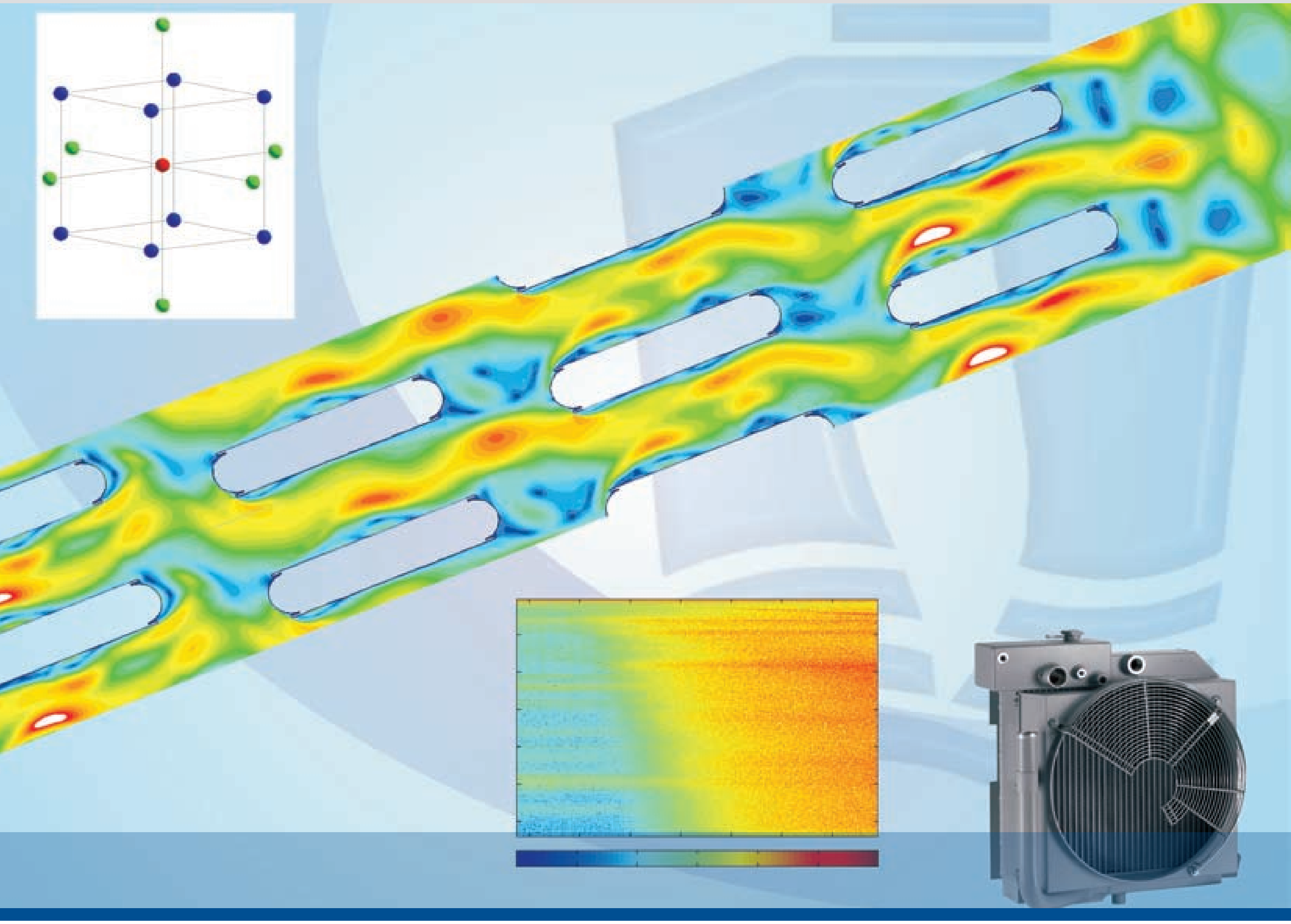

CFD-Simulations for the Development of High-performance Heat Exchangers

Improved performance and rising standards for the energy efficiency of automobiles, construction and agricultural machinery, compressors, railed vehicles, household appliances, etc. require an optimised cooling. AKG develops customised heat exchangers for every single application. Simulation software for stress analysis and optimisation of flow and heat transfer is becoming more and more important. Especially for the development of new heat exchange surfaces numerical simulations (CFD, Computational Fluid Dynamics) combined with Design of Experiments (DOE) methods are essential tools. The advantages of these tools will be shown at the example of a fin design process.

