# A NOVEL AXIAL FAN CONCEPT DEVELOPED USING PARAMETRIC OPTIMIZATION

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## SUMMARY

The present paper describes the tasks, the used tools and the results of the development process for a novel axial fan concept. Simply optimizing the state-of-the-art concept of a fan stage of an axial impeller with tip gap and guide vanes does not seem to have that much potential for improvements. So, the decision was made to change the concept completely to a shrouded impeller with a slightly diagonal approach combined with an inlet nozzle. As a result of the revised fan concept and the use of parametric optimization, the new fan has a higher efficiency than common axial fans, a steeper pressure characteristics with higher stall margin, a good noise behavior, less icing on the fan blades in evaporator applications and a higher throw distance.

## INTRODUCTION

In order to limit global warming, energy saving is an essential component along with the conversion of energy production to renewable energy. As fans considerably contribute to overall energy consumption, increasing efficiency is one of the most important targets when developing new fans.

Another important goal is to reduce fan noise, as fans are often used in a noise sensitive environment like residential buildings.

This paper relates to the development of a new axial fan range from a design size of 300mm to 500mm. A typical state-of-the-art fan, that should be replaced by the new fan range, is shown in Figure 1. These fans consist of an axial impeller that is directly driven by an electric motor. They are typically used inside a nozzle and often combined with a metal guard grille.

*Figure 1: state-of-the-art fan*

Such axial fans are used in a wide range of applications. Therefore, in addition to typical development targets such as efficiency and noise, other aspects must be considered. In evaporation applications for instance, icing of the fan blades and housing could lead to blockage of the motor and must be prohibited. Another important aspect in this application is the throw distance of the fan. Heat pump applications deal with similar problems. In addition to that, the new fan must not exceed the installation space of the existing one.

## AERODYNAMIC CONCEPT

Since the fan that has to be developed will be used in very different applications, there is not only one design point but a wide operating range where the fan has to work properly. In some applications, the operating point even changes significantly during operation due to blockage of filters or icing of a heat exchanger in refrigeration applications.

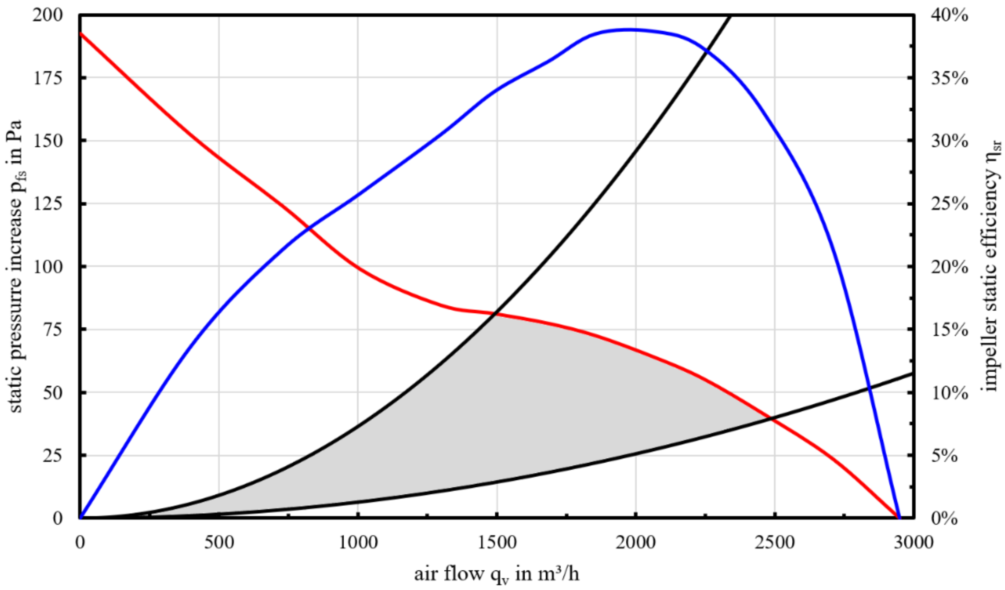


*Figure 2: baseline fan ø350 mm, 1350 rpm*

Figure 2 shows the recent characteristic curve of the baseline fan for further development. The reasonable application range is marked as the grey area in the diagram. In the applications already mentioned with increasing pressure during operation, it can happen that the upper limit of the application range is exceeded and the fan is operated in the stall region. This leads to reduced efficiency, strong noise increase and in some cases to overload of the electric motor.

