Proceedings of Global Power and Propulsion Society
ISSN-Nr: 2504-4400
GPPS Xi'an21
18th – 20th October, 2021
www.gpps.global

GPPS-TC-2021-0072

INVESTIGATION OF WATER DROPLET EROSION IN THE RADIAL TURBINE OF A FUEL CELL TURBOCHARGER

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ABSTRACT

Radial turbines of fuel cell turbochargers are prone to water droplet erosion (WDE). Test bench runs of such a turbine showed erosion zones on the rotor suction side near the leading edge and on the stator suction side near the trailing edge. The aim of this study is to analyze this erosion and determine which droplet trajectories are responsible for it. For this purpose, Euler-Lagrange simulations of the non-equilibrium condensing flow are analyzed with regard to droplet deposition. It is shown that the droplets originating from condensation are not responsible for the observed erosion. It is therefore investigated whether an inflow of droplets from the fuel cell itself can be responsible for the erosion. The study indeed shows that such droplets can form wall films on rotor and stator. Therefore, the observed erosion is most likely the result of droplets formed by the break-up of wall films at the trailing edge of the stator vanes and also at the leading edge of the rotor blades.

INTRODUCTION

Water droplet erosion (WDE) has been a longstanding concern for turbomachinery. The phenomenon is best known from steam turbines. Recently, a new type of turbomachinery has emerged that is also prone to WDE: the turbines of fuel cell turbochargers. A fuel cell turbocharger is the main component of the cathode system of a proton exchange membrane fuel cell (PEMFC). The cathode system is responsible for supplying the fuel cell with air at the correct pressure, humidity and temperature and for managing the fuel cell outflow of humid air and liquid water (Blunier and Miraoui, 2010). Figure 1 shows the schematic of a cathode system of a PEMFC. Air is compressed and humidified upstream of the fuel cell. Liquid water is separated from the fuel cell outflow and the pressure potential of the outflow is used in a turbine. An electric motor is necessary because the turbine can only provide about 1/3 of the power needed for the compressor. Typically, single-stage centrifugal turbo-compressors and radial turbines are selected for compression and expansion. Compressor, motor and turbine together form the fuel cell turbocharger. There are two possible sources of water causing erosion in the turbine. First, the water that condenses when the humid air in the turbine expands. Second, the liquid water from the fuel cell which could not be separated upstream of the turbine. The aim of this study is to analyze the erosion phenomena observed in an automotive fuel cell turbocharger and to discuss plausible sources of water and phenomena responsible for this erosion. Earlier, the authors analyzed the condensation phenomena and their effects on the performance of the turbine studied here (Wittmann et al., 2021b; 2021c). The authors are not aware of other publications dealing with the effects of condensation and liquid water on fuel cell turbochargers. However, both topics are well known from steam turbine research (Hesketh and Walker, 2005). A large number of publications have dealt with WDE in recent years. Therefore, only a small selection can be included here. Ahmad (2018) presented an overview of the relevant aspects of WDE. Experimentally studies were conducted by Ahmad et al. (2009) and Gujba et al. (2016). Chidambaram and Kim (2018) calculated the erosion rate for compressor blades numerically using the model of Lee et al. (2003). Yarin (2006) reviewed droplet impacts and the different impact regimes. For this work, only the deposition and splashing regimes are relevant. According to Mundo et al. (1998) splashing occurs when

$$K = We^{0.5} \cdot Re^{0.25} > 57.7 \qquad (1)$$

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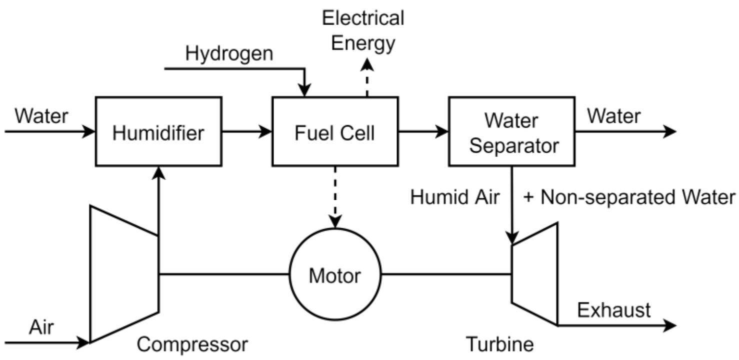

Figure 1 Electrically turbocharged cathode system for a PEMFC

Studies focusing on droplet splashing were conducted by Samenfink et al. (1999) and Li et al. (2019). Schuster et al. (2018a, 2018b) analyzed the deposition of droplets in radial turbines. They also performed numerical simulations of the resulting wall films (Schuster et al., 2014) and were able to show an area near the leading edge of the rotor blades where the wall films are transported outwards against the direction of flow. The disintegration of wall films at edges was studied for example by Schlottke and Weigand (2021). The subsequent secondary droplet breakup was reviewed by Guildenbecher et al. (2009) and recently analyzed experimentally by Wang et al. (2020).

