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Application of Computational Fluid Dynamics for the Thermodynamic Development of a New Generation of Hermetic Reciprocating Compressor

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ABSTRACT

Developing a thermodynamic complex part like a hermetic reciprocating compressor is an ambitious task for engineers. Even understanding all of the physical effects, which appear if implementing a new designed part e.g. the suction muffler into the existing compressor design is quite complex. Even more complex is it to develop a completely new generation of compressors. The rise of computational power and the excessive development of numerical tools for the prediction of engineering problems, gives engineers the possibility to check their considerations before building an expensive prototype. The aim of this paper now is to show how the method of computational fluid dynamics (CFD) can help to obtain faster and better results for different components of the hermetic reciprocating compressor. Results how CFD can be used are shown exemplary for the suction muffler, the discharge muffler the cylinder inflow and also for the suction valve design.

1. INTRODUCTION

Developing a small reciprocating compressor used in household appliances is a complex and time consuming process. In the past the development process was mainly affected by increasing compressor efficiency. But nowadays customers become more and more ambitious. For being successful in future, it is necessary to take additional parameters like reliability, price or acoustics into consideration. With the rising number of relevant parameters, development effort increases significantly.

Traditionally, the development process of small hermetic compressors has been driven by experiments. The new development targets lead to more complex experiments, which increase development time and costs dramatically.

Keeping the general account of shorter time to market cycles in mind, it is obvious, that adhering to the experimental driven development process is not the way to be competitive in future.

An up-to-date development approach for compressor engineering makes use of numerical tools.. The rising computational power of the last years gives the possibility to use complex numerical tools which are able to picture the physics inside the compressor. In Ottisch (2000) the method of computational fluid dynamics (CFD) is used to study the flow through valves. Ottisch's conclusion is that "commercially available CFD packages can predict the effective flow area of a valve with a surprising degree of accuracy". Another work dealing with CFD in compressor development was presented by Fagotti and Possamai (2000). The authors used CFD for investigating the suction line, the cylinder inflow and the discharge line of a small hermetic reciprocating compressor. Their results show quite good agreement between simulation and experimental data.

But CFD is not the only tool which is used in compressor design. Lenz (2000) investigated the stresses in the flapper valves (which are used in such compressors) using the finite element analysis and Svendsen (2008) used the boundary element method to study the pulsation level inside the suction muffler.

The latest efforts are focussing on the interaction of different physical fields. Especially the interaction between fluid and solid domains (fluid structure interaction, FSI, detailed information in Lang (2009) and Shiomi (2009)) is of interest, as the valve dynamics greatly influences the compressor performance.

The aim of this work is to show the today's prospects in the development of a small hermetic reciprocating compressor. It will be shown how basic thermodynamic considerations can be used to determine the main losses of an established production compressor. The main loss mechanisms are resolved for some exemplary compressor components by the use of numerical tools (mainly CFD but also FEM) to get a deeper understanding of the physics and to improve the design or quantify further points of improvement. To check the quality of the simulations, various simulation results are compared with experimental data.

2. Background

Designing a new compressor generation is a great challenge. To give an idea where to start engineering tasks, an existing compressor with comparable dimensions is analyzed. The most comparable compressor is the ACC HTK 55 production compressor, which can be seen in Figure 1. The main dimensions of this compressor are presented in Table 1 for the ASHRAE conditions -23.3°C (evaporation temperature) and +55°C (condensation temperature).