In evaporator applications, the operation in the stall region causes additional problems. Backflow in the inner region of the fan causes icing on the fan blades and the guard grille. This leads to an additional pressure drop on the guard grille. After some defrost cycles of the evaporator, more and more ice accumulates on the fan and under unfavorable conditions, this can lead to blockage of the fan blades. Figure 3 shows this effect on the left side. The shown fan was operated in an evaporator application with high humidity for approximately one hour. The areas where the ice accumulates correlate with the areas with backflow, shown as blue areas in the CFD result on the right.

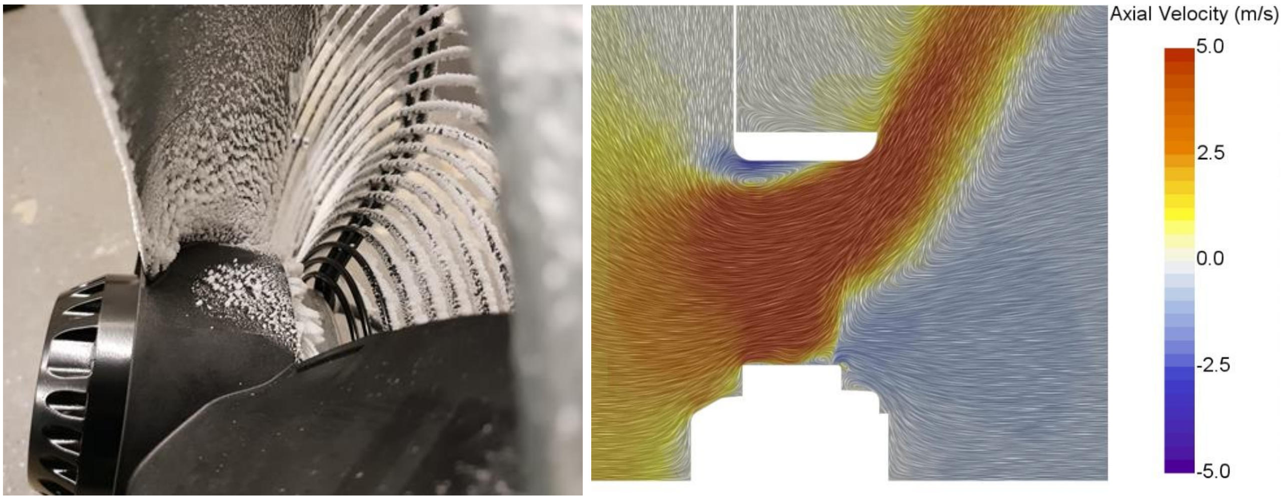


*Figure 3: icing on an axial fan in an evaporator application during operation in the stall region (left) axial velocity from CFD simulation of the same fan in the stall region (right)*

The throw distance also is significantly reduced or even completely lost, when operating the fan in the stall region, because the outflow direction changes from axial to nearly radial. In applications with heat exchangers like heat pumps, the lost throw distance can lead to a thermal short circuit and consequently a reduced efficiency of the complete system. Therefore, an additional target for the development of the next generation of these fans is to increase the stall margin.

