NUMERICAL INVESTIGATION OF A RADIAL TURBINE WITH VARIABLE NOZZLE GEOMETRY FOR FUEL CELL SYSTEMS IN AUTOMOTIVE APPLICATIONS

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ABSTRACT
In automotive fuel cell drives, electrically driven turbochargers are used to increase system pressure and improve efficiency. Due to the low operating temperature of the polymer electrolyte membrane fuel cell (PEMFC) and the resulting low exhaust gas temperature, the turbine power is not sufficient to drive the compressor. Thus, this paper investigate the potential of efficiency increase when using variable turbine geometries in an experimentally validated numerical study. The variable geometries are analysed in detail. The results of the investigation are compared to the results of a non-variable turbocharger version. The numerical study shows that the use of variable turbine geometries is beneficial in PEMFC air supply systems since the operating range enhancement leads to better coverage of the operating line. In addition, the variable nozzle turbine results in improved efficiency at higher pressure ratios.

KEYWORDS
RADIAL TURBINE, VARIABLE GEOMETRY TURBINE, VARIABLE NOZZLE TURBINE, ENERGY RECOVERY, FUEL CELL AIR SUPPLY

NOMENCLATURE
\( \Delta \) Difference
\( \dot{m}_{\text{corr}} \) Corrected mass flow
\( \eta_{\text{is,t}} \) Total isentropic efficiency
\( \pi_{\text{t,34}} \) Total pressure ratio of the turbine
\( n \) Turbine speed
\( p_{\text{t,3}} \) Total pressure at turbine inlet
\( p_{\text{t,4}} \) Total pressure at turbine outlet
\( T_{\text{s,3}} \) Static temperature at turbine inlet
BT Baseline turbine
CFD Computational Fluid Dynamics
CI Confidence interval
DP Design Point
FCOL Fuel cell operating line
LE Leading edge
PEMFC Proton Exchange Membrane Fuel Cell
RMS Root Mean Square
SST Shear Stress Transport
TE Trailing edge
VNT Variable nozzle turbine

INTRODUCTION
Due to the global climate situation and the associated national regulations for limiting exhaust emissions, automobile manufacturers in particular are being forced to develop alternative, future-proof drive concepts. Fuel cell systems offer a good option. To make fuel cell systems...
more efficient and also smaller, fuel cells can be operated at higher operating pressure (Cunningham et al., 2001). Kerviel et al. (2018) quantify the weight savings of the whole fuel cell system at 12.5 percent when increasing the pressure ratio from 2.8 to 4.0.

For this reason, research focuses currently on the air supply on the cathode side of a fuel cell. To compress the process air, a compressor is used, which, however, is the largest parasitic power consumer in the entire fuel cell system (Venturi et al., 2012). In order to improve the efficiency of the fuel cell system, a turbine can be used on the exhaust gas side of the fuel cell to recover power. Cunningham et al. (2000) presented a 14 percent improvement in net power capability by adding a static expansion turbine to an high pressure air supply system of a PEMFC. In addition, an improvement of the net efficiency by 4-5 percent in the high net power range could be shown. Due to the low temperature and thus enthalpy of the exhaust gas of a PEMFC, the recuperated energy of the turbine is not sufficient to drive the compressor. Therefore, PEMFC air supply systems often use an electrically driven turbocharger which causes the high parasitic losses mentioned above.

To further improve the efficiency of energy recovery by the turbine over the whole operating range and to adjust the operating points of the fuel cell, turbines can be equipped with variable features. Possible features, for which Feneley et al. (2017) provide an overview, can influence the orientation of the guide vanes located in the nozzle or the flow cross-section of the nozzle, the volute, or the outlet diffuser of the radial turbine.

**Variable turbine geometries**

One of the most commonly used variable feature is the variable nozzle turbine (VNT). The narrowest flow cross-section in the vaned nozzle is varied by pivoting the vanes, which allows the adjustment of the operating point (Malobabic, 1989). The adjustment also deflects the flow in such a way that an optimum efficiency can be achieved for the turbine rotor at different operating points.

Since the VNT concept results in increased gap losses due to gaps at the hub and shroud, Hu et al. (2018) have developed a concept to reduce the gap losses. The stator blades are split along the chord and can be moved relative to each other. The upstream part of the vane is fixed and has no gap, which makes it possible to reduce the blade tip vortex. It has been numerically shown that a 12 percent better efficiency can be achieved for small mass flows.

