Steady Operating Behaviour of a Screw-Type Supercharger-Expander Module for an Automotive Fuel Cell System

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1 Introduction

Since the early 90's automobile manufacturers and suppliers have been looking for a solution for future propulsion systems and started to develop alternative drive concepts. Especially stricter emission limits all over the world and concern about decreasing oil resources have resulted in rapid progress in this sector. Today all car manufacturers have presented alternative drive systems such as electric, hybrid or fuel cell systems. Among these systems fuel cell electric propulsion systems seem to have the highest potential to compete with the internal combustion engine and the fuel cell is the also most attractive option for a future hydrogen energy supply.

The best known example for this rapid and successful development of fuel cell vehicles is the NeCar-series by DaimlerChrysler. The first NeCar, introduced 1994, NeCar I, was built into a complete small bus without any room for passengers except for the driver. Since then power density and functionality have been improved and now, with NeCar IV and NeCar V, introduced in 1999 and 2000, two "real" cars with room for respectively four and two passengers, are driving around on our streets. Even so most systems today are still prototypes, so the objective of starting a serial production of fuel cell cars in 2004 must be deferred until later. Newer analyses predict market introduction with batch production in 2010 and serial production in 2020.

But although the systems have been dramatically reduced in size, a fuel cell system today is still very complex. Apart from the fuel cell itself, a fuel cell vehicle contains many subsystems: fuel and air supply, cooling, energy management, electric and electronic functions. The next objectives are to improve performance and to introduce high volume production for all systems in order to reduce costs.

An important part of a fuel cell propulsion system is an air supply system. This article describes steady operating behaviour of a supercharger-expander system with small screw-type machines together with a 50kW-PEM fuel cell stack. First the influence of geometric parameters like wrap angle, l/d-ratio and internal compression ratio of supercharger and expander are analysed. Based on the results two different arrangements of the components are discussed.

2 Fuel cells and screw-type machines

For vehicle applications, the polymer electrolyte membrane (PEM) fuel cell is preferred by most car manufacturers as the best solution. The membrane functions both as a gas separator and electrolyte, permitting the hydrogen fuel side to react with the oxidiser (in vehicle applications oxygen in the air) in a controlled manner (so called “cold reaction”) to produce power at the electrodes, **Figure 1**.

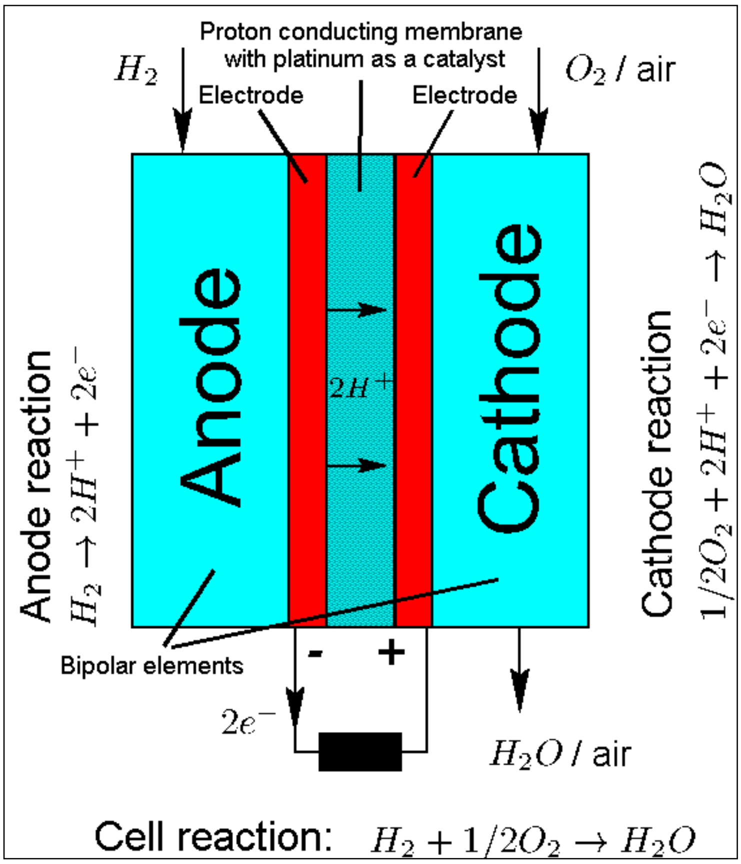

Fig. 1 Schematic diagram of PEM fuel cell

Hydrogen is fed to one electrode. A platinum coating catalyses the dissociation of hydrogen molecules into atoms and the ionisation of these atoms into hydrogen ions. Then protons leave the hydrogen electrode and enter the electrolyte, leaving behind electrons which give the hydrogen electrode a negative charge and polarity. At the other electrode, oxygen is dissociated and ionised by accepting electrons from the electrode and reacting with water.

If an external electric load is connected between the electrodes, an electric current will flow through the load as long as the flows of hydrogen and oxygen/air continue. Since no combustion is involved, the only chemical product from the operation of a hydrogen-oxygen fuel cell is water together with electricity and heat /1/.

Bipolar plates that enclose the electrolyte element distribute the cooling agent used to maintain the desired temperature. Normal operating temperature of a PEM fuel cell is about 80 degrees centigrade. In addition, these plates are used to couple several individual cells to form a combination called a stack to produce higher voltages. For example, NeCar IV uses two stacks, each consisting of 160 fuel cells, to deliver a total of 70 kilowatts of electric power /2/.

