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Optimization of pressure drop in curved conduits using Ansys DesignXplorer

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Abstract. This paper describes the effects of guide vanes installed in curved conduits with the main emphasis on pressure loss reduction. In curved parts of conduits, eddy zones are created due to the flow separation resulting in an increased value of pressure drop. Installation of guide vanes can prevent the creation of large eddy zones. On the other hand, the cross-section of the conduit is decreased by placing the vanes, leading to the growth of the pressure drop. That is why the properties of guide vanes needed to be selected carefully. The goal of this paper is to describe the process of finding the optimal number of vanes in order to obtain the lowest value of pressure drop in the curved conduit. This is achieved by a parametric case study in Ansys DesignXplorer combined with CFD simulations in Ansys Fluent. The case study parameters are the number and thickness of vanes, dimensions of the conduit, and the inlet velocity. Our results are compared with recommendations on the optimal number of vanes from Idelchik [1].

1 Introduction

With the development of software and hardware, numerical simulations became a commonly used tool when creating new products or when improving the current ones. Nowadays, numerical simulations are employed in a wide range of fields including fluid, structural and thermal analysis, optics, electronics and others. The main advantage of numerical simulations is that the performance of proposed designs is evaluated in a short time without the need of manufacturing and testing the physical model. The common goal is to make the product better and cheaper at the same time i.e. to optimize the product.

Parametric optimization is a method of finding the optimum value of output parameters when changing a set of input parameters in defined ranges. A simple tool for such parametric studies is Ansys DesignXplorer which is suitable for data coming either from simulations, inhouse codes or even experiments. Thanks to the concept of Response Surface, DesignXplorer provides the resulting optimum with a significantly reduced number of executed simulations.

DesignXplorer is used to optimize the flow in a rectangular pipe elbow by installing guide vanes. The idea is that there is an existing elbow and the goal is to find the optimal design for the pressure drop to be minimal and compare the results with experimental results published in the literature. The number of guide vanes and their thickness are defined as the input parameters and pressure drop with velocity distribution are monitored

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as the criteria of optimality. These output parameters are evaluated by a numerical simulation in Ansys Fluent.

2 Theoretical background

Centrifugal forces acting on the fluid passing through a curved conduit causing a decrease in the pressure at the inner wall and an increase in the pressure at the outer wall. These changes in pressure are related with the corresponding changes in velocity. As described for example in [1], we speak about the diffuser effect at the outer wall and the bellmouth effect at the inner wall. Due to described effects, the flow is separated from the inner wall and an eddy zone is created leading to a reduction of the main stream section and resulting in increased resistance of the pipe i.e. the pressure drop.

The pressure drop in the curved conduit can be decreased by installing guide vanes. For elbows, it is possible to use simple vanes with constant diameter or airfoils. On the other hand, concentric vanes are recommended for bends. Thanks to the vanes the flow is deflected towards the inner wall and the eddy zone is minimized, therefore the pressure drop is decreased and the velocity distribution behind the turn is improved [1]. In order to accomplish this, the properties of guide vanes such as dimensions, number, shape and angle need to be selected carefully.

Several experimental studies on different guide vanes setups were presented in the literature [2, 3, 4] resulting in guidelines for specific vanes setup and main parameters of guide vanes to consider. Idelchik [1] claims that the most efficient way to decrease the elbow resistance (i. e. the pressure drop) and equalize the velocity distribution is to eliminate the eddy zone at the inner wall and presents a general formula for an optimal number of guide vanes (n) in a 90° elbow:

$$n = 2.13\left(\frac{r}{D}\right)^{-1} - 1\,, \tag{1}$$

where r and D stand for the inner curvature radius of the elbow and the diameter of the pipe.