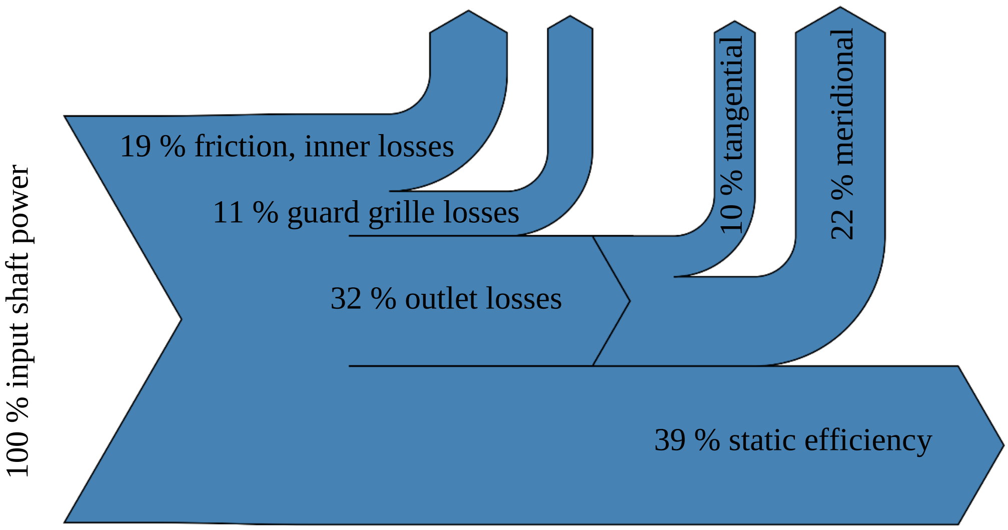


*Figure 4: loss analysis of the baseline fan at the best efficiency point*

In order to improve the existing fan concept, it is necessary to analyze the loss mechanisms. Figure 4 shows the results of a loss analysis of the baseline fan at its best efficiency point. This loss analysis is performed based on measurements and results of CFD simulations. The outlet losses are defined as the dynamic pressure at the fan outlet, that is not recovered as static pressure. The 32 % of the input shaft power, are the largest amount of losses. About one third of the outlet losses are caused by the tangential velocity at the fan outlet, two-thirds of them by the meridional velocity.

Due to the big relevance of the outlet losses, it is obvious to reduce them in a new fan concept. The state-of-the-art concept for this is to combine the fan with a diffusor to reduce the meridional amount of the outlet losses and use guide vanes to reduce the tangential velocity. The disadvantage of this approach is, that the axial overall length of the fan is increased significantly.

The approach of the novel axial fan concept is to combine the axial fan with tip gap and the downstream arranged diffusor to a slightly diagonal, shrouded impeller with an inlet diameter that corresponds to the baseline fan. The impeller is combined with a short inlet nozzle, as it is usual with centrifugal fans. This leads to a better utilization of the available space and a reduction of the outlet losses.

## PARAMETRIC OPTIMIZATION WORKFLOW

For shrouded mixed-flow fans, classic design approaches do not perform very well. Therefore, another design method is required to design and optimize the impeller of the described concept. In this case, it was indicated to start directly with a parametric optimization workflow without a preliminary design method before. The used multi-physics automated optimization workflow is shown in Figure 5. This workflow starts with an initial set of parameters which includes all necessary information to describe the geometry of the impeller and the inlet nozzle.