In mobile applications normally air and not pure oxygen is used for the cathode of the fuel cell. Because in air the partial pressure of oxygen is lower than in pure gas, the cathode is supplied with compressed air. Only with compressed air can the aims of high efficiency, power density and good dynamic performance together with compact dimensions of the stack be achieved. Today's fuel cell vehicle prototypes utilise a supercharger driven by an electric motor, sometimes in combination with an expansion machine to recover part of the compression energy and water from the waste steam. As a rule small screw-type machines are preferred in fuel cell electric propulsion systems.

A comparative study of different superchargers for small capacity Otto-cycle engines describes the technical status of mass-produced or close to production machines /3/. It evaluates the different systems to select possible solutions for a projected supercharger-engine-system and then points out directions for further development and additional potential for twin-screw-superchargers. Former investigations of twin-screw-superchargers for Otto-cycle engines /4,5/ indicated the potential and feasibility of a new load-control concept using rotary valves to control mass-flow and minimize the effective shaft power for a given pressure-ratio.

Similar criteria obtain also for superchargers and expanders for fuel cell automotive systems. In developing a new supercharger-expander-system for fuel cells, high boost pressure (even at small mass-flow), high part-load efficiency and varying the mass-flow of air delivered when changing the electric load of the propulsion system are the most important technical aims. When the system is evaluated, the cost of such a unit also has to be considered. A system based on small screw-type-machines can achieve these aims and is the one most commonly used today by various car manufacturers for boost pressured fuel cell electric propulsion systems /6/.

3 Influence of geometric parameters

3.1 Requirements

The selected PEM fuel cell for further investigations is a 50kW-PEM stack whose parameters are shown in **Fig. 2**. The values correspond approximately to technical requirements for compressor/expander units issued by the U.S. Department of Energy (DOE). This is a typical fuel cell stack for mobile applications to drive small passenger cars like NeCar III.

The exhaust temperature adopted for the fuel cell and also for the inlet temperature of the expander, is 80°C. The operating temperature of the PEM fuel cell is limited to this value. DOE specifies higher values, up to 120°C. The underlying mass-flow of the expander is 30% higher than the mass-flow of air delivered by the supercharger. This is due to a mass-flow coming from the anode and the fuel processor system,

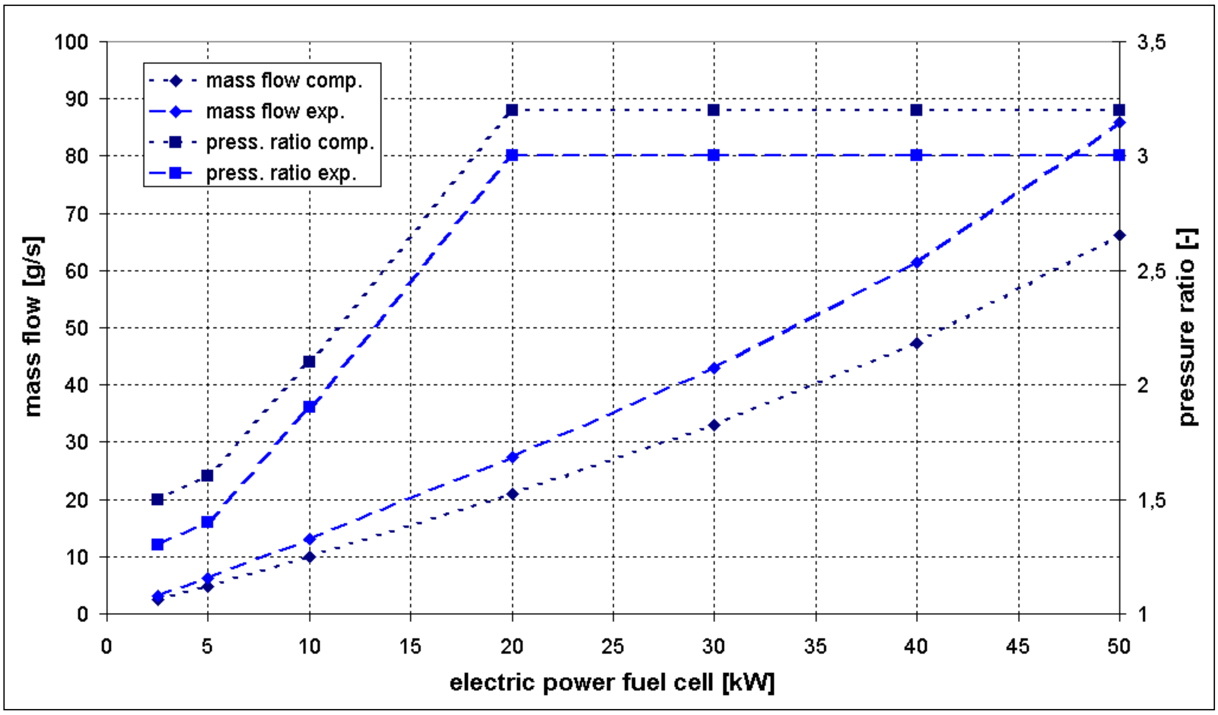

Fig. 2 Parameters of a 50kW-PEM fuel cell stack for simulation, adopted exhaust temperature is 80°C at all points

and it is also expanded in the screw-type-motor. A fuel processor is typical for a first generation fuel cell propulsion system to convert gasoline fuel into hydrogen.

