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Design of a variable passive ejector for hydrogen recirculation of a PEM fuel cell system

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ABSTRACT

In order to increase the overall efficiency of the Polymer Electrolyte Membrane (PEM) fuel cell system the recirculation of excess hydrogen from the fuel cell outlet to the inlet can be conducted by a passive hydrogen ejector instead of an electric hydrogen pump. The disadvantage of a hydrogen ejector with a fixed layout is that it does not cover the necessary range of the fuel cell operating conditions from low to high power. Therefore, in this study a new approach for thoroughly analyzing the influence of variable geometric parameters on the recirculation performance of the passive hydrogen ejector is investigated by Computational Fluid Dynamics (CFD) simulations. Based on a sensitivity analysis the nozzle radius has been identified as geometric parameters which has the largest effect on the mass flow and mass flow ratio. A moving needle concept has been selected as most suitable to vary the nozzle cross section. Compared to a passive recirculation unit with a fixed ejector geometry for a fuel cell operation limited to 100 kW the needle concept allows an operation from 17 kW to 100 kW of fuel cell power. An additional optimization with a two-step needle can further reduce the sensitivity of the fuel cell pressure drop from 50 mbar to 70 mbar on the necessary mass flow at low fuel cell power. System simulations of the hydrogen ejector confirm that the variable recirculation unit can be operated also under dynamic operation of the fuel cell system by maintaining the necessary mass flow and mass flow ratio.

1. Introduction

In recent years, fuel cell systems are becoming popular in several applications. Especially Polymer Electrolyte Membrane (PEM) fuel cell systems are used as energy converters in mobile applications in electric drive trains [1]. The power density of a PEM fuel cell system and its efficiency are behaving contradictory. On the one hand, high volumetric and gravimetric power densities are necessary for mobile applications to match the requirements for the limited space and the necessary load for the transport of persons or goods. On the other hand, an increase in efficiency is targeted for an efficient use of energy and the related costs of the consumed hydrogen. To increase the efficiency of the PEM fuel cell system, not only the design of the active materials and the PEM fuel cell stack are relevant, but also the required power for the balance of plant (BOP) components. The anode subsystem supplies hydrogen to the PEM fuel cell. It is installed as a recirculation system to feed the excess hydrogen of the fuel cell outlet back to the inlet to save hydrogen and thus increase the overall efficiency. Higher hydrogen mass flows on the anode side to help discharge liquid water and to prevent hydrogen undersupply which is critical for degradation [2]. The excess hydrogen cannot be further reduced without reducing efficiency or lifetime. Another relevant effect is the crossover of nitrogen contained in the air from the cathode side over the membrane onto the anode side. This leads to an increase in nitrogen concentration and reduction of hydrogen concentration in the anode gas over time [1] and further increases the recirculated mass flow. For the recirculation of the anode off-gas, an active recirculation pump can be used. Depending on the recirculated mass flow and the pressure drop, a certain electric power is needed for propulsion of the pump which results in a reduced overall system efficiency. The power of such a hydrogen recirculation pump is typically lower than for an air compressor on the cathode side of the PEM fuel cell system, but can lead to a reduced power of 1.47% [2]. One option to save the power of the BOP components is to replace the active hydrogen recirculation pump with a passive hydrogen ejector.

This passive hydrogen recirculation system does not require any external energy as it relies solely on the venturi effect to create the flow. This method, though beneficial in reducing the parasitic energy losses in the system, is not ideal to be used in dynamic applications such as for

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automobiles. The recirculation rate, or the amount of excess hydrogen being pumped from fuel cell outlet to the inlet side is directly coupled with the ejector geometry, which is responsible to create the pressure differential [3].

Since the fixed nozzle geometry can be optimized to work efficiently only in a limited operating region, it poses a problem in mobile fuel cell applications where a wide power range is required. The primary mass flow coming from the hydrogen tank is directly proportional to the stack power. As stack power decreases, the primary flow rate also decreases, thereby reducing the entrainment performance of the venturi ejector. Therefore, fixed geometry venturi ejectors cannot provide sufficient entrainment performance below a minimum specified fuel cell power. It is found that a fixed geometry venturi nozzle is only able to cover 60%–85% of the applicable power, whereas mobile applications such as automobiles generally require a useable power band of 90%–95% [4].

The problem was first approached by optimising the nozzle design to expand the operating range of the nozzle by studying and optimising nozzle geometries such as length, angle, throat diameter, etc. Furthermore, different approaches were conducted optimising the overall geometry of a single ejector or applying a two-stage design as discussed in the review of Kumar et al. [5]. These methods, though they improved the performance of a single fixed geometry, had limitations in terms of optimization. Another approach was seen in the direction of multiple ejector design, it showed slight improvement over the single nozzle, but faced performance fluctuations when switching flow between multiple nozzles [6], [7]. Arabbeiki et al. [8] conducted a literature review of 55 studies with regards to power ranges covered by different types of ejectors for hydrogen recirculation and found that variable geometry ejectors were capable of covering a power range of 0–160 kW in some studies (2024). Hence a variable geometry ejector that can adapt the recirculation ratio without negatively affecting the flow is considered as an ideal solution to this problem.

Needle based variable flow rate ejectors have been researched for fuel cell as well as non-automotive applications. Brunner et al. described in their paper their approach for the design of an adjustable recirculation unit for hydrogen fuel cell application, where they used an electric motor to adjust the position of the needle to vary the recirculation rates [2]. Other works such as [9,10] have also expanded the research further in direction of different needle actuation concepts to move the needle axially.

In summary, the downside of a static recirculation unit with a fixed geometry is the limited range of operating points. First variable recirculation units are described which are capable to extend the range of operation, but are not thoroughly analyzed and compared with different variable geometric parameters. Therefore, in this study a novel method for a detailed analysis of geometric parameters which can be used to vary the hydrogen mass flow and the mass flow ratio is presented. Additionally, the dynamic behavior of the ejector in the fuel cell system is investigated as it is highly relevant for an operation in mobile applications and has to be considered in the overall design development. Therefore, in this work a sensitivity study on the design parameters of a passive recirculation unit is conducted. It considers a wide range of operation for the hydrogen mass flow and the necessary mass flow ratio from low to high fuel cell power as well as the operation under dynamic conditions.

2. Methods

2.1. Working principle of an ejector-based hydrogen recirculation system

The PEM fuel cell system considered in this work contains a PEM fuel cell with a maximum power output of 100 kW based on the design of Scholta et al. [11]. The PEM fuel cell is operated by supplying air and hydrogen as well as cooling water to regulate the fuel cell temperature. The focus of this study lies on the hydrogen supply system and specifically on the recirculation unit (Fig. 1). Within the hydrogen supply system, a hydrogen-nitrogen-water mixture is recirculated from the anode outlet of the fuel cell back to the fuel cell inlet. It further contains a water separator and a purge valve to discharge water and nitrogen which keep the hydrogen concentration at a constant level. The passive recirculation system has to be designed in such a way that the suction pressure, obtained by the high velocity of the hydrogen flow at the ejector nozzle, leads to the necessary hydrogen mass flow supplying the fuel cell at the defined electric load.