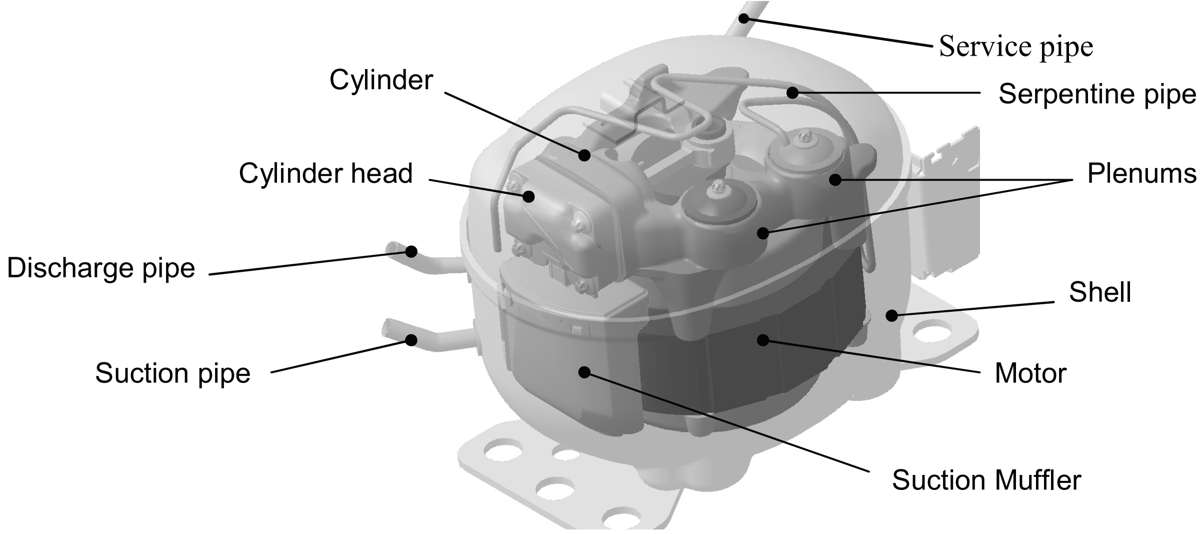


Figure 1: ACC production compressor HTK55

Table 1: key figures of the compressor HTK 55

	HTK 55
Bore [mm]	21.1
Stroke [mm]	16
Displacement [cm³]	5.6
Electric Power [W]	50
Cooling capacity [W]	90
Refrigerant	Isobutane

Inside a hermetic compressor different kinds of losses such as electrical, frictional and thermodynamic appear. The development process is not only driven by reducing these losses, as other parameters like acoustics or appropriateness for serial production have to be taken also into consideration. This work focuses on thermodynamic losses, all the others are only considered if necessary..

The thermodynamic losses occur in various subsystems inside the compressor like suction line, discharge line and the two valves (suction and discharge valve). Examples for loss mechanisms are the superheating of refrigerant until compression start in the suction line or the increase of indicated power due to the gas' expulsion in the discharge line.

The following sections should give an idea of the various loss mechanisms, how to locate and how to avoid them.

3. Applications

3.1 Suction line

One of the main thermodynamic losses, which are typical of the suction line, especially the suction muffler, is the superheating of the gas. A thermodynamic analysis shows the importance of a low compression start temperature. Increasing the compression starting temperature by approximately 1 K, will lead to a COP reduction of about 0.32 percent. Figure 2 presents the correlation between compression start temperature, COP and indicated power. This analysis shows clearly the necessity of a minimized compression start temperature. Figure 3 shows temperature measurements of various points inside the suction line of the HTK 55 compressor.

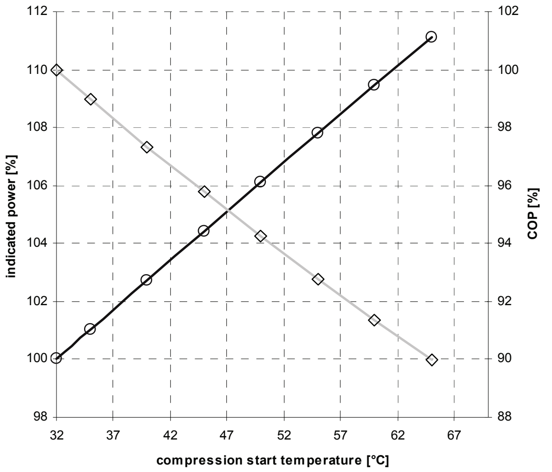
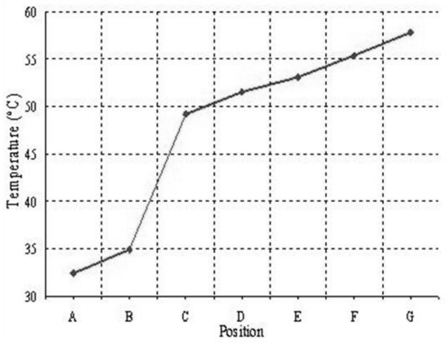