The simulation is based on a self-developed comprehensive simulation software package for twin-screw compressors and expanders that traces back to former development of the GASSCREW /7/. The GASSCREW resembles in construction an air supply system for fuel cells. For this new application the software has been revised in order to cover a supercharger-expander module for fuel cell systems. **Figure 2** shows the main parameters of a fuel cell stack as the basics for supercharger and expander. Process gases are dry air for the supercharger and a mixture of air and steam for the expander. The effects of water injected into the supercharger and condensation of water in the expander are not factored in the simulation. To be able to research these effects in future a new thermodynamic simulation system of rotary displacement machines is being designed at the University of Dortmund.

3.2 Supercharger

Earlier simulation based research on twin-screw superchargers describes the influence of rotor geometry parameters on the efficiency of Lysholm-machines /8/. Important parameters are wrap angle Φ and length/diameter-ratio l/d. The choice of these values has a major influence on operating characteristic for specific uses.

Based on these results an initial geometry of a twin-screw supercharger for a fuel cell system was defined, **Tab. 1**. The diameter of the male rotor was calculated to achieve a maximal air flow (with the fuel cell producing 50 kW electric power) at a rotor tip speed of approx. 150 m/s. The selected rotor profile is a 3 + 6 asymmetric SRM profile which is utilised in superchargers for internal combustion engines.

	Selected values
Profile	asymmetric 3 + 6
Diameter male rotor D_{HR}	46 mm
Wrap angle Φ	150°
Length/diameter-ratio l/d	1.2
Internal compression ratio	2.1

Tab. 1: Initial values of supercharger geometry

Subsequently wrap angle, length/diameter-ratio and internal compression ratio were varied. Simulation results for changing wrap angle and l/d-ratio for a fuel cell supercharger are comparable to the results for superchargers fitted to engines. Reducing both values changes nearly all clearances and axial inlet- and outlet ports in the machine. The isentropic efficiency

$$\eta_{is} = \frac{P_{is}}{P_i} \quad \text{eq. (1)}$$

is a major criterion of energy efficiency, and is used to describe the influence of different rotor geometry parameters.

Changing the wrap angle to lower values reduces the housing gap between rotors and casing while the profile-meshing gap length and blowhole area increase. Also the gradient of the volume curve attains higher values. Therefore the time interval of a working-cycle, and consequently clearance flows, are lower. Otherwise lower wrap angles cause throttling at the outlet port because port area decreases. Recapitulating, a wrap angle of 150° results in high isentropic efficiency both at part and full electric load of the fuel cell compared to higher and lower wrap angles.

A small length/diameter-ratio of the rotors allows larger outlet-ports, reducing dissipative effects in flow at higher superchargers speeds. Otherwise gap areas increase with very small and higher l/d-ratios. Also the time intervals of the working cycle increase with increasing rotor diameter. Together these effects lead to a good compromise for the l/d-ratio at a value of 1.2, which was defined as starting point. Higher l/d-ratios allow a higher isentropic efficiency for an electric power output about 20 kW, but part-load efficiency decreases. High part-load efficiency is more important because a car is predominantly driven in this sector and not at full load. The results of geometry variation for a fuel cell supercharger show a significant match to simulations of twin-screw superchargers for internal combustion engines, so today's supercharger geometries are a good basis for further development in this sector.