3 Model and simulation

In order to execute a parametric study, a parametric model of a 90° rectangular elbow was created in Creo Parametrics. The number of vanes and their thickness are defined as parameters. The overall dimensions of the elbow are kept constant (Fig. 1). This geometry is coupled with Ansys Workbench and serves as an input for meshing in Fluent. In the CFD simulation is set up, that air enters the pipe through the velocity inlet at 10 *m/s* and leaves at the pressure-outlet. The turbulence is modelled by k-ω SST model. As a result, the elbow pressure drop and velocity uniformity after the turn are monitored. The velocity uniformity is monitored in order to quantify the velocity distribution described by Idelchik and it is computed by Fluent function called Uniformity Index – Area Weighted (γ_a) [5]:

$$\gamma_a = 1 - \frac{\sum_{i=1}^{n}\left[\left(\left|\phi_i - \phi_{avg}\right|\right)A_i\right]}{2\left|\phi_{avg}\right|\sum_{i=1}^{n} A_i},\;\; \phi_{avg} = \frac{\sum_{i=1}^{n}\phi_i A_i}{\sum_{i=1}^{n} A_i}, \tag{2}$$

where ϕ is the specified field variable, in our case the velocity magnitude, i is the facet index of a surface with n facets and A_i is the area of a facet.

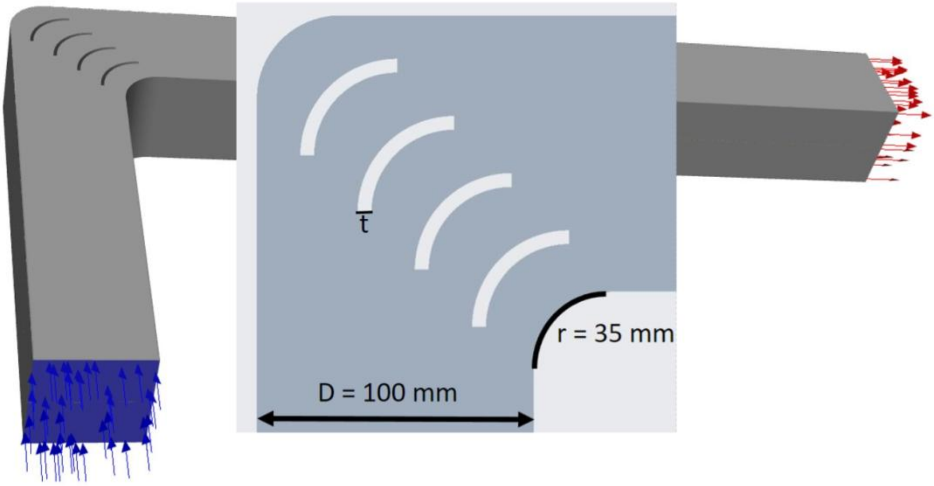

Figure 1: The example of elbow geometry with four vanes defined by characteristic length, radius and thickness (*t*).

In addition to this standard setup, features of DesignXplorer are added to the Workbench thus completing the scheme necessary for running the parametric study and optimization (Fig. 2).

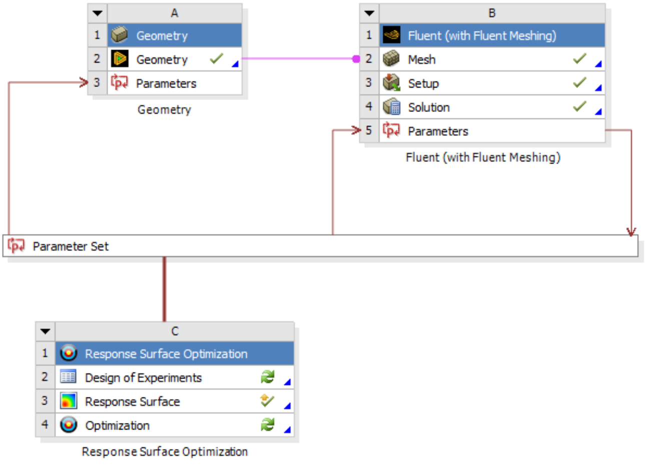

Figure 2: Scheme of the case in Workbench consisting of 3 blocks: geometry, solution and optimization.