Figure 2: Correlation of compression start temperature, COP, and indicated power



Remark:

A	... Suction pipe inlet	E	... Neck inlet
B	... Shell inlet	F	... Neck outlet
C	... Trumpet inlet	G	... Cylinder
D	... Muffler volume		

Figure 3: Temperatures at various positions inside the suction line

In Figure 3, a big temperature increase between position B and C can be seen. This is because of the mixture of the cold refrigerant coming out of the suction pipe with the hot refrigerant inside the shell.

To avoid this mixture a direct suction element has been implemented for the new compressor. The direct suction element is just one step to reduce the heating of the refrigerant during its way through the compressor. A smart design of the suction muffler keeps the refrigerant as cold as possible and avoids acoustic disturbances coming from the suction muffler.

Developing a new part or even a whole compressor is a continuous improvement process leading to various new muffler designs which have to be compared, in order to find the requirements best fitting version. The usage of CFD (computational fluid dynamics) allows the comparison of various muffler variants in far shorter time than years before, when each new version required a real prototype, which had to be surveyed experimentally. For the CFD simulations, commercial finite volume software has been used (Fluent 6.3.26). The method which was used for the prediction of the suction line can be found in Lang et al. (2008). In this method only the domain of interest is simulated in 3D, the interactions caused by the rest of the compressor are provided by the coupling with a 0D/1D gas dynamic tool. Figure 4 shows a comparison of computed and experimentally determined temperatures for different muffler variants. The cycle averaged temperatures fit obviously quite well with the measured ones. In Figure 5 the implemented design of the suction muffler is pictured.

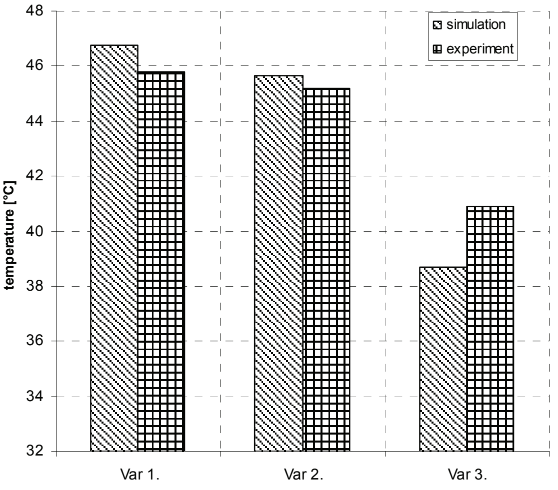


Figure 4: Comparison of different suction muffler variants

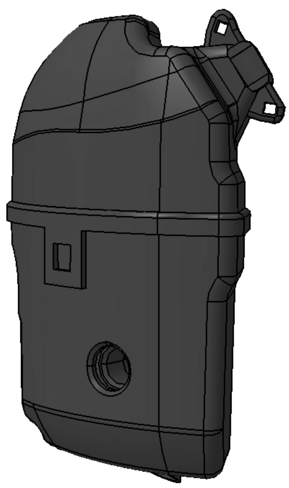


Figure 5: 3D CAD design of the suction muffler for the new compressor

Comparing the pressure distribution of simulation und experiment leads also to well agreeing results, shown in Figure 6.