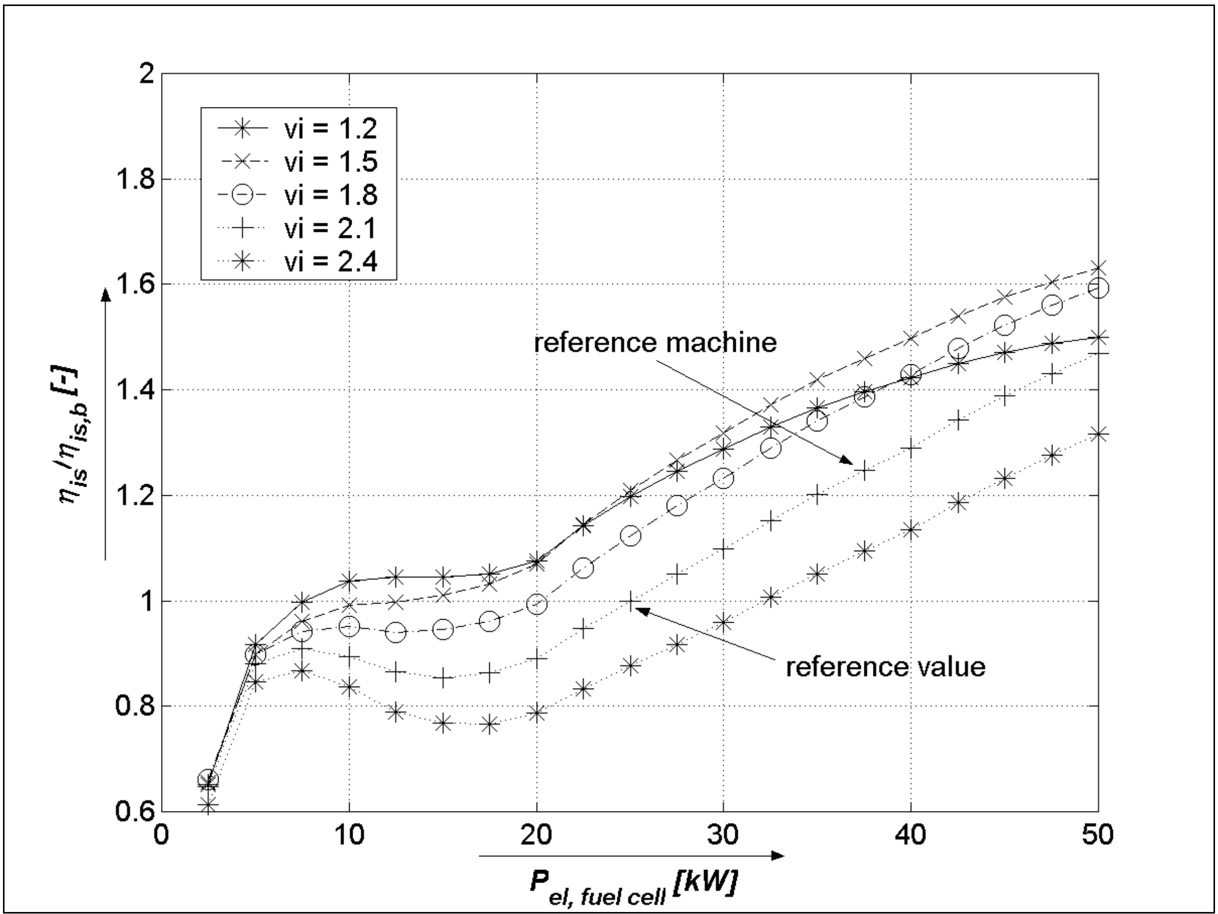

Fig. 3 Isentropic efficiency as function of different internal volume ratios and electric power of fuel cell
Reference values: v_i = 2.1; $P_{el,\ fuel\ cell}$ = 25 kW

Not only rotor geometry, but also the casing with its guiding edges and internal volume ratio influences the operating behaviour and efficiency of the supercharger, **Fig. 3**. The internal volume ratio has a major influence on the size of the discharge port. Reducing its value will increase the outlet area and reduce throttling at higher mass flows. The theoretical internal volume ratio can be calculated from

$$v_{i,\,th} = \Pi^{\frac{1}{\kappa}} \qquad \text{eq. (2).}$$

This application with a maximal boost pressure of 3.2 bar(abs) over a wide range has a theoretical internal volume ratio of nearly 2.3. Figure 3 shows that values near to a vi-ratio of 2.3 are connected to lower isentropic efficiencies. This is due to dissipative effects at the outlet-port at higher electric load and with higher mass flows of air delivered. Especially in these small, high speed superchargers the outlet-port area becomes very small and flow velocity increases. Therefore throttling leads to a higher boost pressure than needed.

Isentropic efficiency at lower internal volume ratios increases considerably. Internal compression and throttling at the discharge port together align maximal boost pressure to the pressure ratio of the cycle. So there is no over-compression and the specific energy is minimized. Additionally with lower internal volume ratios, part-load efficiency (between 5 and 22.5 kW electric fuel cell power) can achieve higher values. The required boost pressure is lower (see **Fig. 2**), and therefore a small vi-ratio can achieve a reduction in specific power needed.

The positive influence of different internal volume ratios on specific energy consumption leads to the question of using load-control concepts for the supercharger. Load-control concepts should be able to minimize the power consumed by the supercharger. Because of the required pressure (curve shown in **Fig. 2**) the system under consideration is not very much affected by changing the internal volume ratio from 1.5 to 1.2 at part load. Maximal boost pressure is already reached at 20 kW electric fuel cell power and constant at higher electric load. Considerable improvement with a load-control concept can be expected if maximum pressure is reached at higher electric power of the fuel cell. This is also a possibility, because fuel cell stacks are still under development and requirements for an air supply system can change at any time. The influence of a load-control system will be discussed later in the article.

3.3 Expander

At the moment there exists no simulation experience with such small screw-type machines for expansion as required in a fuel cell application. Former investigations were made of screw-type motors for the GASSCREW but temperatures, mass flow, pressure ratio and size are not comparable to a screw-type expander for a fuel cell propulsion system. Important parameters are also wrap angle Φ, length/diameter-ratio l/d and internal volume ratio vi, similar to the supercharger, but nevertheless the initial geometry of the expander is only a first guess, **Tab. 2**.

In principle changing the different values leads to same effects on clearances and outlet (in this case inlet) port as in the supercharger, but the consequences are perspicuously different, especially when the wrap angle is changed due to the reversed flow direction. The size of the inlet area and the time interval for intake exercise a major influence on energy efficiency if throttling and clearance flows during the intake phase can be reduced.