To reduce the complexity by reducing the number of moving parts, Franklin (1989) studied the concept of the sliding nozzle turbine. This concept allows a variation of the mass flow through an axially movable hub wall with fixed nozzle vanes. Compared to the VNT, the performance is similar, but the mechanism is simpler, more robust and less expensive. This concept of a sliding nozzle is applied in turbochargers for larger truck and bus engines (Feneley et al., 2017).

Shao et al. (1996) introduced axially movable stator vanes. Depending on the operating point, the concept allows the flow cross-section to be varied by axially inserting a vane by moving a vane sleeve over a smaller, fixed vane. In addition, the vane angle is adjusted by providing the fixed, smaller vane with a different vane angle from the larger vane sleeve.

In this numerical study, the two widely used variable concepts for radial turbines in turbochargers of automotive applications will be analysed under fuel cell operating conditions. These are the VNT and the sliding nozzle turbine. The concepts are investigated with regard to their potential for increasing efficiency for application in the air supply system of a fuel cell. In
addition, the adjustability of the operating points is analysed. To achieve this, turbine maps are numerically determined and investigated. The concept outlined above by Hu et al. (2018) will also be investigated in the future.

The hypotheses of this paper are that the two concepts lead to an improvement of the efficiency over a wide operating range. In addition, the variability of the concepts should allow an adjustment of the operating range of the fuel cell.

BASELINE TURBINE AND GEOMETRY VARIATIONS

The baseline geometry for the following investigation is the radial turbine geometry taken from the research project ARIEL “Charging of Fuel Cell Systems through Interdisciplinary Developed Electrically Driven Air Compressors”. As described by Menze et al. (2019), the project deals, among other things, with the aerodynamic further development of an electrically driven turbocharger that is used to supply air to a fuel cell system. As shown in Fig. 1, the radial turbine consists of a volute, a vaned nozzle, a turbine rotor and a subsequent axial diffuser outlet pipe.

In the first concept, the VNT, the nozzle vanes are rotated through various angles around the vanes’ centers of gravity along their perpendicular axis to vary the flow cross-section. Figure 2a shows the senses of rotation. The camber angle and blade thickness remain the same as in the baseline turbine. Gaps that occur at the hub and shroud, when using a VNT in the real system, are only considered at the shroud for the numerical map investigations in this paper. This can be explained by the fact that future experimental investigations will be carried out with static inserts for the vaned nozzle, which also allow only one gap.

The second concept, the sliding nozzle, is realized by reducing the height of the flow passage of the radial nozzle. As with the first concept, the camber angle and the position of the vanes remain the same as in the baseline turbine. Figure 2b shows the adjustment of the radial flow passage in the vaned nozzle.

NUMERICAL SETUP

In this paper, steady state simulations are conducted with the CFD software ANSYS CFX 19.2. The used numerical setup consists of a volute, a vaned nozzle, and a single passage of the
turbine rotor and an outlet pipe modeled with periodic boundary conditions. The vaned nozzle is modeled as a full 360 degree domain to better capture the asymmetry of the volute geometry and thus the flow in the simulation. The stator has a constant tip gap of 2.1 percent of the nozzle passage height. Along the rotor blade, the tip gap drops linearly from the leading edge of the blade to the trailing edge from 5.0 to 2.6 percent relative to the nozzle passage height. A backside cavity and an associated seal mass flow are not considered.

A frozen rotor approach is used for the interface between the vaned nozzle and rotating domain of the turbine rotor as well as between the turbine rotor and outlet pipe. Total pressure and static temperature are set as boundary conditions at the inlet and the outlet is specified by a static pressure. To generate turbine maps, the total pressure at the inlet of the domain is varied. To reproduce the temperature conditions of a PEMFC, the static temperature at the inlet is kept at a constant $T_{s,3} = 353.15 \text{K}$. Within the scope of these investigations, the simulations are performed with dry air as the ideal gas. The influence of humidity is not taken into account in this study, but it can have a weakening influence on the efficiency depending on the level of relative humidity, which Wittmann et al. (2021) points out in their investigations. For turbulence modelling, the two equation k-Omega SST model developed by Menter (1994) is used.

ANSYS Workbench Meshing is used to mesh the volute and the outlet pipe. The volute is meshed unstructured and the outlet pipe is meshed in a structured way. The vaned nozzle and turbine rotor are meshed structured with ANSYS Turbogrid 19.2. To resolve the boundary layer with low-Reynolds functions and to keep the computational effort as low as possible, $y^+$ values smaller than 2 are targeted. The number of elements for each domain as well as the maximum $y^+$ values at maximum speed and maximum mass flow rate are shown in Tab. 1 for the baseline radial turbine.