The first section of this study introduces the turbine under investigation and the erosion phenomena observed. Next, it is discussed whether liquid water originating from condensation in the turbine could be responsible for the erosion. Subsequently, the possible behaviour and effects of water already liquid when entering the turbine are analyzed. Finally, conclusions are derived.

TURBINE AND NUMERICAL MODELLING APPROACH

In this study, the radial turbine of an automotive fuel cell turbocharger is investigated. As shown in Fig. 2, the turbine consists of 10 fixed stator vanes, 13 rotor blades and a volute. At the design operating point, the volute inlet (green) is defined with a constant total pressure of 1850 hPa and a total temperature of 345 K. The outlet (red) is defined with an average static pressure of 1030 hPa. Depending on the degree of condensation, the flow coefficient with respect to the rotor inlet varies between 0.40 and 0.45 and the working coefficient between -0.8 and -0.9. All walls are no slip walls, except for a free slip wall at the gap between stator and rotor hub. The heat transfer away from the turbine is rather limited therefore the walls are assumed to be adiabatic. The interface between stator and rotor (orange) is modeled as a frozen rotor. A mixing plane is not feasible because the droplet trajectories of the underlying simulation with condensation cannot be transferred across it. The rotor and stator mesh are structured and consist of 756k nodes for each rotor blade and 492k nodes for each stator vane. The volute mesh is unstructured, has 1764k nodes and was provided by Menze et al. (2021). The grid convergence index (GCI) is less than 3% and the average y^+ is less than 1.

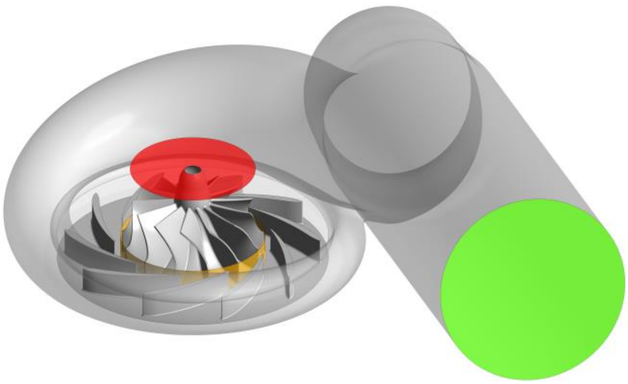

Figure 2 Computational domain with inlet (green), frozen rotor interface (orange) and outlet (red)

The condensing flow in the turbine was previously investigated numerically (Wittmann et al., 2021c). For this purpose, the classical nucleation theory with the non-isothermal correction (NISO) and Young's growth law was implemented in the Euler-Lagrange framework of Ansys Fluent. In this method, the Eulerian gas phase is modeled using the well-known finite volume approach. The Lagrangian droplet phase, on the other hand, is modeled with discrete parcels representing groups of droplets with equal properties. The trajectories of the parcels are calculated according to the forces acting on a droplet as it moves through the flow field. In the case of two-way coupling, the flow field acts on the droplets and the droplets act on the flow field. For a one-way coupling, the flow field determines the trajectory of the droplets, but the droplets do not affect the flow field. Both coupling variants are relevant to this study. Which variant is used for which simulations will be indicated later. All simulations were carried out in steady state and used the SST-k-ω turbulence model with viscous heating. A detailed discussion of the validation of the condensation model (Wittmann et al., 2021a) and its application to the turbine (Wittmann et al., 2021b) have been published as well. These earlier simulation results for the gas phase and condensed droplets will be examined again here with regard to the droplet deposition. The results discussed later for droplets that are already liquid when entering the turbine are based on new calculations.

OBSERVED EROSION PHENOMENA

The turbine introduced above was used in various test campaigns at Volkswagen. Erosion was not part of the investigation during these tests. However, after the tests, clear signs of erosion were observed on the turbine. Unfortunately, the authors have very limited knowledge of the details of the test circumstances. It is known that the turbines were operated in a stationary test rig with humid air from a fuel cell. An inflow of liquid water to the turbine was also observed. Later, Volkswagen provided the authors with the eroded turbines. Figure 3 shows the suction side of a rotor blade near the leading edge and a detailed view of the blade tip. The lighter color of the impact craters makes the effect of WDE clearly visible. Microscopic analysis of the rotor blades revealed the following findings:

- Erosion is limited to a vertical strip of the suction side near the leading edge. Other areas are not affected.
- All blades are affected in a similar way.
- From hub to shroud, the number of impact craters increases.
- Number and size of impact craters decrease from the leading edge in the direction of flow.
- The diameter of the impact craters varies between 5 μm and 50 μm.

The WDE in the rotor is concentrated near the leading edge of the blades. From this it can be concluded that the responsible water droplets are probably part of the incoming stator outflow.