1 Introduction

In a heat exchanger heat is transferred between fluids, which are separated by walls. The goal is a minimised pressure loss and a maximised heat transfer. In a typical case a hot fluid (process media, e. g. coolant) passes in a cross flow with a cold fluid (cooling media, e.g. air) through the heat exchanger. The heat transfer is enhanced by appropriate fins in the flow sections. Apart from other factors the design of these fins is essential for the optimisation of heat exchangers.

The development of heat exchangers and so the development of new fins has to adapt to shortened product cycles in all application areas. Even with the restriction to one fin type the parameters height, pitch, thickness of the material, etc., **Figure 1**, result in a multitude of combinations. As these factors are also interacting with each other this leads to a high effort in finding the optimal combination. An efficient and successful optimisation can be achieved with a structured approach using design of experiments methods. Herewith the available resources can be used most efficiently.

Before building a relative expensive fin prototype, nowadays CFD-Simulations are by default used for fluid- and thermodynamic evaluation of new fin designs, whereas aeroacoustical effects are investigated in physical model tests. Because of generally increasing sensibility towards noise emissions, it becomes necessary for some types of applications to take into account these emissions during the design process of a new fin.

2 Design of Experiments for CFD Simulations

To limit the effort for the development of a fin, only four parameters, where a non-linear correlation with the performance data was expected, were considered: fin pitch, cutting length, offset and the flow velocity, Figure 1. These four parameters were varied in five levels to reliably describe the non-linear effects. The fin height and the material thickness were kept constant.

If according to the classical approach for determining an optimum, the geometrical factors were optimised one after

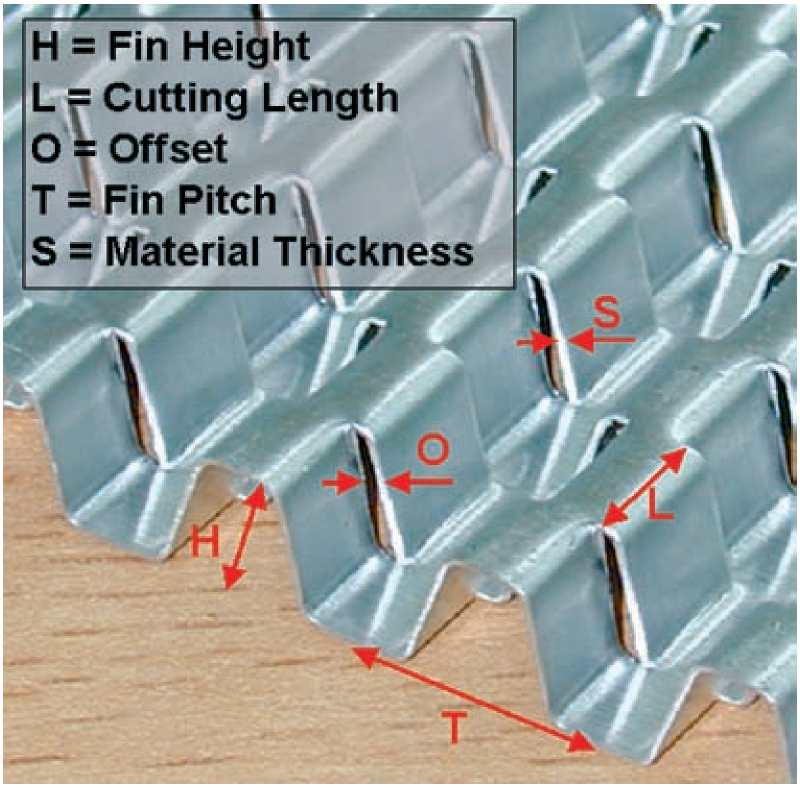

Figure 1: Determining parameters for the fin performance

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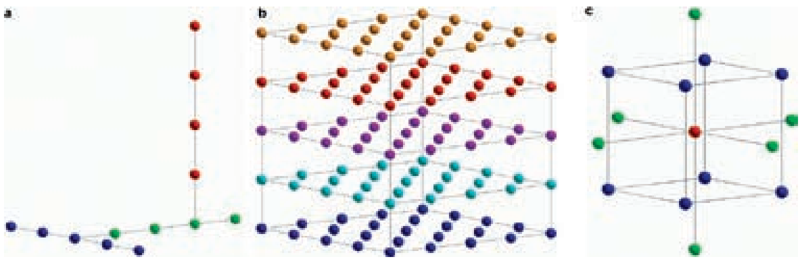

Figure 2: Experimental designs according to the different approaches (a: classic, b: full factorial, c: central composite)

another, 13 experiments would be necessary, **Figure 2** (a). Here parameter interactions are not taken into account, so the detected optimum is not necessarily the over-all optimum.