4 DesignXplorer

The optimization in DX (DesignXplorer) is divided into three steps. The first step is called Design of Experiments where the range of input parameters is defined by the user. Based on that, DX proposes a “smart” set of Design Points with varying parameters to be calculated by the solver (Fluent or others), in order to sufficiently describe the trends within the defined range.

Secondly, the calculated results from Design of Experiments are approximated by a surface in the step called Response Surface (Fig. 3). DX offers a number of methods for approximating the calculated data. For this case, Second Order Polynomial method is used.

Finally, the Response Surface Optimization is executed based on the Response Surface and the defined objectives. In our case, the objectives are to minimize the pressure drop and maximize the velocity uniformity and the Screening method based on Shifted Hammersley Sampling is used [6, 7]. As results, DX provides the best candidates for defined objectives and in the case of multiple objectives, it also shows the graph of Pareto fronts. Pareto fronts graph is a helpful result that describes the trade-off between conflicting objectives.

In a general optimization algorithm, a large amount of output parameters evaluations is necessary to find the optimum. In order to evaluate the output parameters, the CFD simulation needs to be converged therefore thousands of evaluations for finding the optimum would be excessively time-consuming. That is why the concept the Response Surface Optimization is used. The time consumption is reduced due to the fact, that the optimization algorithm draws data from the Response Surface.

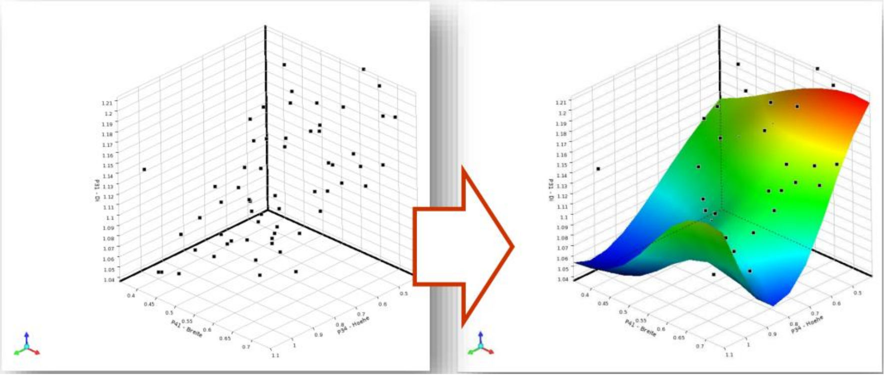

Figure 3: Calculated Design Points based on the Design of Experiments are fitted through with a Response Surface.

5 Results

Based on the Design of Experiments, five simulations with different vanes thickness were computed in Fluent for each number of installed vanes resulting in 30 so-called Design Points. Through these Design Points, a Response Surface is fitted in order to obtain dependency of pressure drop and velocity uniformity on the input parameters (Fig. 4). Computation of the Design Points is the most time-consuming step of the whole optimization in the process of Response Surface Optimization since it requires converged CFD simulations. Our whole optimization case was computed in under 24 hours.