A numerical simulation is considered convergent in the context of this study if the RMS residuals are below $10^{-4}$, imbalances are below a maximum of 0.1 percent and observed integral

<table>
<thead>
<tr>
<th>Part</th>
<th>Volute</th>
<th>Vaned nozzle</th>
<th>Turbine rotor</th>
<th>Outlet pipe</th>
<th>Whole domain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of elements</strong></td>
<td>4,182,958</td>
<td>3,096,720</td>
<td>379,863</td>
<td>84,816</td>
<td>7,744,357</td>
</tr>
<tr>
<td><strong>$y^+$ values</strong></td>
<td>1.93</td>
<td>1.69</td>
<td>1.38</td>
<td>2.10</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1: **Number of elements in each domain**
quantities such as total pressure ratio, mass flow and performance show fluctuations smaller than 0.1 percent. Due to the fact that numerical simulations are subject to different types of errors, a mesh convergence study with three differently refined meshes according to ASME V&V 20 Committee (2009) was conducted to estimate the discretisation error.

**RESULTS**

The following results show turbine maps in which the corrected mass flow and isentropic total efficiency are plotted against the total pressure ratio. It is important to note that all values shown are normalised with the optimal-efficiency operating point at design speed of the baseline turbine investigated numerically.

This results in the definition of the normalised total pressure ratio using the total pressure at the inlet $p_{t,3}$ and at the outlet $p_{t,4}$:

$$\frac{\pi_{t,34}}{\pi_{t,34,DP}} = \frac{p_{t,3}}{p_{t,4}} \frac{p_{t,3,DP}}{p_{t,4,DP}} .$$

(1)

The normalised, corrected mass flow is calculated by relating the corrected mass flow $\dot{m}_{\text{corr}}$ to the corrected mass flow $\dot{m}_{\text{corr},DP}$ at the optimal-efficiency operating point at design speed. The total isentropic efficiency difference $\Delta \eta_{\text{is},t}$ is calculated as follows

$$\Delta \eta_{\text{is},t} = \eta_{\text{is},t} - \eta_{\text{is},t,DP} ,$$

(2)

whereby the difference is formed from the total efficiency $\eta_{\text{is},t}$ of a certain operating point and the total efficiency $\eta_{\text{is},t,DP}$ at the optimal-efficiency operating point at design speed.

**Experimental Validation**

At a later stage of the research project, experimental investigations will be carried out on the turbine with variable geometries. However, in order to validate the numerical data for the current paper, Volkswagen AG has provided experimental data of a comparable radial turbine, which has the same aerodynamic design. The measurements are performed with two straight measurement pipes at the turbine inlet and outlet, each with three Pt100 platinum resistance probes ($\pm 0.03 + 0.005 |T|\degree C$) and two static pressure sensors (0.1% FS). The mass flow is measured directly via the hot film anemometer principle using a Sensy-Flow IG ($\pm 0.9\%$).

Figure 3 shows a comparison of the experimental and numerical data from the baseline turbine (BT) at different speed lines. The differences in mass flow between CFD and experiment are due to small geometrical differences of the turbine configurations and the fact that in the simulations no seal mass flow is considered. Since the mass flow measurement in the experiment is carried out upstream of the seal air supply and the seal mass flow is not measured, an additional measurement uncertainty of 3 percent is taken into account towards larger mass flows. The comparison of the efficiency in Figure 3 also shows a good agreement. Slight deviations are due to the sensitive determination of the isentropic efficiency. Even slight deviations in the total pressure ratio or the temperatures can cause significantly different results.

**Baseline Turbine**

Figure 4 displays the turbine map of the baseline turbine without variable features by plotting the normalised reduced mass flow and the isentropic total efficiency over the total pressure ratio. In addition, the map shows that the desired fuel cell operating line (FCOL) cannot be
achieved by the baseline turbine in the range of low pressure ratios. A maximum mass flow deviation of about 20 percent at about 65 percent of the normalised total pressure ratio is shown. In addition, there are deviations in the range of the normalised total pressure ratio at the turbine design point of up to about 4 percent towards smaller normalised mass flows. The total isentropic efficiency shows a curve with a local maximum at each speed line, which rises with increasing speed. The shape of the curve is characteristic and can be explained by the change in mass flow and the resulting slight flow incidence at the rotor at constant speed. Thus, a slight suction-side inflow occurs when the mass flow decreases and a pressure-side inflow when it increases. The objective of the variable concepts is that the radial turbine with the VNT can also cover these operating points without greater loss in efficiency.