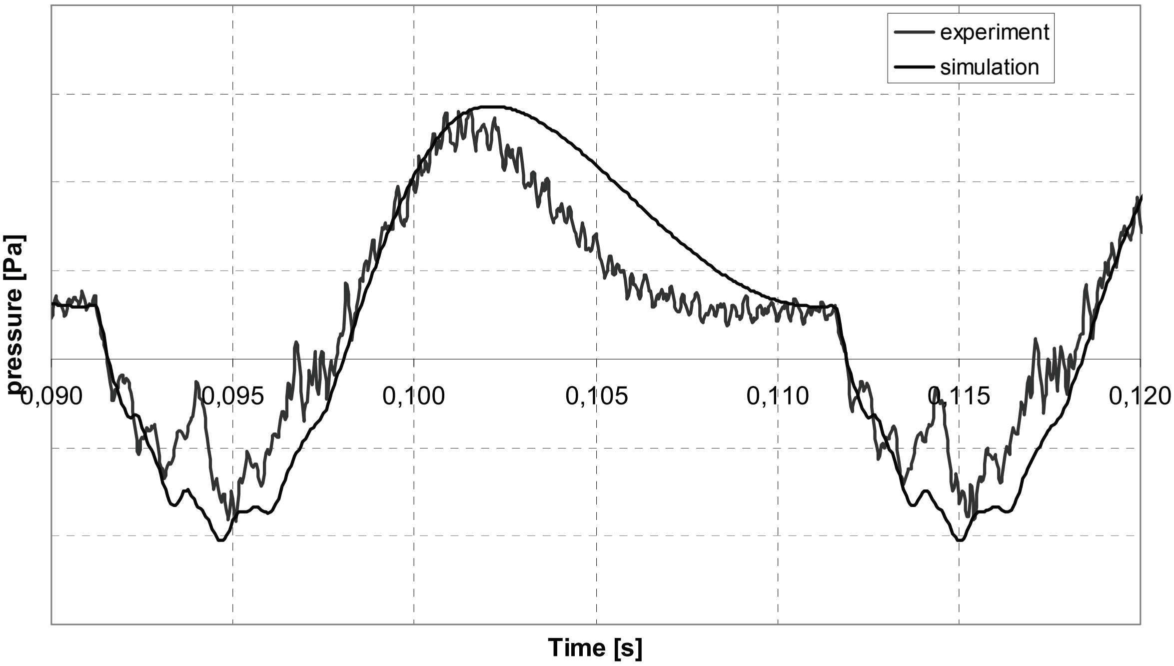


Figure 6: Comparison of pressure trend: experimental vs. simulation data

3.2 Cylinder in- and outflow

Thermodynamically the flow conditions into and out of the cylinder are very interesting as they greatly influence the compressor performance. The appearing loss mechanisms are due to friction, inertia of the gas and the valves as well as temperature gradient driven heat fluxes. In Figure 7 the mass flow rates for three different valve/neck assemblies have been drawn. All three variants have the same inlet and outlet orifices. The simulations have been done stationary for three different valve lifts with a specific pressure difference between in- and outlet. As the boundary conditions have been accurately defined, it is obvious, that friction losses are responsible for the different mass flow rates.

In Figure 8 a velocity plot of one variant is shown. It can be seen that the flow doesn't follow exactly the contour of the suction muffler neck.

The results in Figure 7 and Figure 8 show the strength of numerical tools depicting the weaknesses in the design of components. Knowing where the losses appear enables design modifications, generally increasing compressor performance.