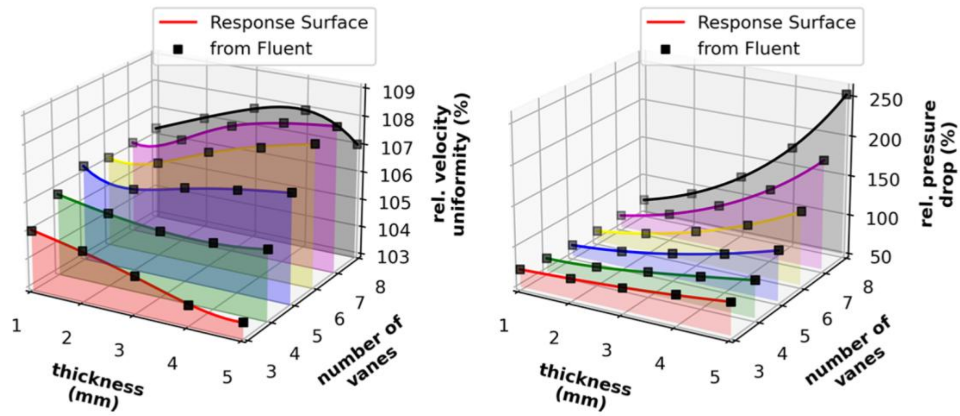

Figure 4: Dependency of the relative velocity uniformity (left) and the relative pressure drop (right) on the input parameters as a result of the Response Surface.

Due to the fact that the number of vanes is defined with discrete values the resulting Response Surface is separated to those discrete values. The use of discrete values also causes the number of Design Points calculated in Fluent to be higher in comparison to cases where the input parameters are defined continuously. For discrete parameter values, DX is not able to approximate for example the values of pressure loss with 5 installed vanes from Design Points computed for 6 and 4 vanes.

Different representation of the result from Figure 4 are displayed in Figure 5. It confirms the fact that vanes decrease the pressure drop when setup correctly. Naturally, the pressure drop increases with the growing thickness of vanes.

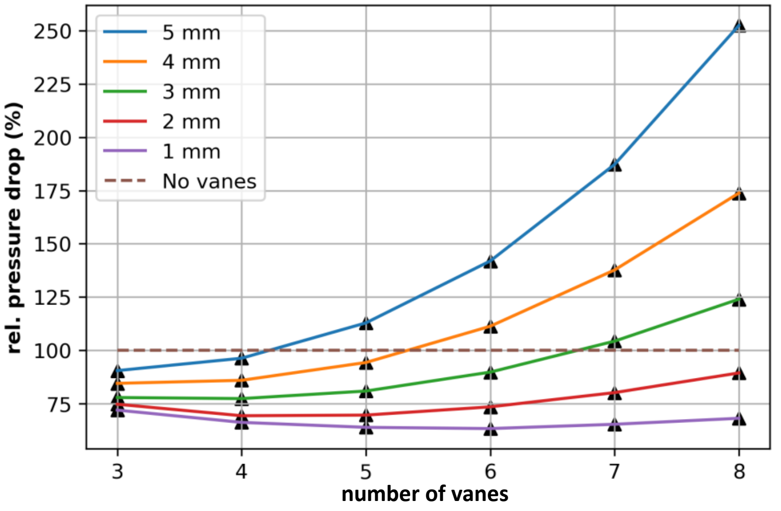

Figure 5: Graph of relative pressure drop depending on the number of vanes for different vane thicknesses.

In the process of finding the optimal vanes parameters, several optimizations were conducted. Firstly, the objective was to minimize the pressure drop. The optimal number of vanes is 6 with thickness of 1 mm (see Fig. 5). This is caused mainly by the fact that with growing thickness and number of vanes the pipe cross-section decreases significantly.

For a graphical comparison of the flow, a case with 4 vanes that are 3 mm thick is compared with the case without any vanes (Fig. 6). From this picture, it is evident that the eddy zone near the inner wall is significantly reduced, and the flow is more equalized when using vanes. This graphic result follows our expectations and agrees with historical theoretical studies.