	Selected values
Profile	asymmetric 3 + 6
Diameter male rotor D_{HR}	38 mm
Wrap angle Φ	225°
Length/diameter-ratio l/d	2.0
Internal compression ratio	2.3

Tab. 2 Initial values of expander geometry

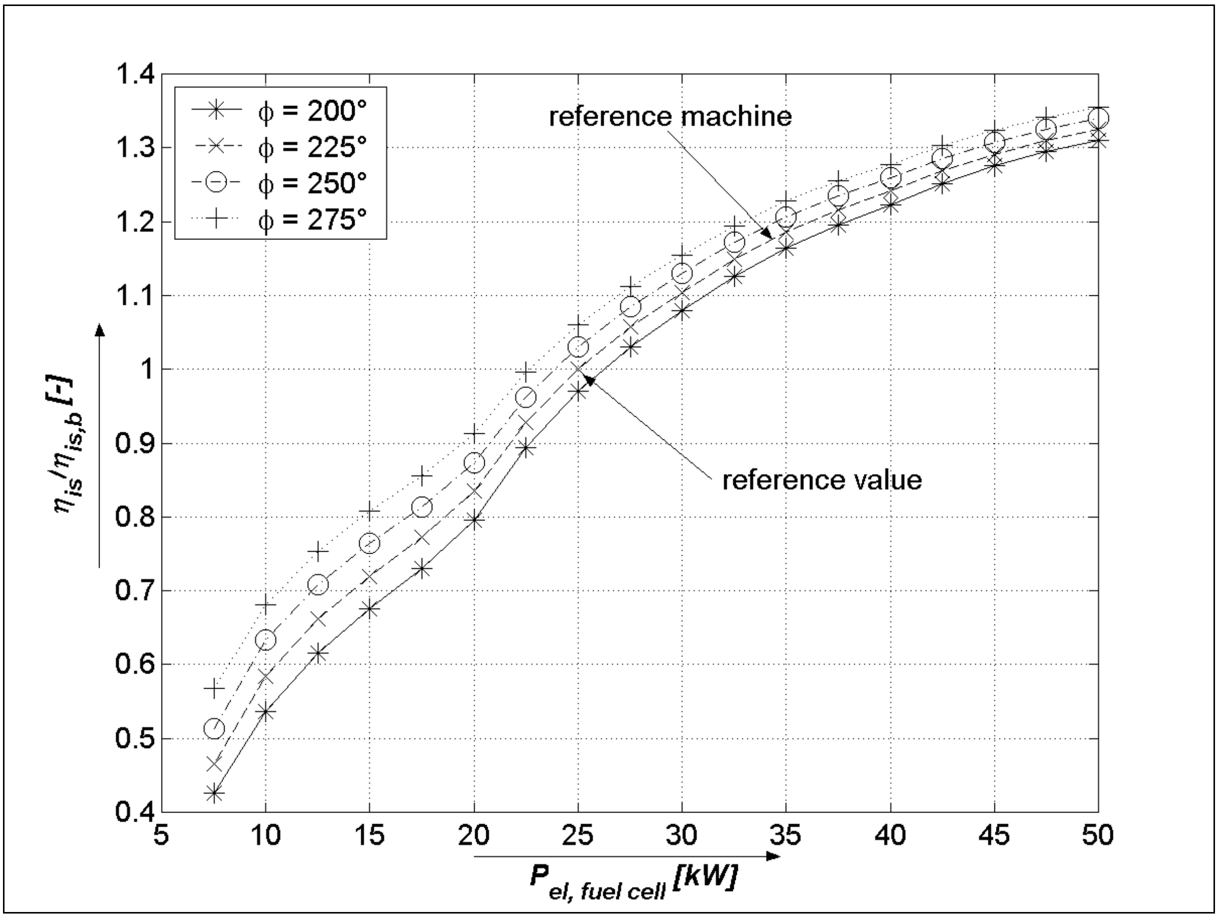

Fig. 4 Isentropic efficiency as function of different wrap angles Φ and electric power of fuel cell
Reference values: Φ = 225°; $P_{el, fuel cell}$ = 25 kW

Reducing the wrap angle will increase the inlet port and the time intervals available for inflow. This reduces dissipative effects at the inlet-port. Starting pressure and mass in the chamber when the intake-stroke is completed reach a higher value and isentropic efficiency improves, **Fig. 4**. Longer housing gaps of male and female rotors do not appear to have any influence.

Changing length/diameter-ratio and internal volume ratio to lower or higher values entail no significant improvement in isentropic efficiency. The initial values seem to be optimal for the application. With lower vi-ratios, pressure in the chamber when opening the outlet-port is higher than ambient pressure, so less than maximum specific energy is recovered and isentropic efficiency is reduced. Vi-ratios higher than 2.3 can lead to negative temperatures during the expansion process and are therefore impossible.

Clearance area and filling behaviour are also important factors for an optimal l/d-ratio, but require different improvement strategies. For further investigations into the influence of wrap angle, l/d-ratio and number of lobes on the duration of filling-process and clearance area, the new model of the chamber filling-process of screw-type engines is a possible solution /9/, in particular to investigate the influence of profile and number of lobes.

4 Steady operating behaviour

4.4 Decoupled system

To describe the quality of a supercharger-expander module a new variable, the energy self-sufficiency ratio D, is defined:

$$D = \frac{P_{e,Exp}}{P_{e,s-ch}} = \frac{\eta_{m,S-ch} \cdot \eta_{m,Exp} \cdot P_{i,Exp}}{P_{i,S-ch}} \qquad \text{eq. (3)}$$

The energy self-sufficiency ratio D specifies the proportion of effective expander power recovered relative to effective supercharger power required. A D-ratio of 1 is comparable to the gas-producer operating state of gas turbines, and describes the self-sufficient operating sector of supercharger and expander. Usually the energy self-sufficiency ratio of a supercharger-expander module will be lower than 1, simply because the inlet temperature of the expander is too low for higher power output. Therefore an auxiliary energy source is required.