2.2. Design study

As a first step, a simulation-based design study has been performed to find out the sensitivity of the ejector geometry parameters with respect to the related operating conditions. Therefore, the boundary conditions of the gas inlets and the gas outlets as well as the geometric parameters of the passive recirculation unit have been defined. The boundary conditions of the inlet and outlet gas flows are mainly dependent on the electric power of the fuel cell stack which is leading to a certain demand of hydrogen mass flow. In an anode recirculation system, the mass flow rate of the primary flow from the hydrogen tank is equal to the hydrogen consumption of the fuel cell, when the hydrogen output at the purge vent is neglected.

For this analysis, three different operating conditions are defined: low power, medium power and high power, reflecting typical conditions

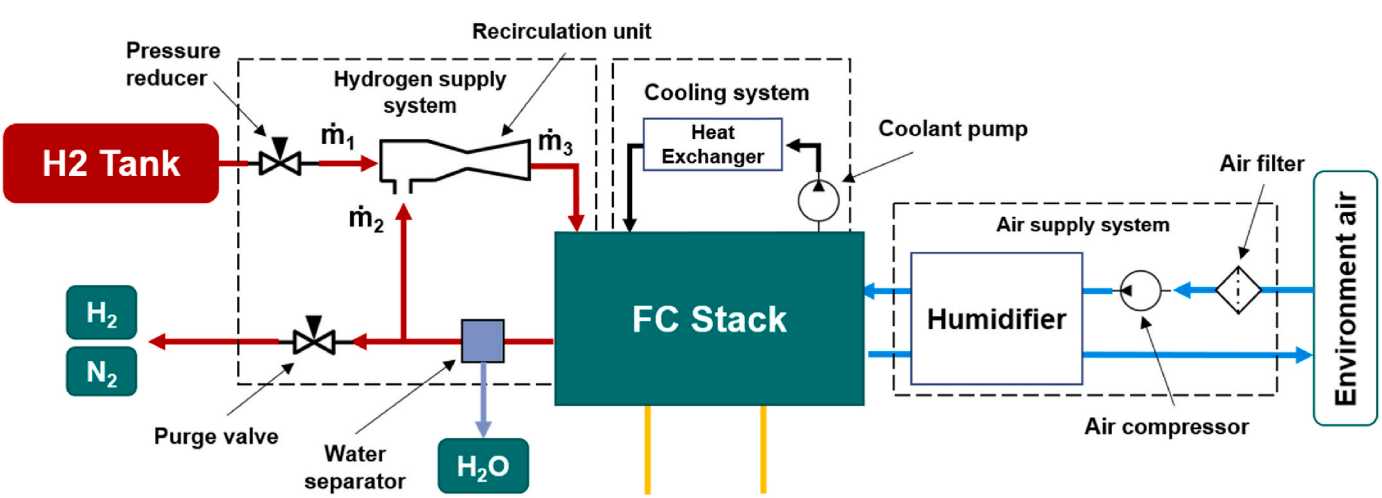

Fig. 1. PEM fuel cell system with passive hydrogen recirculation.

of a hydrogen fuel cell vehicle as listed in Table 1.

Beside the operating conditions of the fuel cell and the resulting primary and secondary flow, the geometric design of the ejector is strongly influencing the recirculation rate at the ejector outlet. The complete ejector is consisting of a primary nozzle, a secondary nozzle, a mixing chamber and a diffusor (Fig. 2). The reference geometry for the primary nozzle is based on ISO 9300 [12]. As radius r_1 for the primary inlet, 6 mm has been chosen. According to ISO 9300 a supersonic flow can be reached when the gas velocity at the critical radius reaches the sonic velocity a_k

$$a_k = \sqrt{\kappa \cdot \frac{R}{M_{H_2}} \cdot T_k} = 1.188 \cdot 10^3 \ \frac{\mathrm{m}}{\mathrm{s}}$$

with

$$T_k = \frac{2}{\kappa + 1} \cdot T_0 = 243.216 \ \mathrm{K}.$$

The critical area can then be calculated as

$$A_k = \frac{d_k^2 \cdot \pi}{4} = \frac{\dot{m}_1}{\rho_k \cdot a_k} = 6.93 \cdot 10^{-6} \ \mathrm{m}^2$$

with

$$\rho_k = \left(\frac{2}{\kappa + 1}\right)^{\frac{1}{\kappa - 1}} \cdot \rho_0 = 0.195 \ \frac{\mathrm{kg}}{\mathrm{m}^3}.$$

Therefore, the critical radius is set to $r_k = \sqrt{A_k / \pi} = 1.485$ mm.

The basic geometry of the secondary nozzle, the mixing chamber and the diffusor are based on the work of Refs. [2,13,14]. The geometric parameters and the values for the reference geometry of the primary and secondary nozzle are shown in Fig. 2 and Table 2.

Table 1
Fuel cell electric parameters and boundary conditions of primary, secondary and ejector outlet flow for the operating conditions low power, medium power and high power.

Parameter		Operating Conditions			Unit
		Low Power	Medium Power	High Power	
Electric stack voltage U_{stack}		243.2	212.8	197.6	V
Electric stack current I_{stack}		70	280	504	A
Electric stack power P_{stack}		17.02	59.58	99.59	kW
Number of cells		304	304	304	
Stoichiometry at fuel cell		1.6	1.6	1.6	
Primary flow	Total Mass flow $\dot{m}_1$	0.223	0.891	1.604	g/s
	Hydrogen concentration	100	100	100	wt. %
	Total temperature T_1	293			K
Secondary flow	Total Mass flow $\dot{m}_2$	0.941	3.765	6.777	g/s
	Hydrogen mass flow	0.134	0.535	0.962	g/s
	Hydrogen concentration	14.2	14.2	14.2	wt. %
	Total temperature T_2	333			K
Ejector outlet flow	Total Mass flow $\dot{m}_3$	1.164	4.656	8.381	g/s
	Hydrogen mass flow	0.356	1.426	2.566	g/s
	Hydrogen concentration	30.6	30.6	30.6	wt. %
	Pressure	0			barg

2.3. Flow simulation

In this chapter, the setup of the flow simulations used within the design study is described. All simulations were carried out on a local 24-core 2.3 GHz computing server. The software used was Siemens Simcenter STAR-CCM+ 2021.2.