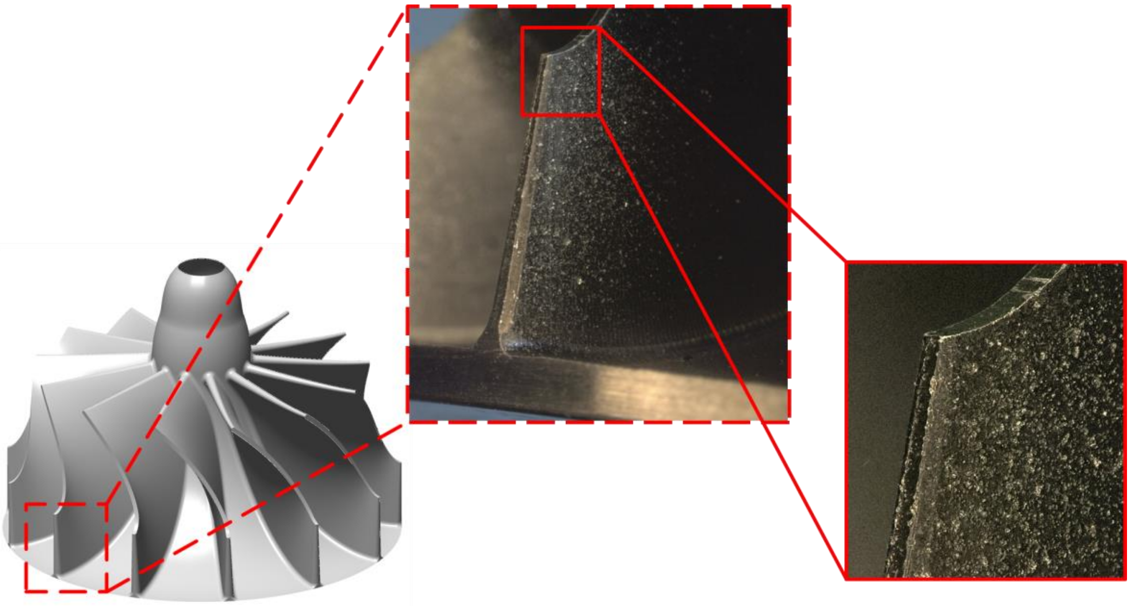

Figure 3 Eroded suction side near the leading edge of a rotor blade with detailed view of the blade tip

Figure 4 presents the erosion phenomena observed in the stator. It should be noted that the photo shows an older version of the turbine, where the stator gap was located at the turbine hub. The simulations discussed later represent the newer version of the turbine shown in Fig. 2, where the stator gap is located at the shroud. However, this change has no influence on the observed erosion. In Fig. 4, the eroded part of the stator vane is clearly visible as a lighter rectangle at the suction side near the trailing edge. Microscopic analysis of the stator vanes revealed the following findings:

- Significant WDE is found on the last third of the suction side of the stator vanes.
- Interestingly, all vanes show very similar erosion. In addition, the boundary between areas with and without WDE is recognizable as a sharp vertical line on all vanes.
- Due to the large number of impacts, it is not possible to extract diameters for single impact craters.

- In addition to the WDE shown in Fig. 4, a few vanes also showed a limited number of impact craters at the leading edge. However, these do not follow a clear pattern and are far less significant.

The fact that all stator vanes show almost identical erosion patterns suggests that the responsible droplets originate from the rotor. For if droplets coming from the volute were responsible, the erosion patterns would reflect the radial asymmetry of the volute flow. This is supported by the sharp, vertical appearance of the boundary between eroded and non-eroded areas of the vanes. This is thought to be due to the vanes in the foreground shielding the non-eroded areas of the vanes behind from droplets emerging from the rotor.