**Variable Nozzle Turbine**

For the turbine map investigation of the VNT, Fig. 5 shows both, the normalised corrected mass flow and the normalised efficiency, over the pressure ratio. It should be mentioned that the 70 percent VNT position corresponds to the baseline turbine.
It is shown that the corrected mass flow rate can be varied by adjusting the VNT positions, which indicates that the operating range is basically adjustable. At total pressure ratios above, mass flow variations of up to 60 percent related to the corrected mass flow at the design point can be achieved in the cases investigated.

However, the mass flow variation also shows that the operating line cannot be completely covered. This could be achieved by further opening the VNT. With the baseline turbine, however, this is not possible with the current chord length of the vane since this would lead to a collision with the volute casing. A reduction of the number of guide vanes or the solidity would also allow a further opening, whereby the fuel cell operating line could be covered and thus an operating point adjustability could be realised.

With the exception of the design speed line, the VNT position of the baseline turbine at 70 percent VNT opening has the highest efficiency. At design speed, an improved efficiency is achieved by slightly closing the VNT. In general, however, this represents an optimum design of the nozzle vane. An increase or reduction of the flow cross-section results in a reduction of the efficiency, which is similar to the case with classic VNT applications in the field of combustion engines (Shaaban, 2004).

In comparison with efficiency distributions of variable nozzle turbines in combustion engines, it is noticeable that the operating line of the fuel cell can be better covered by VNT positions with higher efficiency. This is shown by the fact that the variation of the flow cross-section of the nozzle leads to minor changes in efficiency for operating points in the area of the operating line. Despite only small necessary VNT variations, the operating line of the fuel cell can be covered above a normalised total pressure ratio of 0.7. Below the mentioned normalised total pressure, it should be investigated whether this trend will continue with further opening the VNT, which would be necessary to completely cover the operating range.

**Sliding Nozzle Turbine**

For the map investigation of the sliding nozzle, Fig. 6 shows both, the normalised corrected mass flow and the normalised efficiency, over the pressure ratio. The sliding nozzle mechanism...
Figure 5: **Norm. corrected mass flow and norm. total isentropic efficiency plotted over norm. total pressure ratio of the VNT**

also shows a mass flow variation which can be adjusted by the variable nozzle height, which allows a basic adjustment of the operating range. For the cases investigated, mass flow variations of up to 18 percent in relation to the corrected mass flow at the design point can be achieved at high pressure ratios.

However, the turbine map also shows that the sliding nozzle can not cover the operating line of the fuel cell. The shown potential for the variation of the mass flow suggests that the operating line can be covered by increasing the flow cross-section in the nozzle. This could be achieved by reducing the number of vanes or by redesigning the turbine in terms of nozzle width.

With regard to the efficiency distribution, it can be observed that the efficiency is reduced by reducing the nozzle width. The shifted hub in the nozzle results in a step for the inflow, which causes losses due to flow separation. To further reduce the loss of efficiency, the hub contour at the inlet of the nozzle could be designed to be more aerodynamically favourable. In the area
outside the peak efficiency of a speed line, the influence of the step is also superimposed by the influence of the incident flow of the rotor, which also has a negative effect on the efficiency.

**CONCLUSIONS AND OUTLOOK**

The influence on the efficiency and the mass flow of two mechanisms for adjusting a radial turbine for a fuel cell air supply was investigated. The objective was an improvement in efficiency and operating range.

In general, both concepts allow an adjustability of the operating range by varying the flow cross-section in the nozzle to adjust pressure and mass flow. However, neither concept completely covers the required operating range of the fuel cell on which the present paper is based, especially at low total pressure ratios. For better coverage of the operating range, a redesign of the turbine or a further opening at the VNT with shorter vanes would be necessary. Covering the operating range with the variable turbine would be an advantage, as no additional valve is needed in the system to control the compressor back pressure to generate the operating pressure of the fuel cell.
The efficiency could be slightly improved by the VNT at higher total pressure ratios and for larger flow cross-sections in the nozzle. Otherwise, the VNT feature resulted in a slight reduction of the efficiency due to the pivoting of the vanes and the associated flow incidence of the rotor. However, it was shown that a smaller variation of the flow cross-section is required to cover the operating line of the fuel cell compared to VNT applications in the field of combustion engines and therefore, the variation leads to reduced losses in efficiency.

To validate the variable concepts on the turbine investigated in this paper, experiments will be carried out on turbocharger prototypes with static inserts. These results will be presented in future publications.

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