A complete description of the parameter range for the three geometrical parameters requires a full factorial 53-plan, Figure 2 (b). Herewith all independencies and interactions are captured. But running 125 experiments will be accordingly time-consuming and costly.

For a complete analysis of the single effects and finding possible non-linearities of the parameters, a central composite test plan was created, Figure 2 (c). Combining a full factorial 2-level plan with a centre point and the extreme values for each factor all interactions can be described with only 15 experiments.

According to the test plan 15 models for simulation of an optimised fin were generated with the CFD-software Fluent. Running these geometries at five different flow velocities descriptive coefficients for pressure loss and heat transfer were calculated. The pressure loss coefficient resulted from the averaged pressure gradients along the fin. The temperature change of the cooling air is not appropriate to describe the heat transfer, because the temperature difference between air and wall is decreasing along the fin. Therefore in different cross sections i along the fin heat transfer coefficients k_i were determined and a representative average value was calculated.

Both coefficients for pressure loss and heat transfer were evaluated with commercial DOE-software. The best description of the non-linear dependencies between the parameters and the coefficients was achieved with a quadratic model. As expected both coefficients strongly depend on the flow velocity and the pitch, **Figure 3**.

Besides the four main influencing factors, a multiple regression analysis also identified some interactions as significant. For the heat transfer the interaction between pitch and offset has nearly the same effect as the offset alone. So the interaction between offset and pitch can not be reduced to the ratio of both parameters.

The second important interaction is between pitch and flow velocity. Especially for the pressure loss the pitch is of major influence at higher flow velocities. At lower flow velocities the pitch has only a minor influence.

If an optimal combination between the geometrical parameters should be defined based on the results, the problem occurs again, that a high heat transfer causes a high pressure loss. A regression analysis confirms this with a correlation of 93 % between the two coefficients.

But since both coefficient are not always influenced in the same way by the factors there are configurations, that are more suitable than others for special applications. For limited installation space with necessary high performance often a high pressure loss is accepted. And on the other hand heat exchangers without a fan must supply a maximum heat transfer with a minimum pressure loss. After designing an optimised fin with design of experiments methods, the aero acoustic characteristics of this fin can be analysed in a CFD-Simulation.

3 CFD-analysis of the Aero Acoustic Noise of Fins

Generally the sensitivity towards noise emissions is increasing and especially at automobiles and railed vehicles they are sensed as incommoding. If these noise emissions are detected at the final product, necessary design changes are time and cost intensive. Insofar a specification of the aeroacoustic behaviour of a new fin during the design process would be helpful. A CFD-Simulation can provide this information. Compared to thermodynamic simulations aeroacoustic simulations require a higher discretisation in time and space and therefore a higher computational effort. Increasing of computational power is not always economical. Because of this, the ability of Fluent to simulate aeroacoustical emissions in 2D should be investigated.

To evaluate the result quality, a suitable heat exchanger was chosen for analysis (height 200 mm, length 980 mm, depth 113 mm). Here measurement data

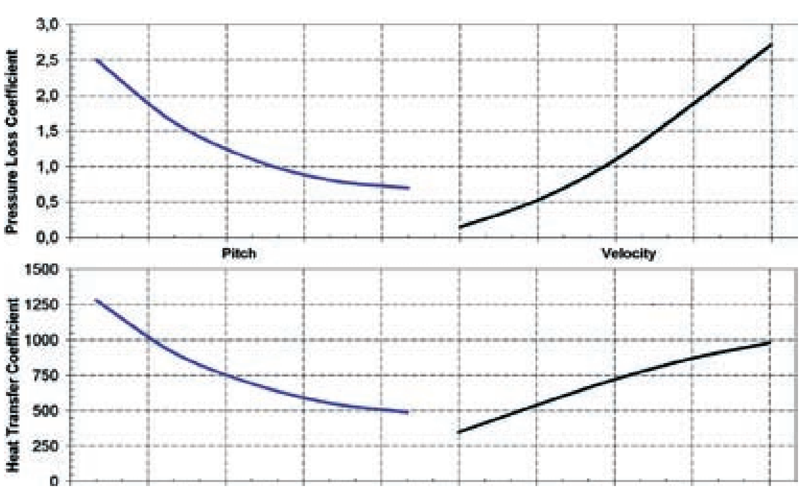

Figure 3: Influence of pitch and flow velocity on coefficients

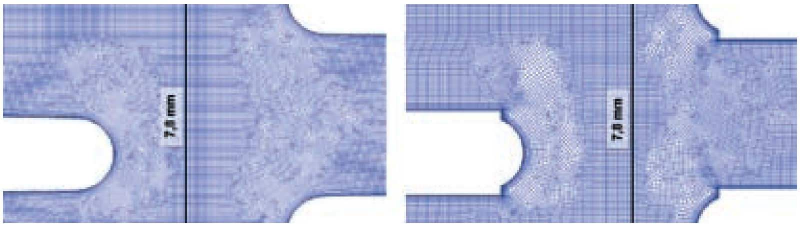

Figure 4: Detail of the computational grid of the fin structure without (left) and with (right) sharp corners