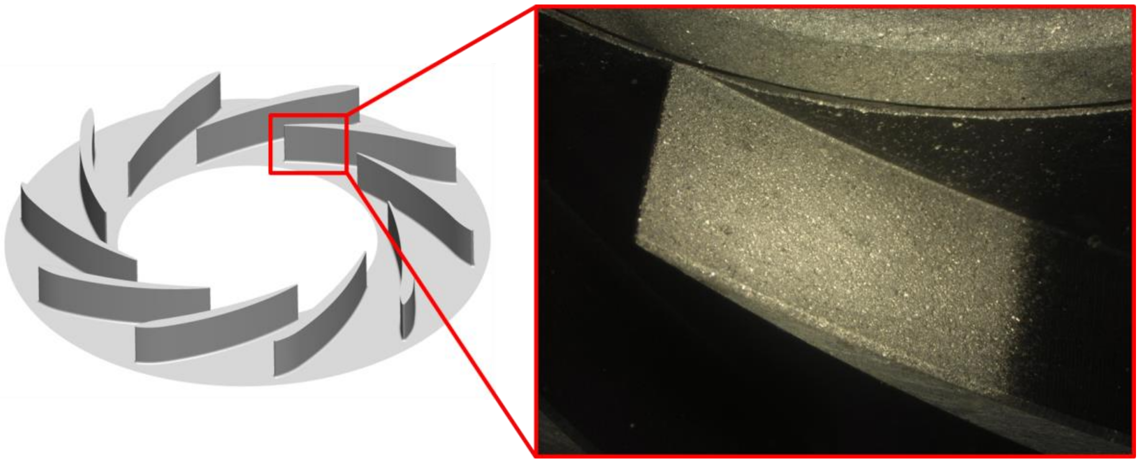

Figure 4 Eroded suction side near the stator vane trailing edge

EROSION DUE TO CONDENSED WATER

Initially, the authors assumed that the water condensing in the turbine is responsible for the WDE. This section explains, why this is improbable. Figure 5 shows red isosurfaces representing the nucleation zones in the turbine rotor for a turbine inflow with 100% relative humidity. A sample of the two-way coupled droplet trajectories is also shown. The forces influencing the droplet trajectories are the drag according to Schiller and Naumann (1935), including the correction for submicron particles by Cunningham (1910), and the thermophoretic force. The latter accounts for the force acting on a droplet subjected to a temperature gradient of the surrounding flow. It is obvious that the vast majority of droplet leaves the turbine with the flow. In fact, less than 1% of the droplet trajectories impact the rotor blades and hub and no droplet reaches the stator. All droplet impacts occur near the trailing edges. This is clearly not consistent with the observed erosion zones in the rotor. Also, WDE cannot be caused by droplets of this small size (max. 400 nm diameter) and low velocity relative to the rotor blade.

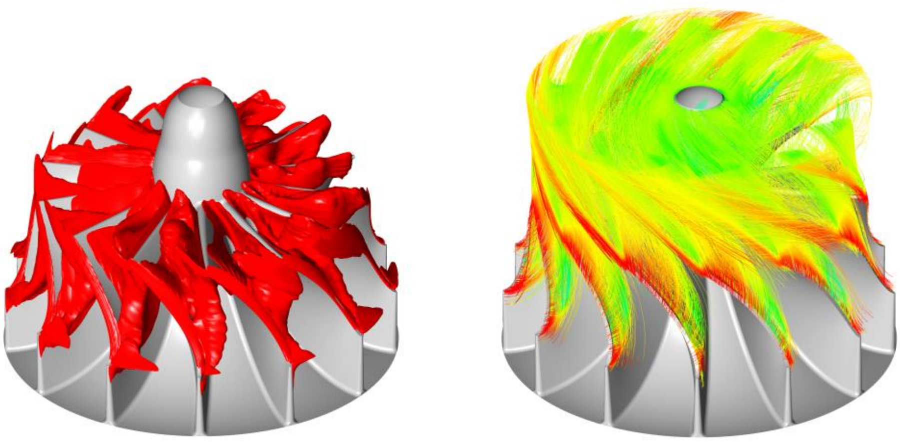

Figure 5 Left: Nucleation zones. Right: Trajectories of condensed droplets.

One could argue, that the droplets originating from condensation contribute to WDE through secondary droplets formed by wall films or splashing. However, this is also unlikely. According to the criterion of Mundo et al. (1998) a splashing of the impacting droplets would require diameters two orders of magnitude larger. Instead, all impacting droplets deposit without splashing. Detailed simulations regarding the further path of these droplets are not within the scope of this study. However, their general behavior can be logically deduced. After deposition, the resulting wall film formed is exposed to the drag of the flow and the centrifugal force due to the rotation of the rotor. This causes the wall film to move in the direction of the flow towards the trailing edge and radially outwards towards the shroud. As mentioned above, Schuster et al. (2014) have performed detailed simulations of wall film motion in radial turbines. Their results show that near the leading edge, centrifugal force can transport the flow outwards, in the opposite direction of the flow. For this to happen in the case studied here, the droplets would have to deposit far further upstream near the leading edge. Since the deposition zones are near the trailing edge of the blade, wall film motion towards the leading edge is not possible. It can therefore be concluded that the droplets originating from condensation do not contribute to the WDE observed for the turbine under investigation.

EROSION DUE TO INFLOW OF COARSE WATER

Since water from condensation is not involved, the WDE must be the result of water from another source. As mentioned earlier, an inflow of liquid water was observed during the experiments. This liquid water is a product of the fuel cell reaction. It should have been separated in a water separator. However, such a device is not capable of separating all droplet sizes. Thus, an inflow of liquid water is plausible not only on a test rig but also in automotive applications. In this section, possible pathways of water leading to WDE in the rotor and stator are discussed. For this purpose, the previously published flow results for the design operating point of the turbine are used as the basis for new, one-way coupled Euler-Lagrange simulations. The droplet trajectories are modeled with the Schiller-Naumann drag law. The thermophoretic force and the Saffmann force are included as well. Growth by condensation is taken into account. The size distribution and droplet velocities at the volute inlet are unknown, as is the mass flow of liquid water. Therefore, the goal is not to quantify the erosion rates. Instead, the aim is to perform variations of the droplet parameters to obtain droplet trajectories that fit to the observed WDE.