The governing equations are the Reynolds-averaged-Navier-Stokes-equations consisting of equations for mass- momentum- and energy-conservation, given in the following equations [15]:

$$\frac{\partial}{\partial t}\int_V \rho \, \mathrm{d}V + \int_S \rho \mathbf{v} \bullet \mathbf{n} \, \mathrm{d}S = 0$$

$$\frac{\partial}{\partial t}\int_V \rho \mathbf{v} \, \mathrm{d}V + \int_S \rho \mathrm{vv} \bullet \mathbf{n} \, \mathrm{d}S = \int_S \mathbf{T} \bullet \mathbf{n} \, \mathrm{d}S + \int_V \rho \mathbf{b} \, \mathrm{d}V$$

$$\frac{\partial}{\partial t}\int_V \rho h \, \mathrm{d}V + \int_S \rho h \mathbf{v} \bullet \mathbf{n} \, \mathrm{d}S = \int_S k \nabla T \cdot \mathbf{n} \, \mathrm{d}S + \int_V (\mathbf{v} \cdot \nabla p + \mathbf{S} : \nabla \mathbf{v}) \, \mathrm{d}V + \frac{\partial}{\partial t}\int_V p \, \mathrm{d}V$$

To close the system of equations, the ideal gas law and the k-omega-SST turbulence model [16] are utilized. The three gaseous phases of pure hydrogen, pure nitrogen and water vapor are considered. The material properties are given in Table 3. The separate phases do not react, but can mix. The material properties of the gas mixture are given by the sum of the mass-fraction-weighted properties of all species:

$$\Phi_{mix} = \sum_{i=1}^{N} Y_i \Phi_i$$

where Y_i is the mass fraction of component i, Φ_i the corresponding property value and N the total number of components.

All simulations are 2-dimensional axisymmetric simulations. Only steady-state solutions are considered in the numerical flow simulations. Transient effects which can occur during startup or shutdown are not modelled. The simulations were run until all residuals reached a constant value. When all residuals were below 1.0^*10^{-4}, we considered the simulation converged.

For the inlet boundaries, a stagnation condition was chosen. The stagnation conditions pertain to the state within a theoretical plenum located significantly upstream, where the flow is entirely stationary. In the simulations considered here, the inlet flow conditions are determined using the total pressure, total temperature, and flow direction. The pressure at the first inlet p_1 depends on the operating condition and was varied throughout this work. All walls are modelled as adiabatic no-slip walls.

To determine the necessary resolution of the mesh, a grid convergence study was carried out. Five meshes of different resolution were created and evaluated. Table 4 shows the results, comparing the final energy residual for each mesh. As can be seen, the second-coarsest mesh with a cell count of 95105 provides a low value for the energy residual, which does not decrease further noticeably. However, the y + -values for this mesh were not in the necessary range. We therefore refined the mesh and decided upon the mesh with a cell count of 129399 for our simulations. The mesh consists of polyhedral cells with an average area of 0,0066 mm^2. To accurately capture discontinuities and strong gradients in the flow field, regions where those are expected are discretized more finely. These regions are namely the nozzle throat and the mixing zone. Additional boundary layers were introduced to resolve the velocity gradients near the wall.

2.4. System simulation

With the integration of the variable hydrogen ejector within the fuel cell system model, it is possible to directly observe the effects of the passive hydrogen recirculation operation at a system level. In this work,

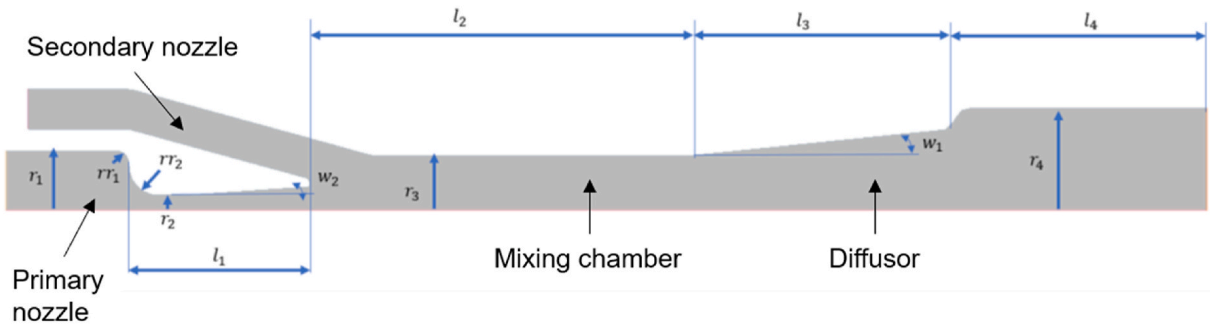

Fig. 2. Identified geometric parameters influencing the hydrogen recirculation.

Table 2
Reference parameters for the geometric parameters of the ejector.

Description	Parameter	Value
Inlet radius	r_1	6 mm
Nozzle radius	r_2	1.5 mm
Mixing chamber radius	r_3	5.4 mm
Outlet radius	r_4	10.2 mm
Diffusor angle	w_1	6°
Nozzle angle	w_2	4°
Nozzle length	l_1	18 mm
Mixing chamber length	l_2	37.5 mm
Diffusor length	l_3	27 mm
Outlet length	l_4	25 mm

Table 3
Material properties of individual gaseous phases for the CFD-simulations.

Gas phase	Dynamic viscosity [Pa·s]	Molecular Weight [kg·kmol^{-1}]	Specific heat capacity [J·kg^{-1}·K^{-1}]
Hydrogen	$8.87789*10^{-6}$	2.01594	14292.3
Nitrogen	$1.78837*10^{-5}$	28.0134	1040.76
Water vapor	$1.26765*10^{-5}$	18.0153	1938.19

Table 4
Results from the grid convergence study for different mesh sizes.

Cell Count	Energy residual
63127	$19.3889*10^{-6}$
95105	$1.61056*10^{-6}$
129399	$1.87386*10^{-6}$
158219	$1.65587*10^{-6}$
197257	$1.13523*10^{-6}$

a fuel cell system model developed by MathWorks is used as the base and adjusted to meet the requirements of this study [17]. The model is capable of dynamic simulations and can react to various operation loads. The model contains a fuel cell model programmed to replicate the chemical reaction according to the hydrogen and air supply. The hydrogen supply system representing gas supply from a 700-bar tank and pressure reducing valves is modelled. The air supply system consists of a compressor model which compresses air from environment and supplies it to the fuel cell according to the electric load and stoichiometry. The modelled hydrogen recirculation system consists of the hydrogen ejector and the purge valve where the hydrogen ejector can be adjusted to recirculate the desired amount of hydrogen between the fuel cell outlet and fuel cell inlet. To analyse the system performance, the hydrogen ejector was modelled to switch the recirculation rates according to three power levels. This was done with the help of a lookup table in Simulink where flow rates were directly taken from the

Table 5
Effect of different mass flow ratios on the fuel cell and the hydrogen recirculation.