The result of varying geometry parameters is an optimised rotor geometry of supercharger and expander, **Tab. 3**. The steady operating behaviour of these machines in connection with the fuel cell stack is shown in **Fig. 5**. *Decoupled* means that the two components, supercharger and expander, are free to rotate at different speeds. This arrangement requires no internal or external load-control systems; modulation to the mass flow takes place as a result of rotation.

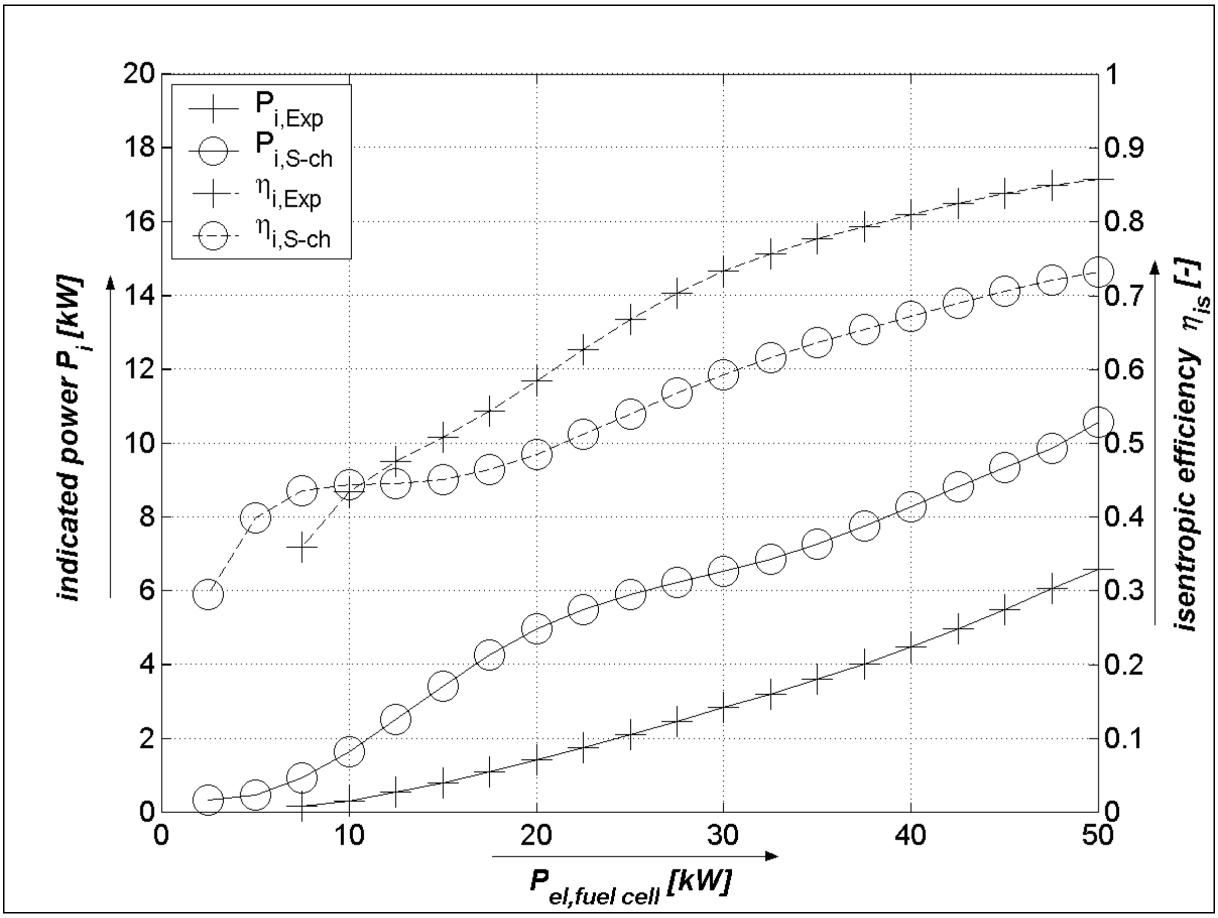

Fig. 5 Steady operating behaviour of a decoupled supercharger-expander module, indicated power P_i and isentropic efficiency η_{is} versus electric fuel cell power $P_{el,fuel\ cell}$

	Supercharger	**Expander**
Profile	asymmetric 3 + 6	asymmetric 3 + 6
Diameter male rotor D_{HR}	46 mm	38 mm
Wrap angle Φ	150°	275°
Length/diameter-ratio l/d	1.2	2.0
Internal compression ratio	2.1	2.3

Tab. 3 Optimised geometry parameters of supercharger and expander

There are two construction options for a decoupled system:

- supercharger with an electric drive and the expander with a generator are two totally separate, not connected systems,
- the two machines can be coupled by variable-ratio gearing and an electric drive. An electric drive is necessary due to the fact that the energy self-sufficiency ratio of the decoupled system only attains values between

minimum 0.2 (in part load area) and maximum 0.63 at full load (without consideration of the mechanical efficiencies of expander $\eta_{m,Exp}$ and supercharger $\eta_{m,S\text{-}ch}$).

4.5 Coupled system

In this configuration expander and supercharger are coupled by gearing or, even better, directly by the rotors, and rotational speed no longer has a degree of freedom. The expander sets the rotation limit for accepting the mass flow coming from the fuel cell. Therefore the rotation speed of the supercharger is also fixed. An internal or external load-control has to adjust the air mass flow delivered to the fuel cell cathode. An internal bypass, the pre-discharge valve, is used in this case to regulate mass flow. The pre-discharge valve alters the supercharger's delivery rate. A part of the air mass in the working chamber is blown off via the valve to the suction side. The specific function is described in /10/.