First, it must be investigated how droplets entering the turbine at the volute inlet behave in the flow. For this purpose, droplets are injected at the volute inlet with the temperature and velocity of the surrounding flow field. A variation of the diameter shows that droplets smaller than 0.8 μm pass the turbine without deposition. All droplets larger than 3 μm deposit in the volute. In contrast, droplets in the range of 0.8 μm to 3 μm show a more interesting behavior. They partially deposit on the stator suction side and the rotor pressure side. However, impacts on the rotor occur too far downstream to be relevant to the WDE. The left side of Fig. 6 shows the trajectories of droplets injected at the volute inlet with a diameter of 2 μm. Some droplets impact the leading edge of the stator vanes (A). In general however, the droplets are well able to follow the flow. As expected, the pressure sides of the stator vanes are not impacted by droplets. In contrast, a significant proportion of the droplets impact at the suction side of the stator vanes. This occurs in particular, when the droplet trajectories are influenced by pressure side separations such as in (B). The color scale of the trajectories, which represents the droplet diameter, shows a clear growth of the droplets along their trajectories. The droplets with the longest residence time in the flow double their diameter (C). The increased inertia causes a larger proportion of these droplets to deposit on the stator vanes (D). It should be noted that this growth by condensation can only be observed at high humidities, when the water vapor is already subcooled in the volute. In the case discussed here, the flow entered the turbine at 100 % relative humidity.

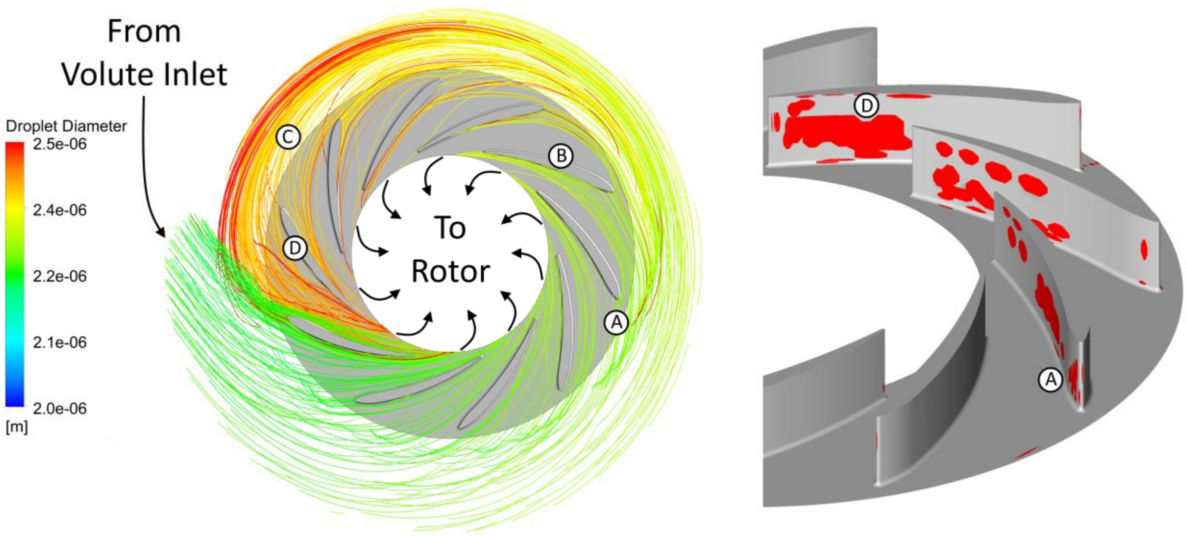

Figure 6 Left: Diameter of droplets in the stator. The trajectories originate with 2 μm diameter at the volute inlet. Right: Droplet impact zones in the stator.

On the right side of Fig. 6, the impact zones of the droplets are shown in red. It is obvious that these do not correspond to the erosion zones shown above. This is plausible because droplets with the rather small diameter of 2 μm and the low normal velocity relative to the vane cannot cause erosion. Instead, the droplets deposit on the vane surface. Splashing of the droplets is unlikely due to the small diameters and low normal velocity. Of course, the droplets causing erosion are not only 2 μm in size, but are part of a spectrum. However, the results shown in Fig. 6 indicate that the liquid inflow to the turbine causes the formation of a wall film on the suction side of the stator vanes. The stator does not rotate, so the drag of the gas phase moves the wall film radially inwards towards the trailing edge of the stator vanes. There, the water separates from the vanes and breaks up to form secondary droplets. This process of separation and droplet break-up is complex and depends on many parameters. Due to lack of sufficient input data, this process cannot be modeled in this study. Instead, droplets with different diameters are injected at the stator vane trailing edges with zero velocity and tracked using the Euler-Lagrange approach introduced above. It is found that droplets smaller than 5 μm follow the flow and leave the domain at the outlet. Droplets larger than 50 μm cannot enter the rotor because the dominant centrifugal force transports them radially outwards, resulting in an impact on the suction side of the stator vanes. Droplets in the range of 5 μm to 50 μm can enter the rotor and impact the suction sides of the rotor blades. On the left in Fig. 7, several trajectories of droplets with a diameter of 20 μm are shown as examples. The droplets are injected at the trailing edges of the stator vanes (A) and accelerated by the flow. However, due to their high inertia, the droplets are too slow to match the circumferential speed of the rotor. Thus, when the droplets enter the relative system of the rotor, they impact the suction side of the rotor blades near the leading edges (B) with a relative velocity of over 100 m/s. Mundo's criterion predicts a splashing of droplets with this diameter and speed. However, some droplets may show different trajectories depending on the relative position of the rotor and stator. The trajectories marked (C) are initiated at zero velocity, accelerate, narrowly miss the rotor blade, continue to accelerate and then leave the rotor due to the increasing circumferential force. Finally, they impact the suction side of a stator vane. In a next step, the droplets were released not only at the trailing edges of the stator vanes, but over the entire circumference. This allows the tracking of trajectories for all possible relative positions of rotor and stator. The resulting impact zones in the rotor (B) and stator (C) are shown in the center and right of Fig. 7. These impact zones match very well with the observed erosion zones in Fig. 3 and Fig. 4. For the rotor, the larger impact zones near the shroud were found to be an effect of the higher flow velocity there, which allows the droplets to move radially farther inward. It was also investigated whether droplet injection with velocities greater than zero and different injection angles can significantly influence the trajectories. However, the effect of these changes is very limited. Droplet growth through condensation is likewise not relevant for these droplets, as they are already quite large and also impact after a very short time.