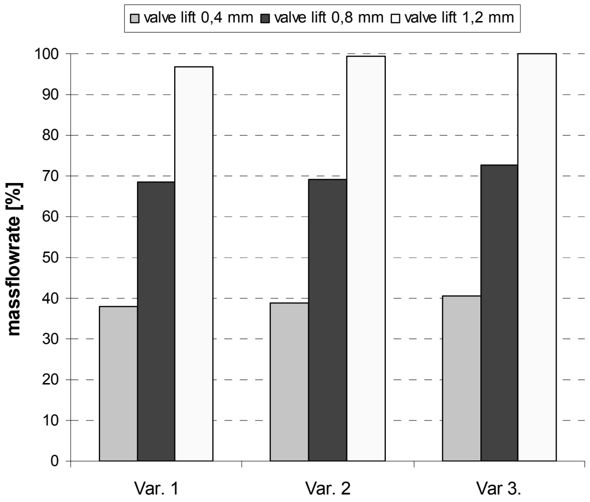


Figure 7: Comparison of mass flow rates through different valve neck assemblies

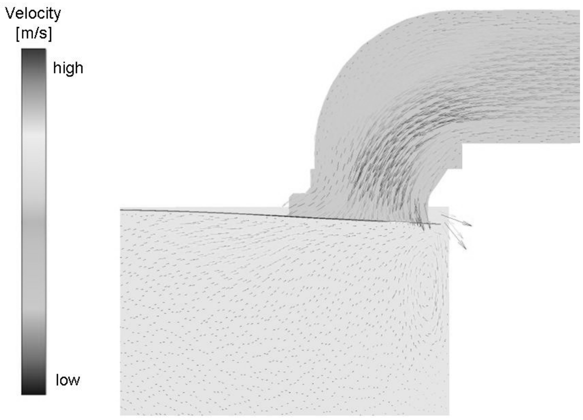


Figure 8: Cylinder inflow; velocity plot

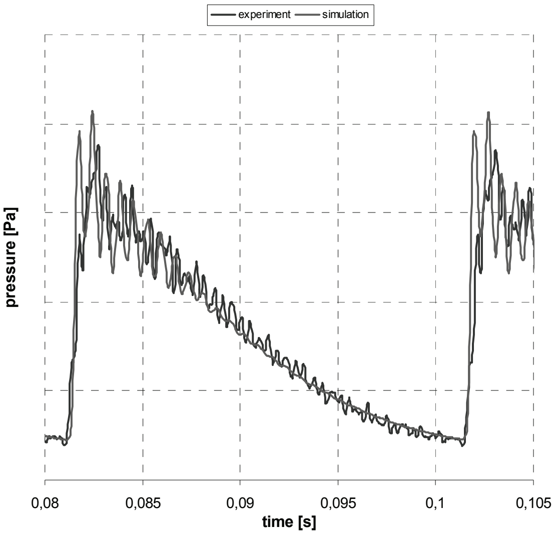
3.3 Discharge line

Another important component concerning the thermodynamic behavior of a hermetic reciprocating compressor is the discharge line. The discharge line design should not only keep the work of expulsion as low as possible but it should also reduce pressure pulsations running out of the compressor into the cooling appliance.

An additional negative mechanism which is caused by the discharge line are the heat fluxes from the discharge components to the refrigerant inside the shell. These heat fluxes lead to an increased shell gas temperature, directly rising compression start temperature with all the negative effects already mentioned in former sections.

The discharge line of the new compressor is made of an innovative material with extremely low thermal conductivity. The novel material and the smart design of the discharge line lead to a significant gas temperature level reduction inside the shell.

The optimization strategy of the discharge muffler layout is quite similar to the method used for the suction line (see Lang et al. 2008). The quality of the simulations results concerning the discharge muffler can be seen in Figure 9. The figure shows a comparison of the transient pressure fluctuations inside the first volume of the discharge muffler with experimental data. In both ways, simulation and experiment, an anechoic outlet has been used as boundary condition, so reflecting pressure waves could be avoided. It is obvious that the two curves fit pretty well to each other. Also the results of the pressure fluctuations inside the serpentine have been captured with a high degree of accuracy (see Figure 10).



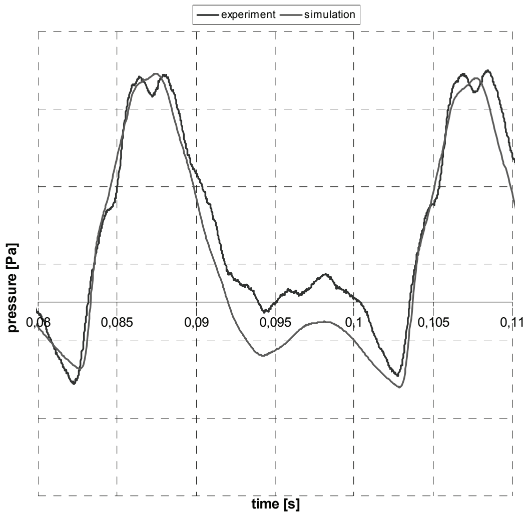


Figure 9: Pressure fluctuations of the new compressor (discharge muffler)

Figure 10: Pressure fluctuations of the new compressor (serpentine)

Besides predicting the pressure trends, simulations can also be used to analyze the frequency spectrum of the pressure fluctuations, as depicted in Figure 11.