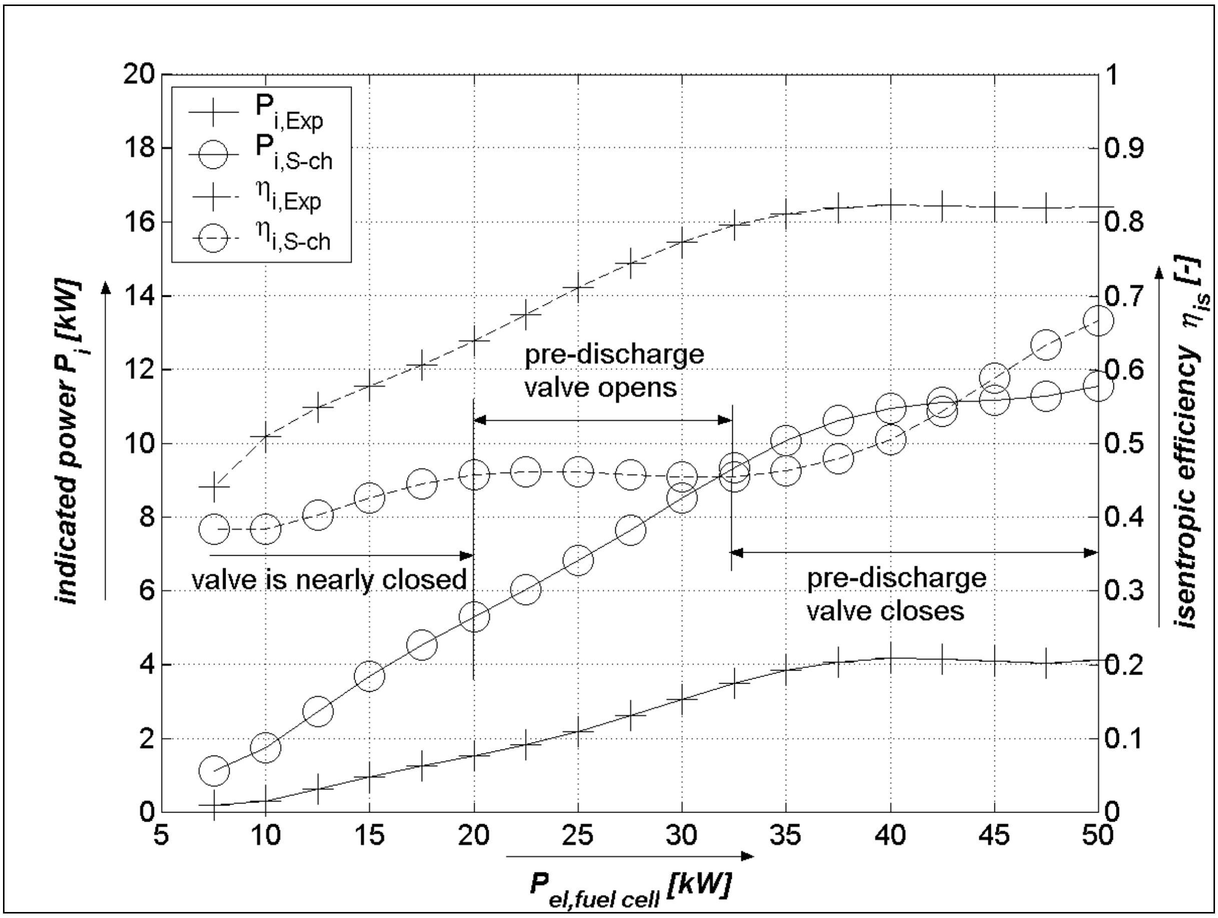

***Fig. 6** Steady operating behaviour of a coupled supercharger-expander module, asymmetric 5+6 expander profile, indicated power P_i and isentropic efficiency η_{is} versus electric fuel cell power $P_{el,fuel\ cell}$*

The rotation speed of the expander and supercharger referred to above at part and full load is extremely different. To adjust the gear ratio and to keep the optimal geometry parameters a new expander rotor profile had to be selected. With the a 5+6 profile a transmission ratio of 1.66 between male rotors can be achieved if the machines are coupled at the female rotors. Nevertheless the supercharger reaches a maximum rotor tip speed limit of 150 m/s at a fuel cell power of 32.5 kW. Above this point excessive expander mass flows off via a bypass, **Fig. 6**. This configuration was selected to allow cooperation of the machines particularly under part-load conditions. For comparison steady operating behaviour of the same components is shown as decoupled system in **Fig. 7**.