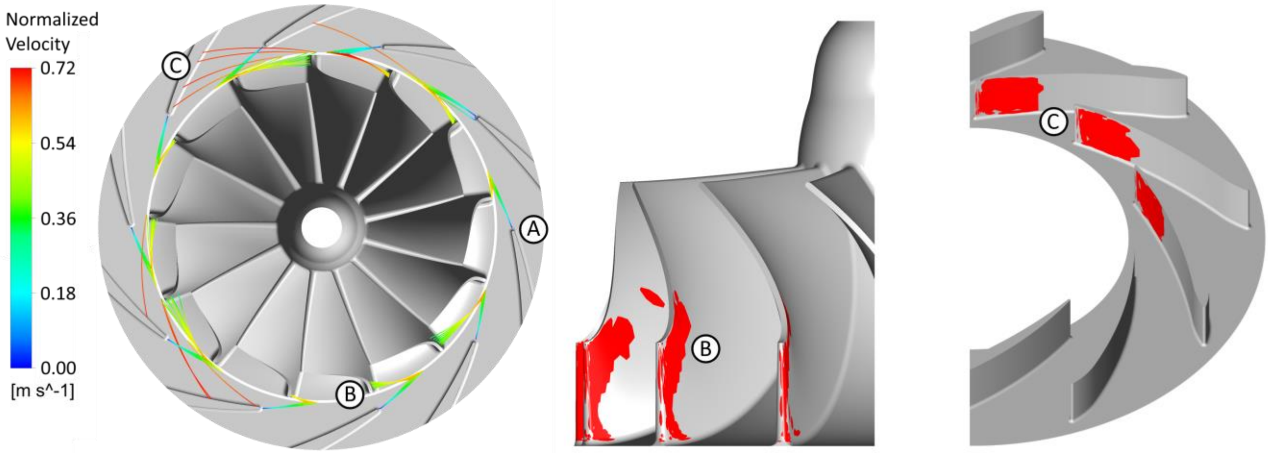

Figure 7 Left: Trajectories of droplets with 20 μm diameter released from the stator vane trailing edges. Velocity normalized with the rotor speed. Middle: Impact zones on the rotor blade suction sides. Right: Impact zones on the stator vane suction sides.

The splashing of droplets and the further path of smaller droplets that form from splashing are not modeled in this study. However, it is possible that these droplets deposit on the suction side of the rotor blades after splashing. In addition, droplets released from the stator that are smaller than the example shown above may deposit on the suction side of the rotor blade without splashing. According to the findings of Schuster et al. (2014), it is assumed that the resulting wall film is transported to the leading edge of the rotor blades. Therefore, a third possible source of coarse water in the turbine must be investigated: Droplets released from the leading edges of the rotor. For this purpose, droplets with different diameters are injected with zero relative velocity at the leading edges of the rotor blades. It was found that, as previously with the injection in the stator, droplets smaller than 5 μm follow the flow and leave the domain at the outlet. Droplets between 5 μm and 7 μm orbit the rotor. Larger droplets impact the suction sides of the stator vanes. As an example, the left side of Fig. 8 shows the trajectories of droplets with a diameter of 20 µm. The trajectories appear as an almost straight line from the leading edge of the rotor blades to the stator vanes. The droplets of this example are relatively large and have a high velocity at impact. Therefore, according to Mundo et al. (1998), the droplets will splash into smaller droplets. The droplet trajectory marked (B) gives a good explanation for the sharp vertical boundary between eroded and non-eroded zones at the stator suction sides. The trajectory narrowly misses the trailing edge of one stator vane and impacts the next vane. If the trajectory had been a little further to the right, it would have impacted the first stator vane and not made it to the second. The right side of Fig. 8 shows the impact zones in the stator for a large number of droplets injected over the entire circumference. The results are consistent with the erosion patterns in the stator (see Fig. 4) and are very similar to the results shown in Fig. 7 on the right. Droplet impacts in the rotor were not observed. Again, injections at a velocity greater than zero and different injection angles had no significant effect. Growth due to condensation is also not relevant.