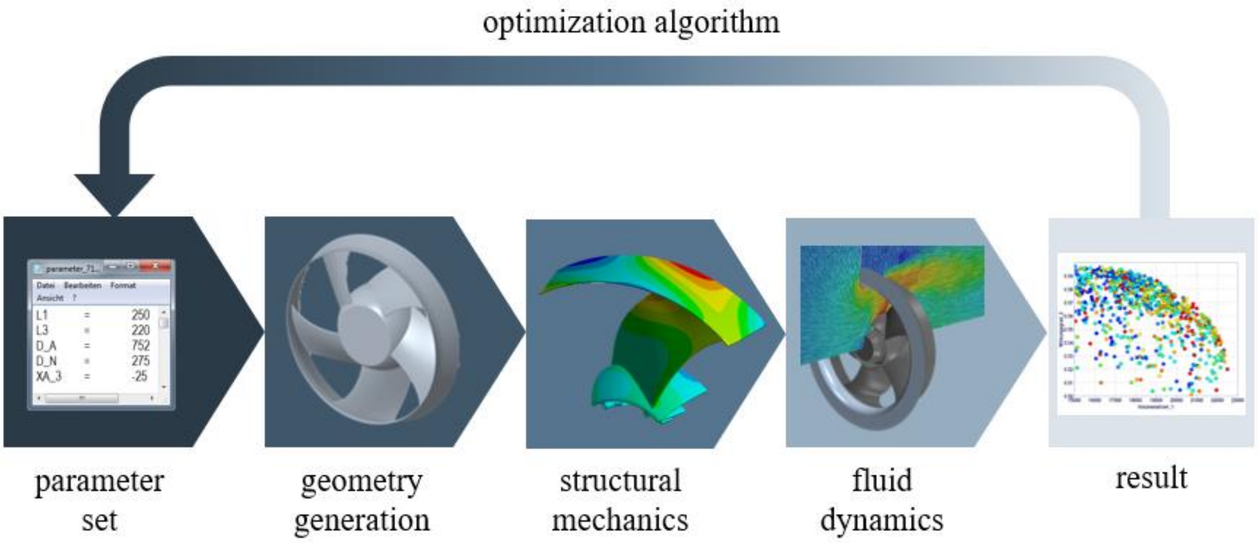


*Figure 5: parametric optimization workflow*

In the next step a parametric CAD model is used to build up the geometry models of the impeller and the nozzle based on the parameter set. The advantage to use a common CAD system (in this case Creo from PTC) is the easy use of the geometry model for the following steps in the development process like building prototypes for measurements and design tasks. This reduces the duration of development loops significantly and improves the quality as the relevant geometry is exactly the same. Therefore, there is no need to redesign the impeller based on cross sections afterwards. The blade is defined using the four-digit NACA series description of the chamber line [1] for each of the five cross sections. As the mixed-flow fan will be not that much radially oriented, this typical parametrization for axial fans can be used simply wrapping the two-dimensional camber lines on conical surfaces. As the thickness distribution of the four-digit NACA series is not suitable for an injection molding process, because the thickness varies too much, a self-defined one is used. This thickness distribution is no free parameter in the optimization. Other important parameters are the definition of the leading edge shape and the description of hub and shroud. The model has 23 free parameters for the optimization:

- definition of the blade shape with 15 parameters
- five parameters to define the leading edge shape
- three parameters for hub and shroud

After the geometry generation, the CAD model is made available as a step file for the following simulations.

Based on the CAD model, a structural-mechanical simulation of the impeller is carried out in order to analyze the deflection under speed load. It is very important to consider this directly in the design loop, because the blade shape influences the deformation of the impeller significantly. Therefore, optimizing structural mechanics and aerodynamics sequentially is not that efficient and the result is often worse. The deformation of the shroud is one of the objectives for the optimization that must be minimized. The equivalent stress is not traded as an objective, but it is constrained.

The CFD simulation follows the consideration of the structural mechanics. In this case, a periodic RANS model with a realizable two-layer k-epsilon turbulence model and a moving reference frame approach is used. The operating point is defined with zero pressure boundary conditions for inlet and outlet and a porous region in front of the fan, which allows to perform the simulation on a quadratic system characteristic curve. Preprocessing, solving and postprocessing is done with an automated workflow within Star-CCM+. The integral values volume flow, static pressure increase, torque and static efficiency are exported to a text-file. The static efficiency and the volume flow are objectives that need to be maximized in this optimization.

In the last step, the results of the simulations are integrated into the optimization's database. Afterwards, the optimization algorithm defines new parameter sets for the following designs based on the updated database. Then the process chain is started again.

## RESULTS

As a result of the revised fan concept and the parametric optimization workflow, a completely new fan concept for typical axial fan applications emerged. The new impeller is shown in Figure 6.

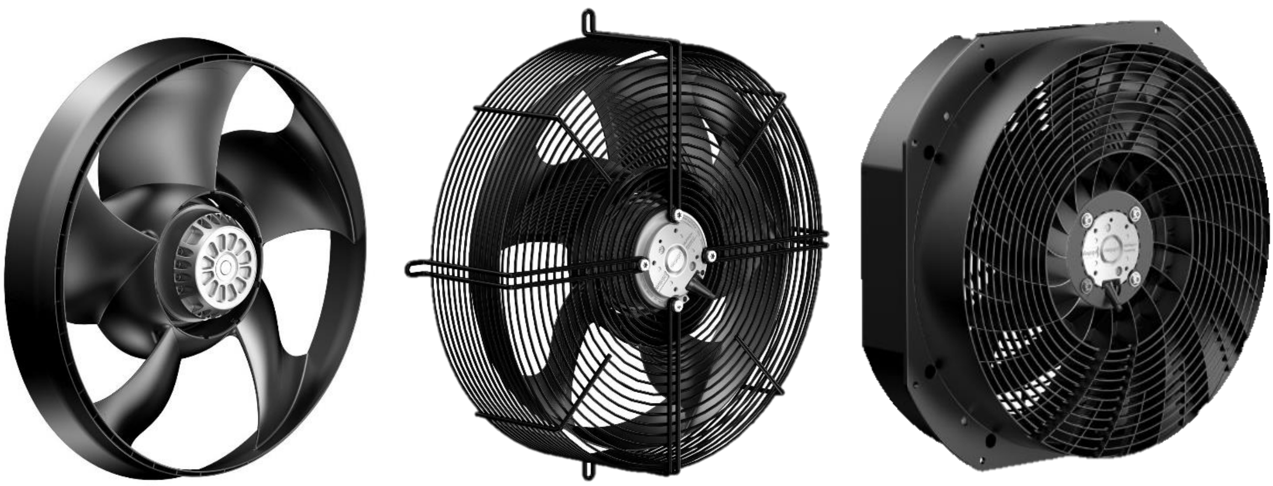

*Figure 6: impeller of the new fan concept (left), version with guard grille (middle) and with housing (right)*