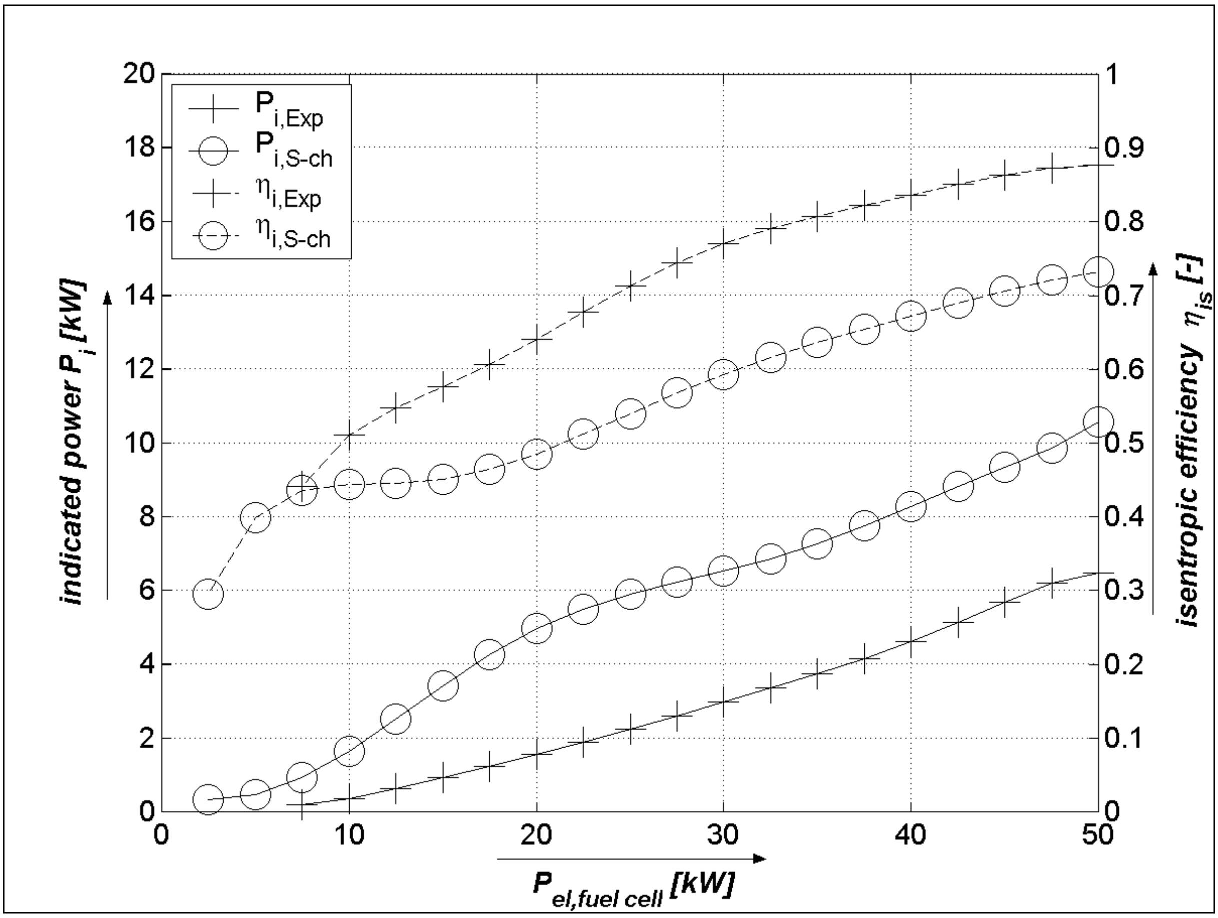

Fig. 7 ***Steady operating behaviour of a decoupled supercharger-expander module, asymmetric 5+6 expander profile, indicated power*** P_i ***and isentropic efficiency*** η_{is} ***versus electric fuel cell power*** $P_{el,fuel\ cell}$

The lower isentropic efficiency in comparison to the uncoupled system is very striking in the area between 20 and 50 kW electric fuel cell power, due to the influence of the pre-discharge valve. The valve opens gradually until electric power of 32.5 kW is being produced. At this point maximum rotation speed of expander and supercharger is reached (rotor tip speed of the supercharger is now 150 m/s) and the valve is in the fully open position. Isentropic efficiency until this point is nearly constant due to the influence of decreasing delivery rate. At higher electric power and air mass flow, the valve closes and isentropic efficiency rises to the same value as in the uncoupled system, due to the fact the pre-discharge valve is closed nearly completely at 50 kW fuel cell power.

The energy self-sufficient ratio of the coupled compared to the decoupled system is very much lower, resulting in higher power consumption of the supercharger and lower power recovery of the expander. Otherwise dimensions and costs of such a coupled configuration, important aims for automotive systems, will be lower. In order to improve the coupled system, a load-control concept for the expander has to be developed. It should allow better coordination of the rotation speed between expander and supercharger.

Another possibility for improvement would be a new small variable gearing. Module dimensions will also be small, and the energy self-sufficient ratio in simulation is already high at present and could be further improved by means of load-control concepts and new rotor profiles.

5 Conclusion

Screw-type machines are one possible solution for an air supply system for future fuel cell propulsion systems. The simulation of steady operating behaviour could confirm that supercharger and expander can work together in a supercharger-expander module. A considerable part of supercharger power consumption can be covered by recovered expander power, especially in a decoupled layout.

To improve the efficiency and energy self-sufficient ratio of a coupled system, further investigations of load-control concepts for both machines should be undertaken. Also the dimensions and costs of the unit could be reduced by this way.

In future transient operating behaviour will become a major criteria for the air supply system. Power consumption during acceleration and start-up time, for example in the range from 10% to 90% of air flow delivered, are central aspects. Therefore a new simulation program and further investigations of the total system consisting of supercharger, expander and electric drive in combination with the fuel cell stack are planned.

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