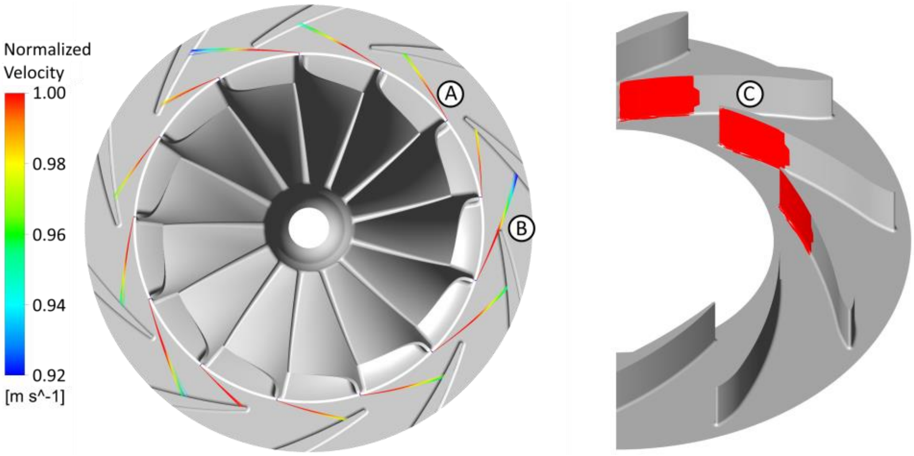

Figure 8 Left: Trajectories of droplets with 20 µm diameter released from the rotor blade leading edges. Velocity normalized with the rotor speed. Right: Impact zones on the stator vane suction sides.

CONCLUSIONS

In this study, water droplet erosion in the radial turbine of an automotive fuel cell turbocharger was investigated. The turbine under investigation was operated on a test rig with an inflow of humid air and some amount of liquid water. After the experiments, erosion was found in two areas of the turbine. First, the last third of the suction side of the stator vanes showed significant erosion with the distinct feature of a sharp vertical line separating eroded and non-eroded zones. Second, the suction side of the rotor blades showed a narrow vertical strip of erosion near the leading edge. The next steps were to analyze the processes responsible for this erosion. Basically, there are two sources of liquid water in the turbine that can cause erosion. The first source is droplets formed by condensation. The results of earlier flow simulations involving condensation were re-analyzed, now focusing on the deposition of droplets. It was found that these droplets are not involved in erosion because condensation starts too far downstream. The second source of liquid water in the turbine is droplets already present at the volute inlet and originating from the fuel cell. During the tests of the turbine, an inflow of liquid water was observed, but no data is available on the mass flow and droplet size distribution of this water. Therefore, a parameter study of possible droplet trajectories was carried out. The aim was to find trajectories that fit the observed erosion zones from the experiments. The droplet trajectories were calculated using a one-way coupled Euler-Lagrange approach. It was found that the droplets injected at the volute inlet are not responsible for erosion. However, these droplets can deposit on the stator vanes and possibly form wall films. It is assumed that these wall films are transported to the trailing edge of the stator vanes where they break down into secondary droplets. Droplet injections at these trailing edges result in trajectories impacting the suction side of the rotor blades and stator vanes. The resulting impact zones are very similar to the observed erosion patterns. The third injection point for erosion-relevant droplets is the leading edges of the rotor blades. Droplets originating from there are caused by the break-up of wall films, which in turn are a result of deposited droplets coming from the stator. The trajectories result in impact patterns on the stator vanes that also closely match the observed erosion zones. Therefore, it is concluded that erosion of the rotor blades is caused by droplets from wall film break-ups at the trailing edges of the stator. The erosion of the stator vanes is caused by droplets from wall film break-ups at the stator trailing edges and the rotor leading edges.

The simplest way to avoid water droplet erosion in the turbine of a fuel cell turbocharger is to separate all liquid water from the inflow to the turbine. If this is not completely possible, an attempt should be made to remove wall films on the stator suction sides. This will break the chain of droplets responsible for erosion. Techniques for water removal in turbomachinery are well known from steam turbines. Another way to avoid erosion is not to remove the water but to protect the erosion-prone surfaces with coatings, which are likewise known from steam turbines. Further research should also attempt to experimentally verify the hypothesis developed in this study regarding the droplets responsible for erosion. Furthermore, this research was limited to relatively compact turbines for automotive applications. Larger turbines or greater pressure ratios could show a different behavior. In particular, droplets from condensation could become relevant for erosion.

