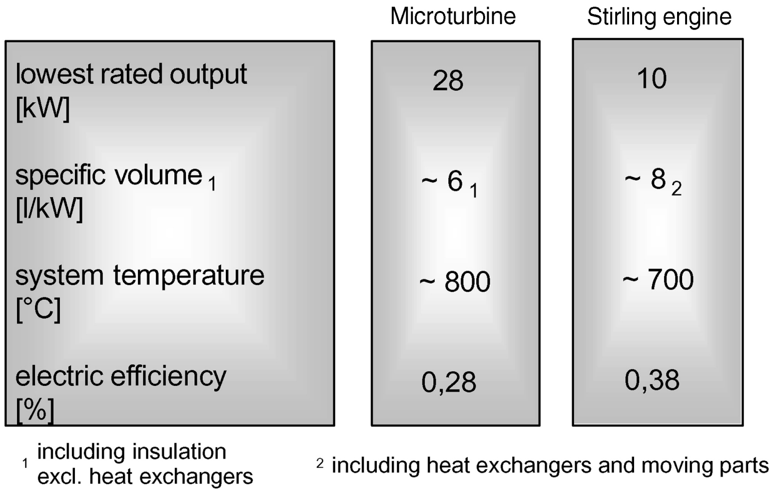
Stirling Thermal Motors, Inc.
STM 4-120

~ 25 kW

Power Pac TA-45™

~ 45 kW

Fig. 4. Industrial examples of a Stirling engine and a microturbine (sources: www.powerpac.com;grz08u.unileoben.ac.at/~m9435175/stirling/product.htm).



	Microturbine	Stirling engine
lowest rated output [kW]	28	10
specific volume $_1$ [l/kW]	~ 6 $_1$	~ 8 $_2$
system temperature [°C]	~ 800	~ 700
electric efficiency [%]	0,28	0,38

$_1$ including insulation excl. heat exchangers

^{2} including heat exchangers and moving parts

Fig. 5. Values of microturbine and Stirling engine important for the automotive energy system.

ical energy as well. As a result of this new design philosophy we can expect a required volume of the new design that is near to that of conventional propulsion systems.

3. The general design of SOFC–HE automotive systems

A general layout as shown in Fig. 6 can be used for the design studies of both technologies. This automotive power system is designed like an electric grid. The SOFC–HE module is the mid load power plant. The electricity storage e.g. a battery system is the peak load power plant and the power electronic is the load distributor.

The start-up operation strongly influences the system design. Two principle possibilities cause the limits of the study. The necessary power during the heat-up of the SOFC can be supplied by the batteries only or by the HE only.

The important influence of some effects of down-sizing on a SOFC–GT system had been already shown in [1]. A resulting decrease of the isentropic efficiencies of the compressor and the GT and a combination of the capacities, one-third GT and two-third SOFC, fixed by the start-up conditions, lowers the overall performance. Finally an increase of the heat transfer coefficient is needed to reduce the heating surfaces and thus the volume. An increasing flow velocity increases the pressure loss. The increasing pressure loss decreases the efficiency clearly at a lower system pressure. Therefore, the system pressure should not be lower than 4 bar. But the highest loss is caused by the combustion in the oversized GT.

There are no indications that a design with a Stirling engine has to be totally different. Thus the first analyses dealt with the maximum heat supplied by the SOFC and heating up the working fluid helium of the Stirling engine. The SOFC cooler is the heater of the Stirling engine in the SOFC–Stirling cycle as shown in Fig. 3. The exhaust gas of the fuel cell is only used for preheating the air and the fuel. A low value of the excess air, λ, is recommended to minimise the exhaust gas losses and maximise the heat supply of the Stirling engine. The above mentioned use of a turbo-charger

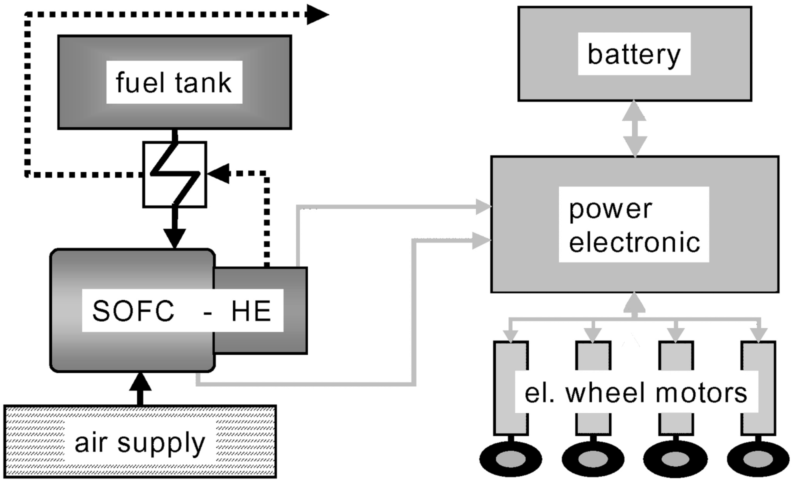


Fig. 6. The integration of the SOFC–HE system in the power train.