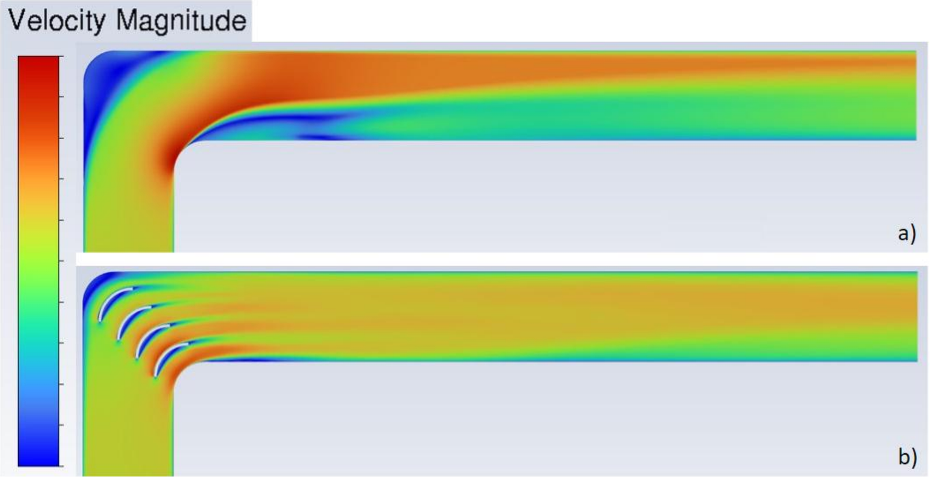

Figure 6: Contours of velocity magnitude for geometry without vanes (a) and with 4 vanes that are 3 mm thick (b).

In addition to the two input parameters previously used, a set of simulations was computed with different inlet velocities. In Figures 7 and 8, examples representing the minimum and the maximum vane thickness are presented. For the vane thickness of 1 mm, the relative pressure drop for different inlet velocities reaches similar values. On the other hand, the relative pressure tends to differ with the growing number of vanes due to the coefficient of local resistance generally depends on the flow velocity. This behaviour is the most noticeable for the case of vane thickness of 5 mm and inlet velocity 35 m/s (see Fig. 8).

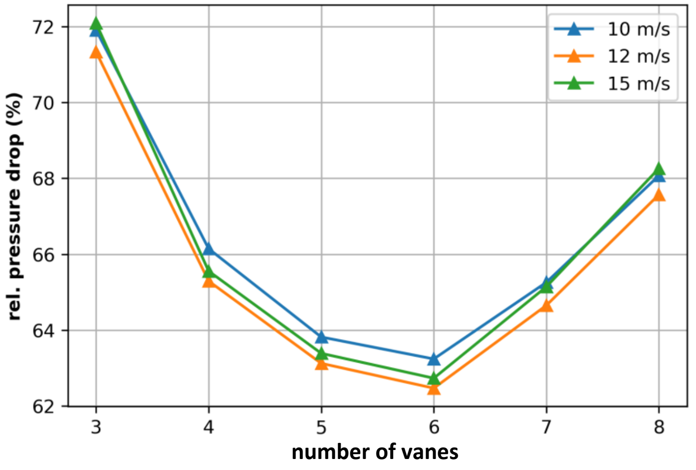

Figure 7: Dependency of relative pressure drop on the number of vanes for different inlet velocities. The vane thickness is 1 mm.

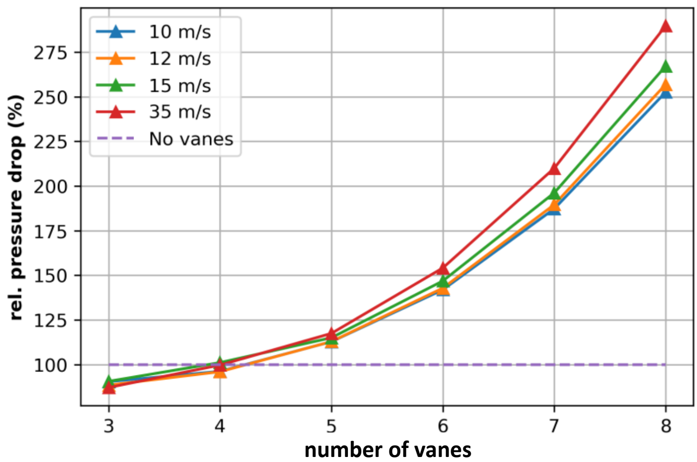

Figure 8: Dependency of relative pressure drop on the number of vanes for different inlet velocities. The vane thickness is 5 mm.