It can be combined with a typical guard grille and a sheet metal inlet nozzle or with a housing which has integrated guide vanes and a guard grille on the outlet side. The housing was also designed with the workflow described above. The characteristic curves of the baseline fan and the new concept in both versions are shown in Figure 7. All fans have a guard grille on the outlet side of the fan. An increase of 22 % in static efficiency is reached with the new concept and a metal guard grille in comparison to the baseline fan. The new fan version with plastic housing and integrated guide vanes even achieves an efficiency increase of almost 50 %. Both versions significantly extend the range of application to higher pressures.

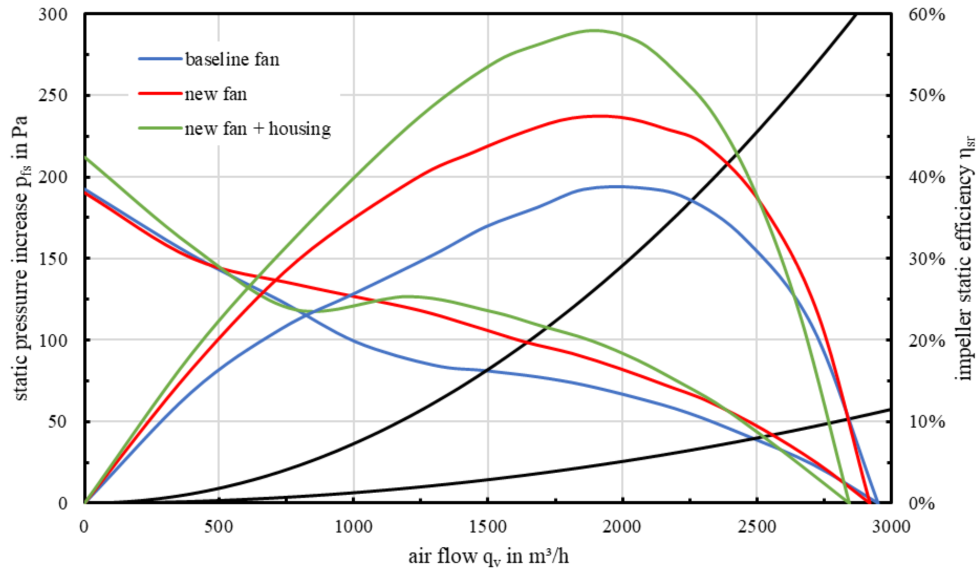


*Figure 7: characteristic curves of the new fan solo and with housing in comparison to the baseline fan*

The diagonal fan design eliminates backflow in the hub area completely and especially the version with plastic housing has no longer the problem of icing described above. Icing tests [3] show, that there is almost no icing on the guard grille when the fan is operated under the same conditions that lead to icing on the axial fan's guard grille. Figure 8 shows the result after two icing loops. In addition to that, the danger of the blades freezing is reduced, as there is no tip-gap. This is very important for refrigeration and heat-pump applications.