NOMENCLATURE

K	Droplet impact criterion	NISO	Non-isothermal correction
We	Weber number	PEMFC	Proton-exchange membrane fuel cell
Re	Reynolds number	WDE	Water droplet erosion
GCI	Grid convergence index		

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ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the German Federal Ministry of Transport and Digital Infrastructure for the ARIEL project (Grant No. 03B10105D2). The authors are responsible for the content of this publication. Mr Daniel Grundei and Mr Manuel Meier from Volkswagen AG are thankfully acknowledged for their support and the provision of the turbines. The authors would like to thank Mr Marco Menze from the Institute of Fluid Dynamics and Turbomachinery, Leibniz Universität Hannover for providing the volute mesh. The student assistants Ms Catherine Rau and Mr Lars Hinz are gratefully acknowledged for their contributions to this study.

REFERENCES

Ahmad M (2018) An Overview of Droplet Impact Erosion, Related Theory and Protection Measures in Steam Turbines. In: Borek W, Tański T and Król M (eds) *Cavitation - Selected Issues:* IntechOpen.

Ahmad M, Casey M and Sürken N (2009) Experimental assessment of droplet impact erosion resistance of steam turbine blade materials. *Wear* 267(9-10): 1605–1618.

Blunier B and Miraoui A (2010) Proton Exchange Membrane Fuel Cell Air Management in Automotive Applications. *Journal of Fuel Cell Science and Technology* 7(4): 727.

Chidambaram PK and Kim H-D (2018) A numerical study on the water droplet erosion of blade surfaces. *Computers & Fluids* 164(1): 125–129.

Cunningham E (1910) On the velocity of steady fall of spherical particles through fluid medium. *Proceedings of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 83(563): 357–365.

Guildenbecher DR, López-Rivera C and Sojka PE (2009) Secondary atomization. *Experiments in Fluids* 46(3): 371–402.

Gujba AK, Hackel L, Kevorkov D, et al. (2016) Water droplet erosion behaviour of Ti–6Al–4V and mechanisms of material damage at the early and advanced stages. *Wear* 358-359(2): 109–122.

Hesketh JA and Walker PJ (2005) Effects of Wetness in Steam Turbines. *Proc IMechE, Part C: J Mech Eng Sci* 219(12): 1301–1314.

Lee B-E, Riu K-J, Shin S-H, et al. (2003) Development of a water droplet erosion model for large steam turbine blades. *KSME International Journal* 17(1): 114–121.

Li J, Zhang H and Liu Q (2019) Characteristics of secondary droplets produced by a single drop impacting on a static liquid film. *International Journal of Multiphase Flow* 119(10): 42–55.

Menze M, Schödel M and Seume J (2021) Numerical investigation of a radial turbine with variable nozzle geometry for fuel cell systems in automotive applications. *Proc: The 14th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics*.

Mundo C, Sommerfeld M and Tropea C (1998) On the modeling of liquid sprays impinging on surfaces. *Atomization and Sprays* 8(6): 625–652.

Samenfink W, Elsäßer A, Dullenkopf K, et al. (1999) Droplet interaction with shear-driven liquid films: analysis of deposition and secondary droplet characteristics. *International Journal of Heat and Fluid Flow* 20(5): 462–469.

Schiller L and Naumann A (1935) A Drag Coefficient Correlation. *Zeitschrift des Vereins Deutscher Ingenieure*(77): 318–320.

Schlottke A and Weigand B (2021) Two-Phase Flow Phenomena in Gas Turbine Compressors with a Focus on Experimental Investigation of Trailing Edge Disintegration. *Aerospace* 8(4): 91.

Schuster S, Benra F-K, Dohmen HJ, et al. (2014) Sensitivity Analysis of Condensation Model Constants on Calculated Liquid Film Motion in Radial Turbines. In: *Volume 1B: Marine; Microturbines, Turbochargers and Small Turbomachines; Steam Turbines:* American Society of Mechanical Engineers.

Schuster S, Brillert D and Benra F-K (2018a) Condensation in Radial Turbines - Part I: Mathematical Modeling. *Journal of Turbomachinery* 140(10): 768.

Schuster S, Brillert D and Benra F-K (2018b) Condensation in Radial Turbines—Part II: Application of the Mathematical Model to a Radial Turbine Series. *Journal of Turbomachinery* 140(10): 289.

Wang Z, Hopfes T, Giglmaier M, et al. (2020) Effect of Mach number on droplet aerobreakup in shear stripping regime. *Experiments in Fluids* 61(9): 193.

Wittmann T, Bode C and Friedrichs J (2021a) The Feasibility of an Euler–Lagrange Approach for the Modeling of Wet Steam. *Journal of Engineering for Gas Turbines and Power* 143(4): 1301.

Wittmann T, Lück S, Bode C, et al. (2021b) Modelling the Condensation Phenomena within the Radial Turbine of a Fuel Cell Turbocharger. *International Journal of Turbomachinery, Propulsion and Power* 6(3): 23.

Wittmann T, Lück S, Hertwig T, et al. (2021c) The Influence of Condensation on the Performance Map of a Fuel Cell Turbocharger Turbine. *ASME Turbo Expo 2021 (in Print)*.

Yarin AL (2006) Drop Impact Dynamics: Splashing, Spreading, Receding, Bouncing… *Annual Review of Fluid Mechanics* 38(1): 159–192.