Mass flow ratio $MV = \dot{m}_3/\dot{m}_1$	Effect on Fuel Cell	Effect on Hydrogen Recirculation
$0 \leq MV < 1$	No sufficient hydrogen mass flow to operate the fuel cell	The main gas stream flows partially backwards to the secondary nozzle and is mixed within recirculation area, no recirculation
$1 \leq MV < 1.4$	Hydrogen is supplied to the fuel cell, but operation is undersupplied with risk of material degradation	The suction stream is mixing with the main stream to be transported to the fuel cell, recirculation occurs
$1.4 \leq MV \leq 1.6$	Hydrogen is supplied under optimal conditions	Recirculation occurs
$MV > 1.6$	The humidity is influenced by the higher stoichiometry and can deviate from the optimal operating conditions	Recirculation occurs, more hydrogen is present in recirculation circuit than necessary

StarCCM + simulations. The lookup table contains steady-state operations only. The system was simulated for three operation loads, i.e., low power, medium power, and high power depicting an electric current load of 70 A, 280 A, and 504 A, corresponding to a current density of 0.25 A/cm^2, 1 A/cm^2 and 1.8 A/cm^2 respectively (Fig. 3).

The hydrogen ejector model was adjusted to emulate three recirculation rates representing three adjustable positions of the designed variable geometry nozzle. Depending upon the varied recirculation

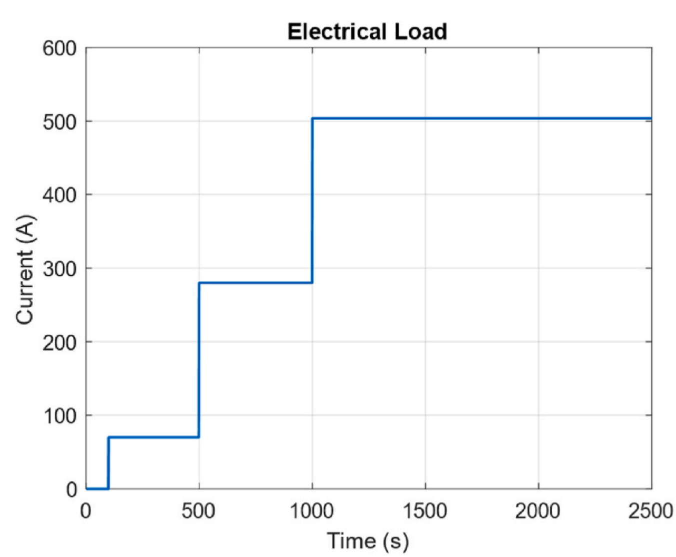

Fig. 3. Fuel cell electrical load.

rates, different stoichiometries on the anode path can then be observed and analyzed. The purge valve was operated in such a way that every 100 s it opened for 5 s to expel the diffused nitrogen out of the system.

3. Results

3.1. Reference case

As a first step, the reference geometry has been simulated to analyse the flow conditions under the set of reference parameters. Fig. 4 shows the resulting flow of the reference geometry parameters and operating parameters of the high-power operating condition. Slices through the axisymmetric simulation domain are given for velocity, Mach-number, pressure and the hydrogen mass-fraction. The gas velocity reaches up to 1150 m/s at the nozzle exit, corresponding to a local Mach number of 0.959. The gas pressure reduces meanwhile from 3.88 bar absolute pressure to ambient pressure. In the mixing region after the nozzle, pure hydrogen from the tank mixes with the recirculated gas mixture with 14.2 wt% of hydrogen leading to a homogeneous hydrogen concentration at the diffusor outlet of 30.6 wt%.

To evaluate the reference ejector geometry, the ejector performance under the chosen fuel cell power conditions has to be analyzed. As a criterion to evaluate the ejector performance, the mass flow ratio (MV) $\dot{m}_3/\dot{m}_1$ is chosen as it indirectly represents the stoichiometry factor and guarantees the stable operation of the fuel cell.

In Fig. 5 the relation of the inlet pressure p_1 and the resulting mass flow $\dot{m}_3$ as well as the mass flow ratio and the Mach number for the reference geometry are shown. Under the given conditions and parameters, the high-power operating condition can be set with a mass flow ratio of approximately 1.6 and the required mass flow rate of 1.6 g/s. It can be seen that for primary inlet pressures below 1 barg, the mass flow ratio drops suddenly to values even below zero. This indicates a breakdown of the suction flow from the secondary inlet. The mass flow resulting from such a low pressure at the primary inlet does not create velocities high enough to cause suction through the secondary inlet. Instead, gas is flowing out through the secondary inlet. Therefore, the medium power and low power operating conditions cannot be achieved with the given reference geometry, since the required mass flow ratio is not attainable. On the other hand, higher mass flows should be avoided as the Mach number will increase ≫ 1 and a stable operation with a stable jet is difficult to achieve.

3.2. Design study

To extend the operation range with a variable ejector to allow a broad range of hydrogen supply from low fuel cell power to high fuel cell power, the relevant design parameters have to be identified. Therefore, a parametric design study has been conducted, using the 10 defined