Table: Boundary conditions of the numerical models

Discretisation (Boundary Layer)	0,06 mm (0,01 to 0,06 mm)
Temporal Discretisation	2.5 μs
Solver	Large Eddy Simulation (LES)
Acoustic Model	Ffowcs-Williams and Hawking Model

for the acoustic emissions were available for Reynolds-Numbers from 1850 to 3300. At Re > 2225 a high pitched whistle of 120 dB developed.

For the CFD-Simulations two grids with simplified fin structures were set up, **Figure 4** and **Table**. The construction of the heat exchanger contains sharp corners protruding in the cooling air flow. To analyse the influence of the corners on the aero acoustic emissions, the corners were only taken into account in one model. If a whistle would occur in the simulation without sharp corners the fin structure would be responsible for the whistle. A whistle in the second model with sharp corners would specify the sharp corners as the origin.

During the simulation the resulting forces on the fin structure were recorded. With the integrated acoustic model in Fluent the noise emissions were calculated and the sound pressure level was exported for the single frequencies.

The simulation results without sharp corners show a similar characteristic as the measurement data at Re = 2900, but the measured peaks at 1475, 2950, 4400, 5900, 7350 and 8800 Hz are not visible in the simulation results, **Figure 5**. For proving the grid independency of the simulation result, the grid was refined based on velocity gradients. A simulation with the refined grid and the same boundary conditions neither improved the results, nor did the results change significantly at all. This proved the grid independency.

The simulation with sharp corners used the same boundary conditions and the acoustical analysis used the same parameters. The comparison with the measurement data shows a better match, Figure 5. Again the characteristic of both curves is similar and additional peaks are visible. The frequency of the first peak has a deviation of 100 Hz to the measurement data. The second peak has a deviation of 200 Hz. Only higher modal peaks are not visible in the simulation results.

The numerical simulation results indicate, that the sharp corners induce local separation zones and herewith pressure fluctuations, which are responsible for the noise emissions of the investigated heat exchanger. Taking into account the uncertainties in the measurement recording, the boundary conditions and the simplification to a two-dimensional model, the agreement between measurement and simulation is satisfactory.

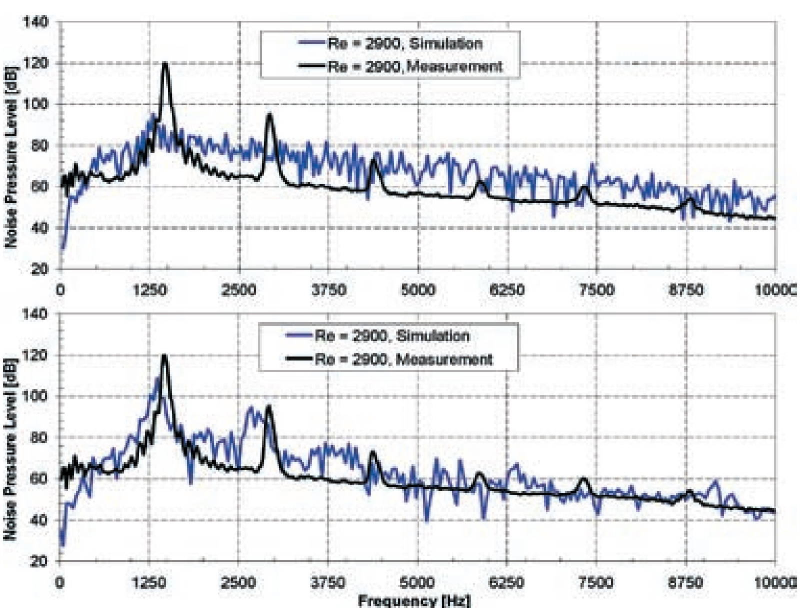

Figure 5: Comparison of sound pressure level between measurement data and simulation results without (top) and with (bottom) sharp corners

4 Conclusions

For integrating new methods in the development process of a product, knowledge about the capabilities and restrictions of the methods is necessary. Investigations of the design process of a fin and aero acoustic behaviour of a heat exchanger show, that design of experiments and computational fluid dynamics are important tools for a faster and customised development of heat exchangers and their components.

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