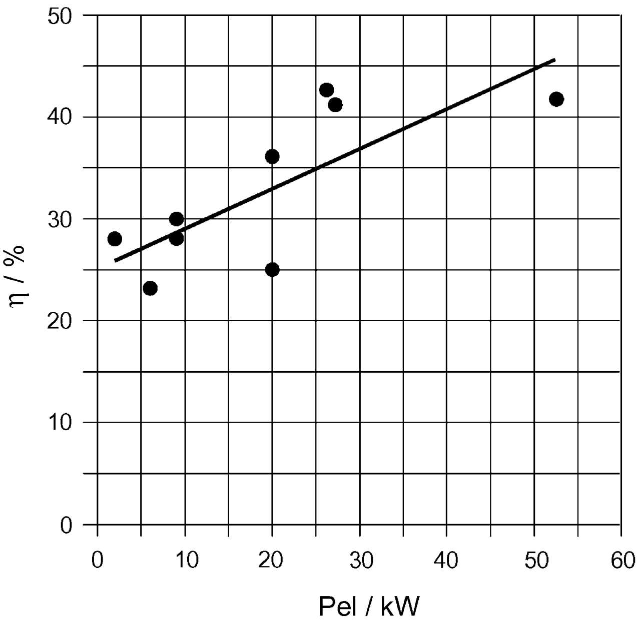


Fig. 7. The electric efficiency of available Stirling engines.

instead of a fan would increase the heat transfer coefficients and minimise the heat exchanger surfaces. Two parameters are important for high efficiencies of the Stirling process, the temperature difference between the hot and the cool piston and the pressure ratio of the engine. The fuel-related heat supplied by the SOFC has values between 12 and 16 MJ/kg diesel fuel of the SOFC at an excess air, λ, between 1 and 2 and a constant temperature between 800 and 1000 °C.

The data delivered by the different suppliers give a first impression of the potential of SOFC–Stirling systems. An analysis of the market delivers the efficiencies and working temperatures of available engines. In Fig. 7 [8] the electric efficiency is shown over the power output of the engine.

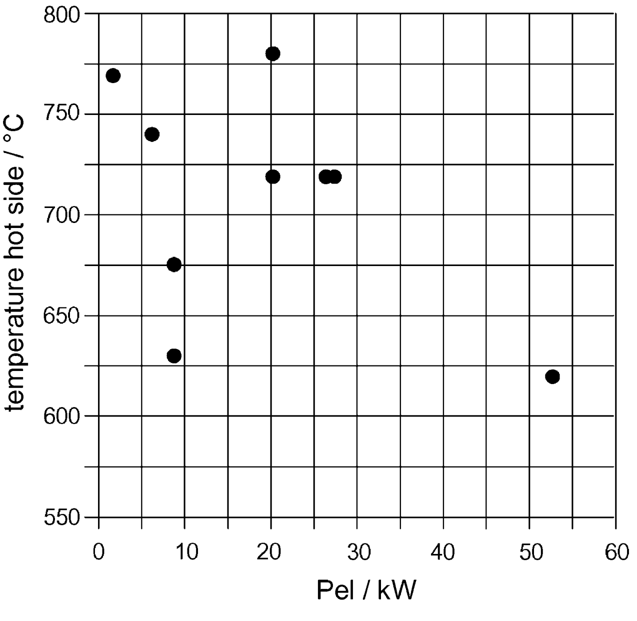


Fig. 8. The upper system temperature of available Stirling engines.

The increase of the power output increases the efficiency as known from all HEs. An other interesting item is the upper temperature of the hot piston, which is shown in Fig. 8. The heat should be supplied with a temperature between 650 and 780 °C. This meets the temperature target of mobile SOFC operation very good. The Carnot factor, representing any HE, reaches values between 64 and 68% at outlet temperatures between 30 and 80 °C. Assuming the environment ($T_0 = 25$ °C) as the heat sink the values of the exergetic efficiency rise to maximal 71%. With these informations an overall efficiency of the system can be calculated and values of more than 60% might be possible. The exhaust gas temperature of about 100 °C is another positive characteristic of the Stirling engine. Higher temperatures of about 500 °C will be measured at the GT outlet. But the microturbine is a very simple device compared with a Stirling engine that includes an operation with a turbo-charger. Further design studies are necessary to estimate the potential of both technologies more detailed.

4. Conclusion

The expected high system efficiency is the main reason for a further treatment of SOFC–Stirling engine cycles in mobile applications. Other reasons are low specific volumes and small available units. The heat extraction of the SOFC by a Stirling engine doesn't affect the combustion reaction because the coolant is the separated working fluid of the Stirling engine. But the coolant of the SOFC in a SOFC–GT cycle is always connected with the combustion reaction in the cell. First studies indicated the assumption that the design problems of such cycles should be solvable. The study of the SOFC–GT system confirmed the indicated benefits of an all electric car. In generally this concept could be used for SOFC–Stirling systems as well. Further design studies and a further development of the micro-sized SOFC tubes are necessary to gain more deeper results needed for later possible industrial projects.

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