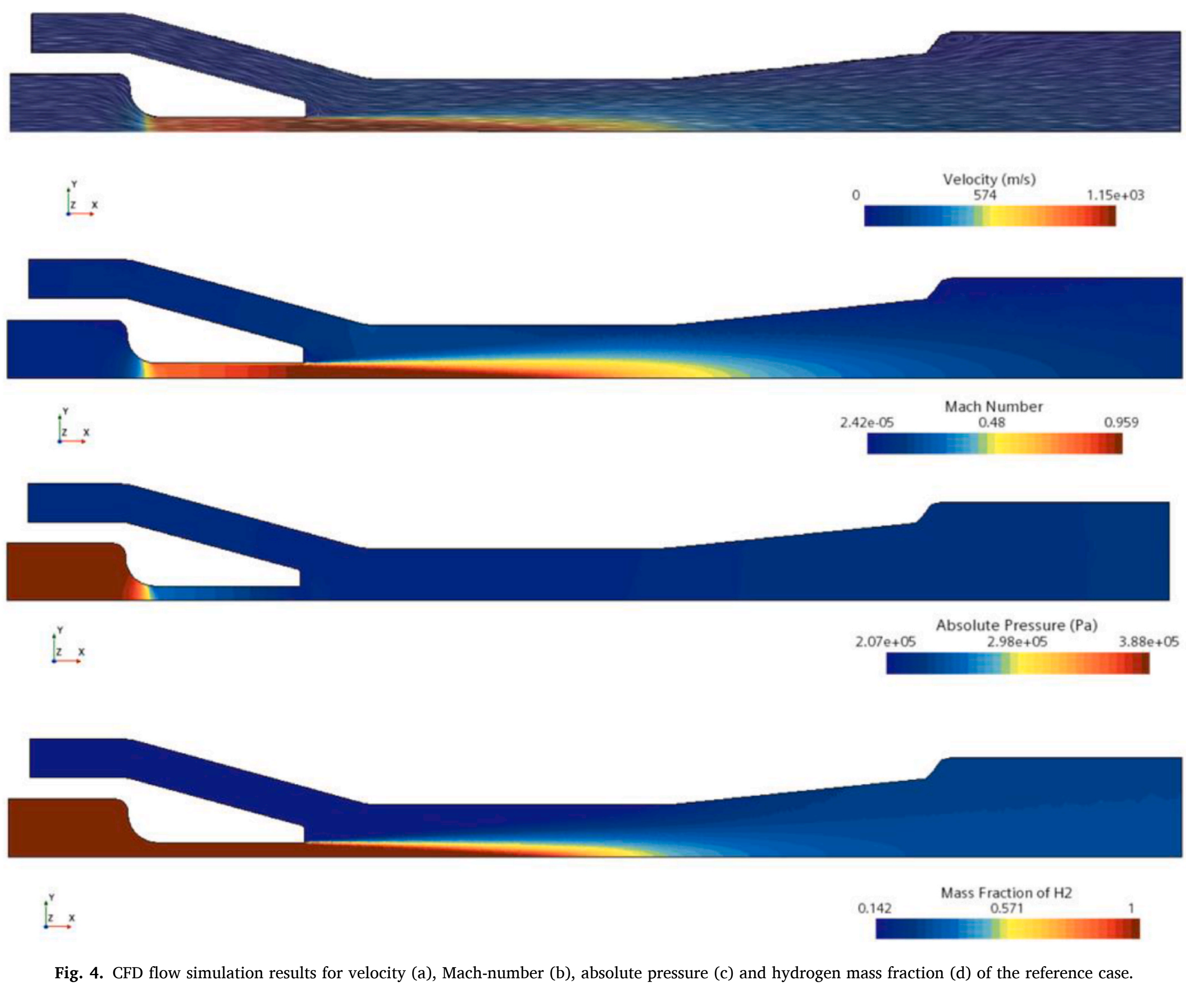

Fig. 4. CFD flow simulation results for velocity (a), Mach-number (b), absolute pressure (c) and hydrogen mass fraction (d) of the reference case.

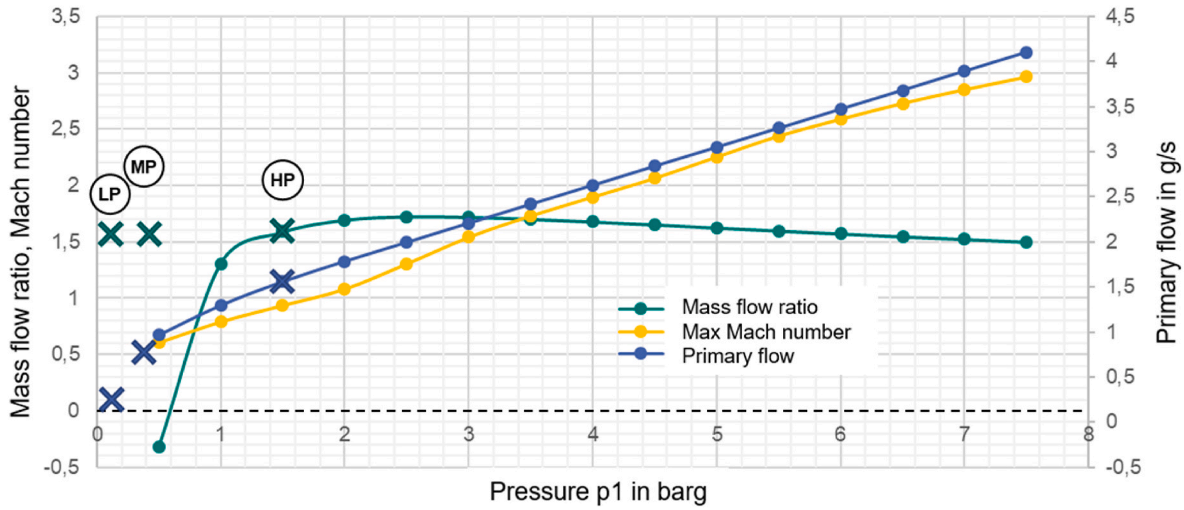

Fig. 5. Performance map of passive recirculation pump.

geometric parameters (Table 2, Fig. 2). More than 800 variations have been simulated, leading to the following results for the relation between inlet pressure p_1 and resulting mass flow ratio $\dot{m}_3/\dot{m}_1$ (Fig. 6).

Certain combinations of geometric and flow parameters resulted in an over- or underexpanded nozzle design. This creates undesirable discontinuities in the flow field, such as compression shocks. If the opening angle of the nozzle is too large or the primary inlet pressure too low, the nozzle flow is overexpanded. In this case, flow separation at the nozzle wall can occur which results in an unstable jet and must be avoided. A too small nozzle opening angle or a too high primary inlet pressure in turn results in an underexpanded nozzle flow and creates undesired shock waves and expansion fans. Although it is possible to create efficient ejector designs with supersonic flow [18], these flow phenomena significantly increase the complexity of system. O'Hern et al. [19] showed that subsonic ejector geometries are feasible as well. Another flow phenomenon which occurred, but should be avoided, was backflow through the secondary inlet. The final geometries were chosen such that no undesirable flow phenomena occurred.

The analyzed mass flow ratio for all variations is evaluated and leads to the findings listed in Table 5.

The findings of the design study reveal that the four geometric parameters mixing chamber length l_2, mixing chamber radius r_3, diffusor angle w_1 and nozzle radius r_2 have the strongest effect on the mass flow ratio and therefore on the ejector performance. These geometric parameters are evaluated to be useable as variable parameters to extend the operation range of the ejector. The change of the mass flow ratio, the change of the total mass flow and the feasibility are analyzed and serve as criteria for a comparison in Fig. 7.

It is found that the parameters mixing chamber length l_2, mixing chamber radius r_3 and diffusor angle w_1 show in the selected range only a slight change in mass flow ratio, which is a mass flow ratio difference of 0.33 for the mixing chamber length l_2, 0.16 for the mixing chamber radius r_3 and 0.31 for the diffusor angle w_1, but show not effect on the primary flow of the ejector. Only the variation of the nozzle radius r_2 shows a very strong effect on the mass flow ratio with a mass flow ratio difference of 1.77 and additionally a strong effect also on the primary flow of the ejector which leads to a range of 0.2–10.7 g/s of mass flow. Therefore, the radius r_2 is selected as useful geometric parameter for variation of the mass flow ratio and primary mass flow of the ejector.