Idelchik claims that the resistance of the elbow is decreased by equalizing the velocity distribution, therefore an optimization with the objective to maximize the uniformity of velocity was calculated. However, this result is different from the previous optimization as the maximum velocity uniformity is obtained with 8 installed vanes that are 5 mm thick.

That is why the third optimization was conducted with both previous objectives used together. It is tricky to find the optimum when multiple objectives are defined, that is why Pareto fronts are used (Fig. 9). Pareto fronts show how the resulting objectives change when varying input parameters. In multi-objective optimization, it is usually necessary to make a compromise between the two or more goals as moving closer to one goal causes a drop in the performance of the other objective.

This chart shows that a design with 5 vanes and 1 mm thickness (green line) is the best candidate for the defined objectives as we are looking for the lowest pressure drop and highest uniformity. This result corresponds with the general formula presented by Idelchik when applied to our pipe dimensions.

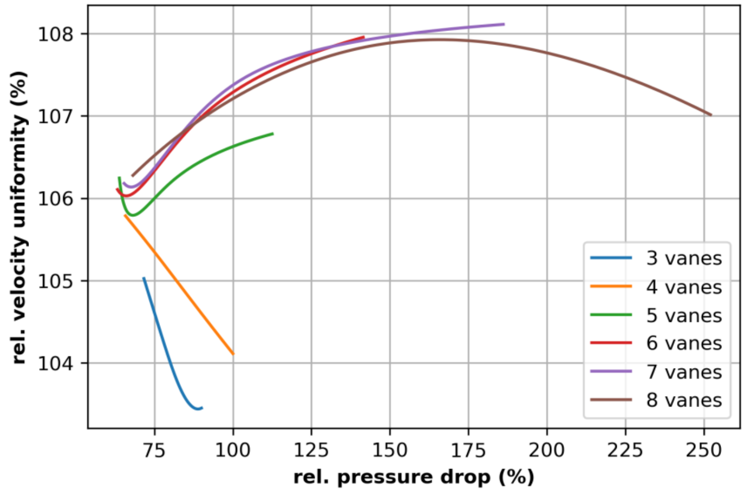

Figure 9: Graph of Pareto fronts used for finding the optimum number of vanes.

6 Conclusion

This paper deals with finding an optimal number of guide vanes and optimal thickness in order to decrease the resistance of a curved conduit, more specifically a 90° elbow. To achieve this a parametric optimization tool called Ansys DesignXplorer is used as well as a CFD solver Fluent. DesignXplorer proved to be a suitable tool for this type of problem as it was possible to quickly execute several optimizations with different objectives when the Response Surface was once obtained. The concept of Response Surface simply increases the efficiency of finding the optimal design when dealing with simulations.

When comparing results from optimization with literature, our assumption that the optimal vane parameters would be the same for minimizing the pressure drop as for maximizing the velocity uniformity behind the bend did not prove to be correct as the optimal vane parameters differ for these objectives. That is why a multi-objective optimization was conducted with both previously mentioned objectives. The resulting Pareto front chart shows that the optimal number of vanes agrees with the general formula presented by Idelchik.

Our findings show that the general formula is certainly useful as a guideline when dealing with such problems, but does not necessarily provide the result that some users expect, e. g. achieving the most uniform flow does not imply the lowest possible pressure drop. Moreover, it is possible to expect that the optimal vane parameters will differ in conduits with various shapes before and after the elbow (multiple bends, change in diameter). That is why a parametric study is a helpful and efficient tool when dealing with such cases.

In future work, the optimal design from our calculations could be enhanced by using the Adjoint Solver [8] in Ansys Fluent which is able to adjust the shape of vanes based on defined criteria through gradient based optimization. Based on comparison of our methodology and literature results optimization of more complex conduit systems could follow.

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