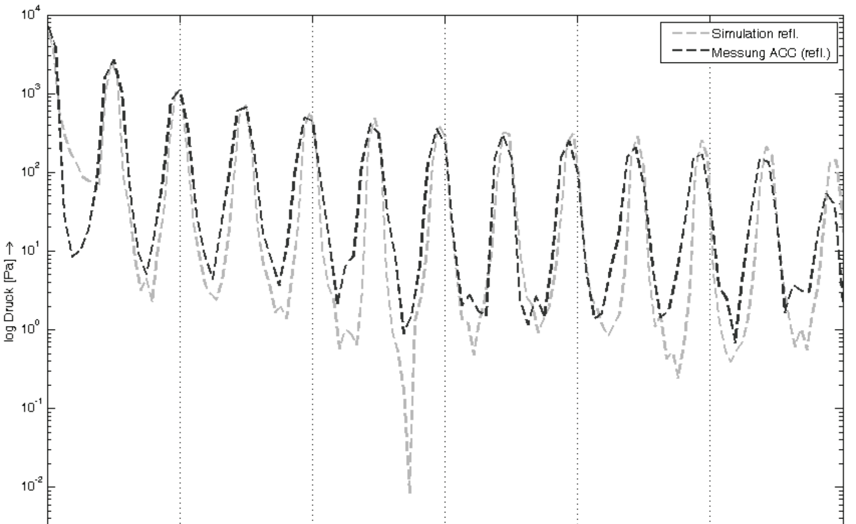


Figure 11: Discharge muffler of the HTD 55 compressor

The diagram shows the frequency spectrum inside the first volume of the discharge muffler. Quite good results can be achieved up to 600 Hz. To resolve higher frequencies other simulation methods than URANS CFD have to be used.

4. Results

Considering all losses consequently a new generation of compressors can be created which sets a huge step forward to an efficient thermodynamic compressor design. The comparison of the main performance parameters of the old established compressor HTK 55 with the new compressor shows the influence of the thermodynamic improvements on the overall performance parameters (see Table 2 and Table 3).

Table 2: Comparison of compressor performance (Evaporation: -23,3 °C/ Condensation 55°C)

	HTK 55	**Change [%]**	**New compr.**
COP	1,62	**+5,5**	1,71
Q_0 [W]	93,0	**+6,6**	99,1
P_{el} [W]	57,4	**+0,9**	57,9

Table 3: Comparison of compressor performance (Evaporation: -23,3 °C/ Condensation 45°C)

	HTK 55	**Change [%]**	**New compr.**
COP	1,78	**+7,9**	1,92
Q_0 [W]	98,0	**+8,5**	106,3
P_{el} [W]	55,0	**+0,7**	55,4

It can be seen that for the new compressor generation considerable improvements could be realized, strongly driven by thermodynamic innovations.

5. Conclusion

The presented results reveal that numerical methods became operational development tools within the last decade. A comparison of ten year old applications of CFD and FEM simulations with up-to-date ones shows similar content and similar quality. Nevertheless, ten years ago, CFD and FEM simulations were a research task with high effort of data preparation and the need for considerable computer capacity. Because of the complex pre-processing, the long time elapsing for computation and the expensive soft- and hardware equipment, CFD and FEM applications seemed to be improper for industrial use. To get simulation results with affordable resources, computation domains had to be simplified significantly, leading to inaccurate results. In the last few years computer performance has increased significantly whereas hardware purchasing costs have decreased dramatically, so computer capacity has become affordable for industrial applications. The continuous development of CFD and FEM tools and specific simulation strategies enable nowadays detailed, transient and multi-dimensional investigations of complex geometry, without making considerable simplifications. With advanced simulation tools, it is now possible to understand the working process of machines in such a detail, that improvements can be applied fast, efficiently and cheap.

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