3.3. Concepts for varying the relevant geometric parameter "nozzle radius"

Different concepts were evaluated how the nozzle radius r_2 can be

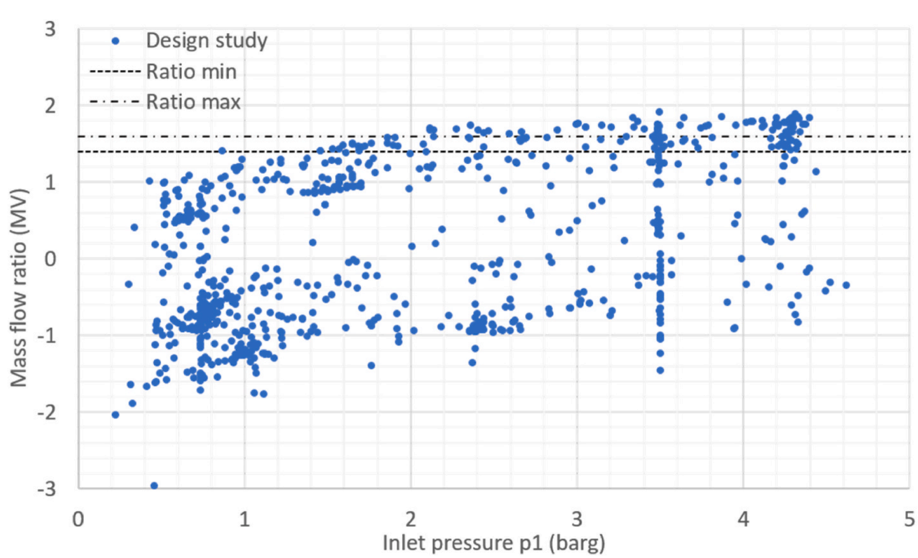

Fig. 6. Results for the relation between inlet pressure p_1 and mass flow ratio for all variations within the design study.

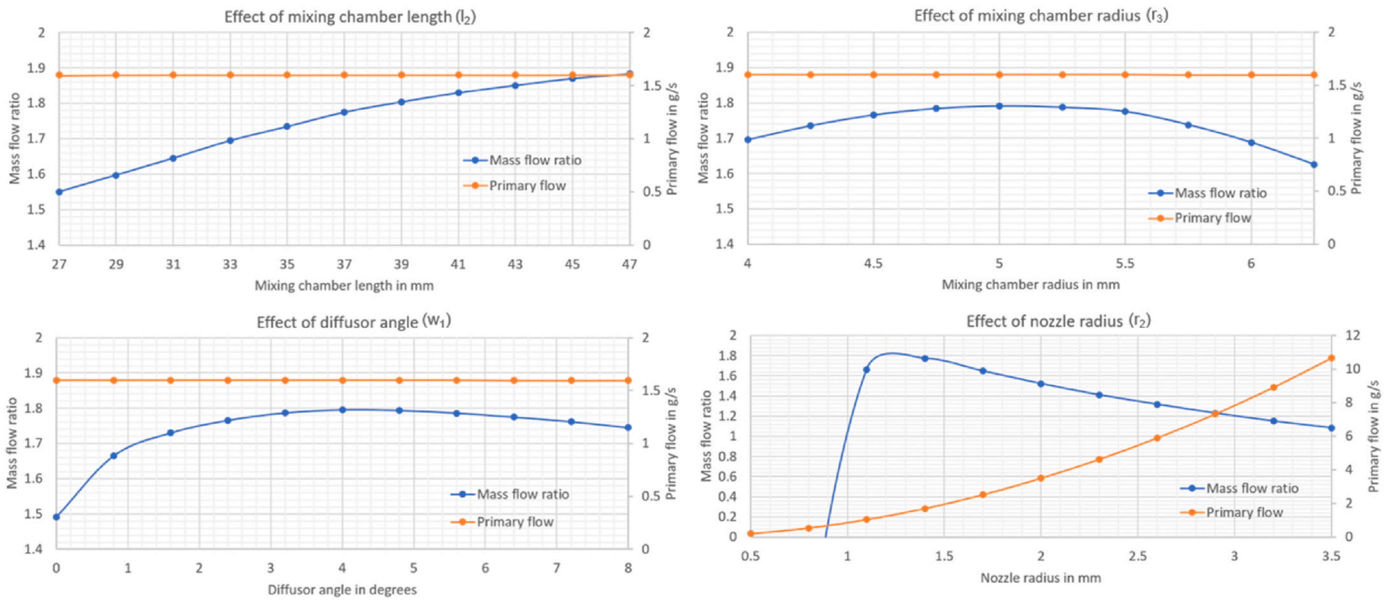

Fig. 7. Influence of geometric parameters on the performance map of the passive recirculation pump.

influenced and how this can be integrated in the ejector. It is found that moving a needle inside the nozzle is varying the nozzle cross section, and therefore the effective nozzle radius, in the most precise and most simple way. This is in line with already published and patented solutions [9, 10].

In Fig. 8 it is shown how the position of the needle is changing the opening area of the nozzle and therefore varying the nozzle cross section or effective radius. The simulation results revealed that with a nozzle cross section variation of 28 % at 1.5 barg, 100 % at 1.5 barg and 100 % at 4.5 bar g all three operation points high power, medium power and low power can be set, if a maximum pressure drop of 50 mbar at low power and 100 mbar at medium and high power for the fuel cell is not exceeded.

In real operation of the PEM fuel cell, the pressure drop inside the fuel cell can change due to condensation and accumulation of liquid water in the channels of the bipolar plate [20]. Hence, the ejector has to be robust with respect to such pressure drop changes. In Fig. 9 the three operation points high power, medium power and low power are compared under different pressure drops and its influence on the mass flow ratio. The results show that medium and high power are relatively