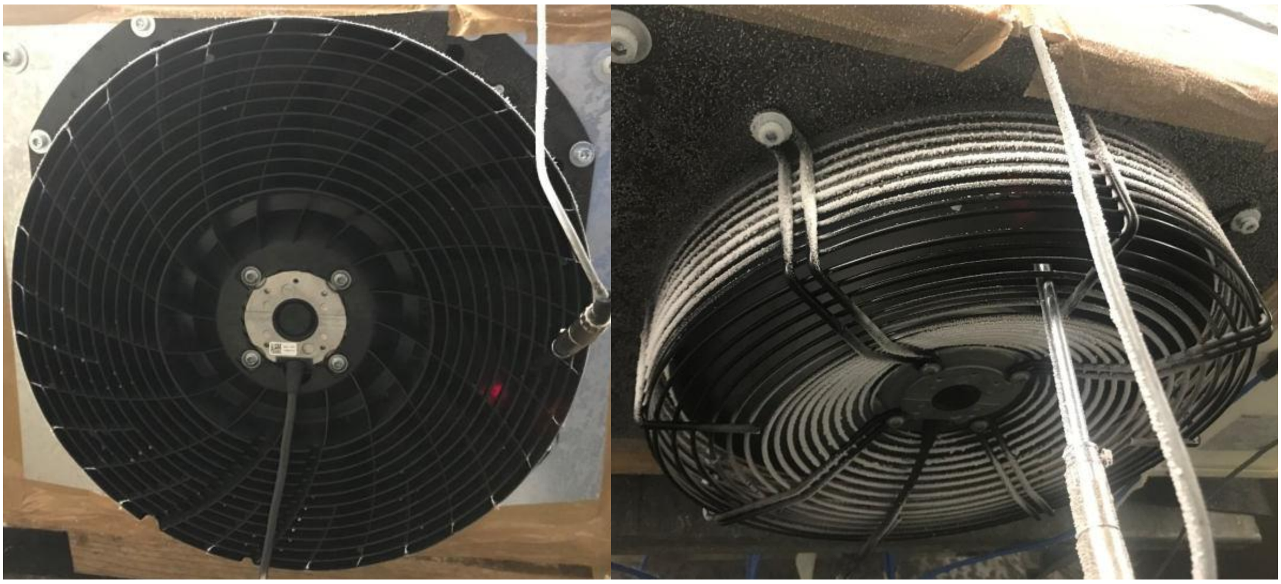

*Figure 8: icing test result of the new fan (left) vs. the baseline fan (right) [2]*

Typically, mixed-flow fans are not suitable for applications, that need a big throw distance. Axial fans seem to be the better solution in this case. Nevertheless, the housing with guide vanes lead to an improved throw distance of the new fan in comparison to the axial baseline fan. Figure 9 is shows the results of measurements of both fan concepts, which are performed with hot-wire anemometers on a large test grid. The throw distance is increased by around 25 % compared to the axial fan. The reason for this can be identified in the measurement results: The outflow of the new fan is more axially orientated.

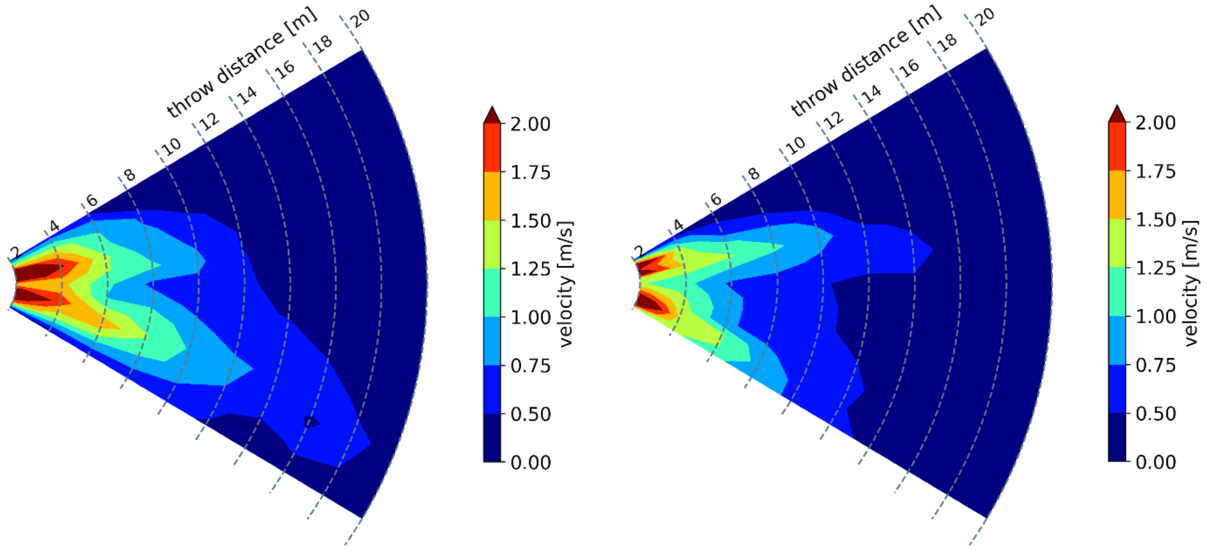


*Figure 9: throw distance of the new fan (left) in comparison to the baseline fan (right)*

## CONCLUSION

The procedure described above clearly shows that it is still possible to increase the efficiency of existing fan concepts significantly. Simply using an automated optimization workflow often does not lead to such an improvement. It is necessary to deeply analyze the flow and detect the most important mechanisms of losses. However, such a workflow offers great potential for improvement once the relevant approaches for improvement have been found. In this case, this procedure leads to a novel fan concept, which can be used in a wide range of applications.

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