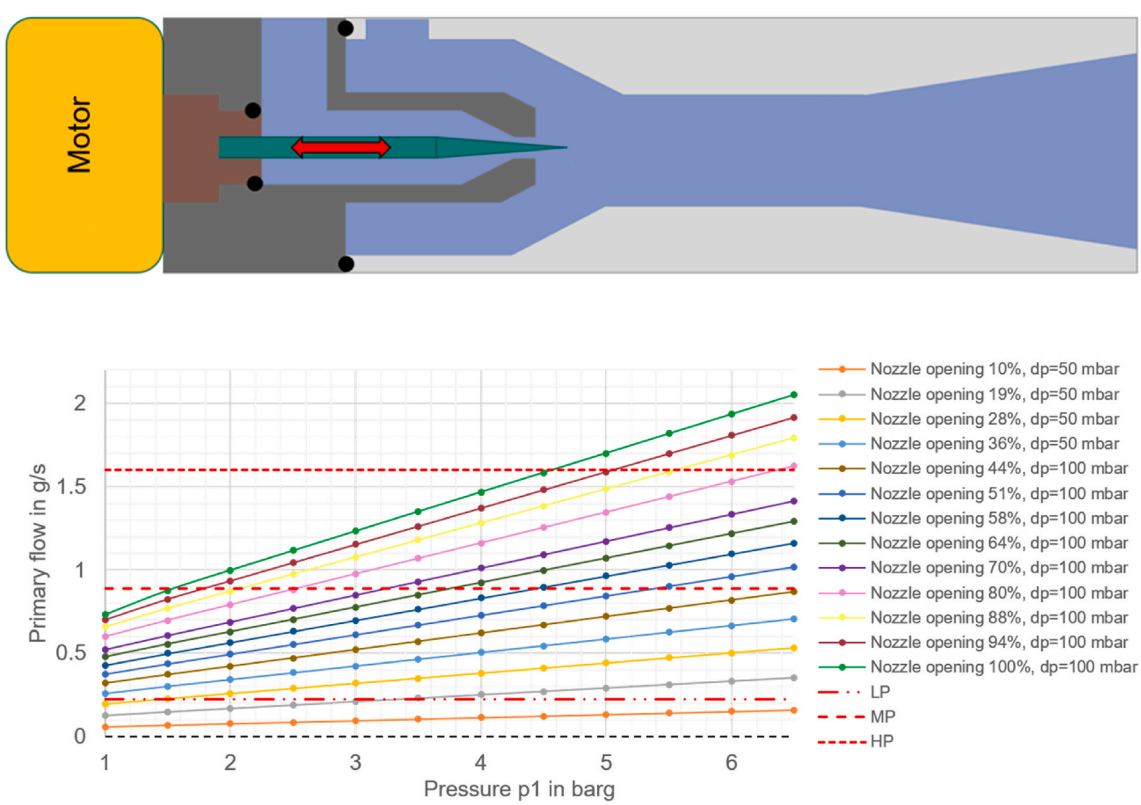

Fig. 8. Design of the needle concept and influence of the nozzle cross section in combination with the inlet pressure p_1 on the main gas stream.

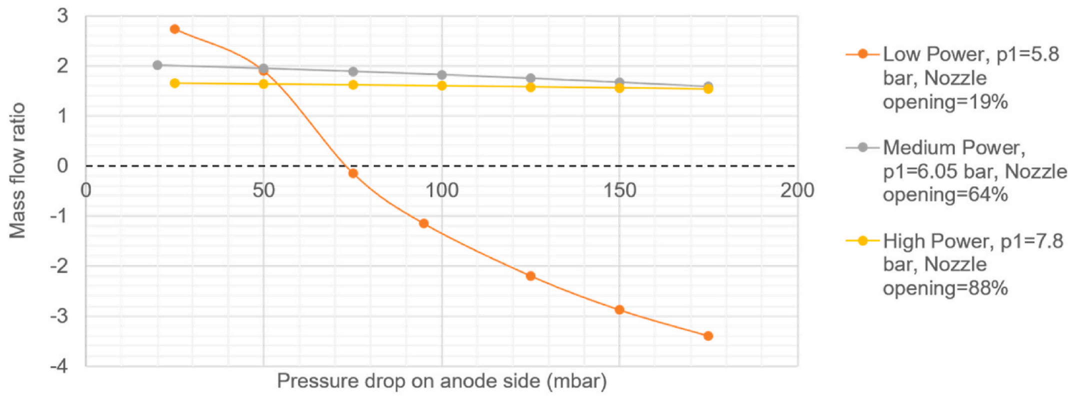

Figure 9: Influence of the pressure drop on the mass flow ratio of the ejector

Fig. 9. Influence of the pressure drop on the mass flow ratio of the ejector.

robust with respect to the change in pressure drop in a range from 25 to 175 mbar which results in a mass flow ratio decrease of 18 % for the medium power and 7 % for high power leading to a minimum mass flow ratio of 1.58 and 1.53, respectively. Instead the low power operation shows a significant drop in the mass flow ratio from 2.7 at 25 mbar to 0 at 75 mbar. Thus, the fuel cell can only be operated with this configuration until a maximum pressure drop of 50 mbar where a mass flow ratio of 1.89 is maintained.

To improve this sensitivity to the pressure drop, a two-step-needle concept was developed and simulatively analyzed (Fig. 10). Due to the simultaneous change of the nozzle radius and the inlet radius, the flow could be optimized especially at low mass flows. The first step effectively reduces the inlet pressure p_1 and therefore creates better flow conditions in the low power operation point. In fact, Fig. 10 reveals that the pressure sensitivity of the low power operation could be improved to a pressure drop up to 70 mbar where a mass flow ratio of 1.5 is reached.

3.4. System simulation

To understand the behaviour of the ejector within the operation of the fuel cell system, the system simulation has been conducted to evaluate the interaction between the ejector and the fuel cell under dynamic operation.

Fig. 11 shows the reactant stoichiometry for hydrogen and oxygen on anode and cathode side, respectively. At low loads, the designed variable geometry recirculation unit maintains a stoichiometry of 2.35, at medium loads a stoichiometry of around 2.28 is maintained and at high loads, a stoichiometry of around 2.17 is maintained. Thus, a durable operation of the fuel cell system can be obtained also under dynamic operation with the configuration of this variable passive hydrogen ejector.

4. Discussion

The results from the design study revealed that in fact the needle concept as it is reported from several studies [2,21]is the most useful

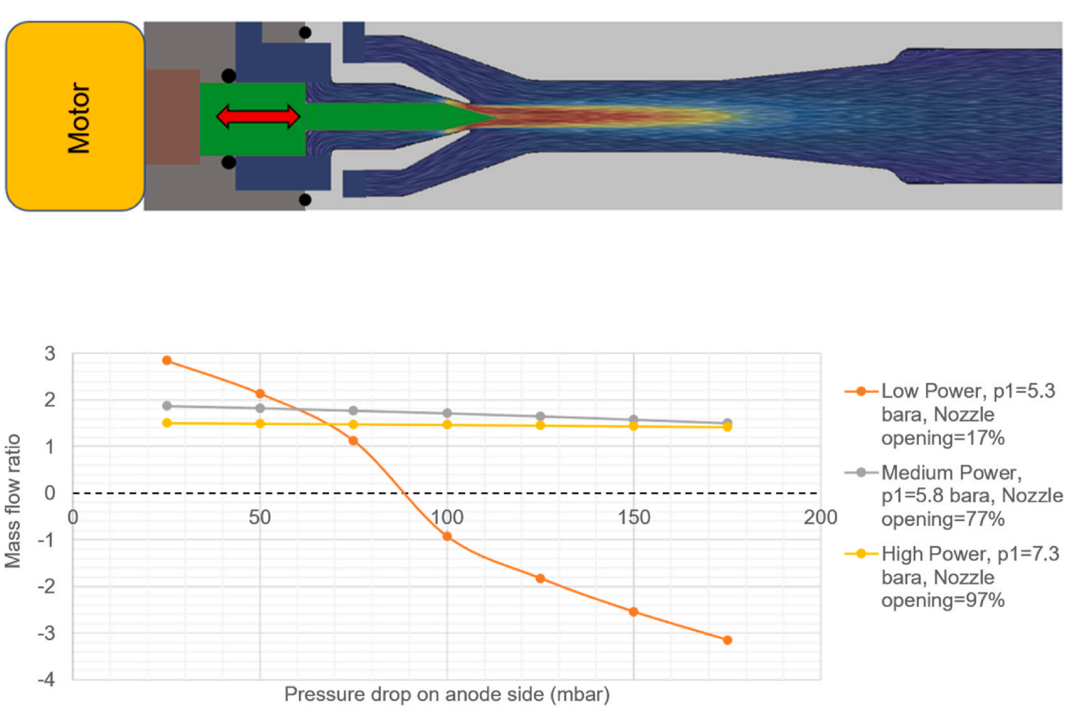

Fig. 10. Influence of applying the double needle concept on the mass flow rate of the passive recirculation pump.

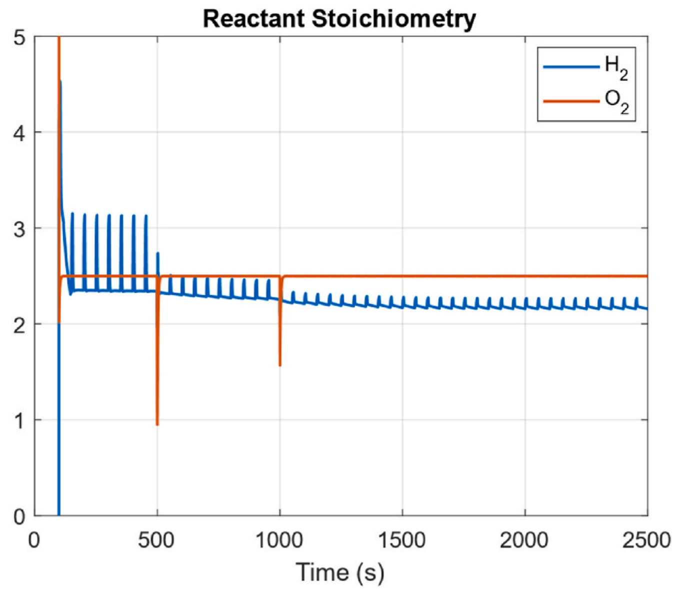

Fig. 11. Fuel cell system stoichiometry.

option to vary the mass flow and the mass flow ratio according the requirements for different fuel cell power levels. The analyzed alternative geometric parameters could be extended in the chosen parameter range, but the effect, as reported in this study, leads to the expectation that further solutions in an extrapolated range will not be useful for fuel cell operation. The simulation results show that alternative parameters are only changing the mass flow ratio at a constant primary flow and therefore enable to vary the stoichiometry at the fuel cell inlet, but do not vary the primary flow to extent the power range of the fuel cell itself. An additional variation of the needle as a two-step needle design can further increase the robustness to pressure changes which is useful for a dynamic operation of the fuel cell system. This is in line with the findings of [2] which revealed that water droplets inside the fuel cell leading to a pressure drop change is a challenge to maintain the primary flow and mass flow ratio for passive hydrogen ejectors. By comparing the results of the flow simulations of the ejector and the fuel cell system simulations, it is revealed that the passive recirculation can fulfill the requested specifications, if an adjustable needle is used. The respected power range between 17 kW and 100 kW can be seen as a typical case for passenger cars or light duty vehicles. It is expected that the results can be transferred to either smaller or larger fuel cell systems where a similar power range between 17 % and 100 % is necessary. The conducted CFD simulations revealed that a geometric scaling factor of 10 leads to comparable flow characteristics, so that a suitable variable passive ejector geometry can be obtained by direct scaling. With respect to the dynamic operation of the fuel cell system, the system simulations show that the ejector is able to fulfill a continuous hydrogen supply with a minimum stoichiometry of 1.6 to avoid hydrogen undersupply situations which can provoke performance losses and a reduced lifetime. Also, large Mach numbers can be avoided which would lead to an unsteady hydrogen flow and could lead to pressure fluctuations which might be harmful for the fuel cell.

As a next step, the optimized ejector geometry with the needle concept has to be manufactured and tested to verify the characteristics found in the CFD and system simulations. Especially, effects which were not simulated will be relevant, i.e., effect of condensed water, dynamic flow changes inside the ejector or the speed of the needle position changes as well as the influence of these settings on the performance and lifetime of the fuel cell.

5. Conclusion

In this study, an ejector for the passive hydrogen recirculation unit in a PEM fuel cell system has been designed and analyzed as it offers the possibility to operate a fuel cell system in recirculation mode without additional energy consumption. It is found that the ISO normed layout of such an ejector does not meet the defined requirements to be operated at a necessary range between 17 % and 100 % of the maximum fuel cell power. CFD simulation results show that the suction pressure is reduced at lower mass flow rates and the mass flow ratio drops under the minimum value necessary for the operation of the fuel cell. An operation of the ejector at higher mass flow rates instead is limited due to undesirable flow phenomena at Mach numbers greater than one. To extend the operation range of this passive ejector, a variable ejector design was developed. To identify adjustable geometric variables, a design parameter study has been conducted considering all 10 defined geometric parameters. The four parameters mixing chamber length, mixing chamber radius, diffusor angle and nozzle radius have been identified to be the most relevant for changing the primary mass flow and the mass flow ratio as well as considering the feasibility of the design implementation. It is found that the nozzle radius has the largest effect on the primary mass flow and the mass flow ratio and is therefore chosen to be considered for the design implementation in an adjustable ejector concept. A needle concept has been chosen as being the most suitable for design and implementation. The results of the CFD studies show that with applying the needle concept to the ejector all three power points can be operated. Furthermore, a sensitivity study of the operation parameters reveal that the pressure drop of the fuel cell stack has a high influence on the mass flow ratio. A further optimized concept of a two-step needle showed that a further improvement of this behavior can be achieved and increases the operation range at low power from 50 mbar to 70 mbar. The system simulation confirms the applicability of such a passive ejector considering the operation of the BOP components. Additionally, by switching between the three operation points in dynamic operation, a stable operation of the fuel cell with the hydrogen recirculation by the passive ejector can be achieved.

CRediT authorship contribution statement

Bhanu Seth: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Simon Knecht:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Marton Szalai:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Jan Haußmann:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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