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A conjugate heat transfer analysis of a hermetic reciprocating compressor

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Abstract. Thermodynamic efficiency of a household refrigeration compressor is considerably affected by superheating that occurs inside the compressor. This phenomenon can be defined as the temperature increment of the refrigerant before entering the compression volume. On its flow path; refrigerant gains heat from suction pipe, suction muffler, suction chamber and related compressor components, which are at higher temperatures. In purpose of investigating conjugated heat transfer mechanism inside a hermetic reciprocating compressor a detailed numerical model is presented. The numerical conjugate heat and flow model is formed both with fluid domain (refrigerant) and solid domain (compressor components). Effects of using different materials on temperature distribution of some key components such as the crankcase, cylinder head and the valve plate are investigated. In addition to steady state analysis, transient CFD analysis is performed in order to understand fluid flow characteristics and its influence on superheating of the refrigerant.

1. Introduction

Detailed temperature measurement is a significant study to understand heat transfer network and temperature distribution of various components in compressors. This knowledge is necessary for designing compressor components and choosing their materials. However instrumentation of experimental test setup, which requires hard efforts, causes deviations from the original situation. Experiments are also to be repeated in order to see the effect of every prototype component. A valid numerical model, serving for thermally mapping the compressor, would be an appreciable alternative against aforementioned drawbacks.

CFD applications are widely used for improvement of compressor technologies. Raja et al. [1] simulated heat transfer network of a compressor numerically and presented the temperature distribution. Padhy et al. [8] developed a heat transfer model for rotary compressors. Nakano et al. [3] performed CFD analysis specifically on suction muffler. Sarioğlu et al. [6] studied transient pressure variations in suction muffler of a hermetic compressor both experimentally and numerically. Kara et al. [4] achieved a numerical model for crankcase of a compressor with the support of experimental temperature measurements and convective heat transfer correlations. Almbauer et al. [9] performed 3D simulations to obtain heat transfer correlations. Dutra et al. [10] investigated heat transfer in compressor components experimentally. Deschamps et al. [11] developed heat transfer model of a



reciprocating compressor by combining differential and integral formulations. Pereira et al. [2] studied the fluid flow in cylinder region numerically.

Kawai et al. [7] studied the relation between suction gas temperature and compressor efficiency. Morriesen et al. [5] express superheating as the dominant factor in thermodynamic losses with 49%, while viscous effects during suction and discharge processes and cylinder-piston leakage are responsible for 47% and 4% respectively. It is seen that most of the studies concern heat transfer mechanisms between compressor components or fluid flow characteristics in any refrigeration path separately. This eliminates the necessity of including all compressor components in numerical model in a detailed way. On the other hand, developing a detailed compressor model, which would be capable of investigating conjugate heat transfer, might provide more realistic view in basis of superheating phenomenon.

This study presents detailed non-isothermal CFD analyses of a hermetic reciprocating compressor for several cases including the base situation as well as modifications for lowering suction gas temperature with the aim of increasing volumetric efficiency.

2. Experimental studies

Experimental studies are discussed in two parts which are temperature and pV measurements. These studies are carried out to obtain boundary condition data for numerical analyses and to provide experimental data to validate the numerical model.

2.1. Temperature Measurements

Temperature distribution inside the compressor is investigated primarily. The compressor being investigated is designed for R600a and has a cooling capacity of 170W at ASHRAE conditions. The compressor is instrumented with several T-type thin thermocouples. Sensitivity of the thermocouples are $\pm 5^\circ\text{C}$. Temperature values are recorded while the compressor is operating on a fully automated calorimeter system with conditions of -23.3°C evaporation temperature and 54.4°C condensation temperatures. Sub-cooling, superheating and ambient temperatures were 32.2°C . Sample images of temperature measurement setup are given in Figure 1.

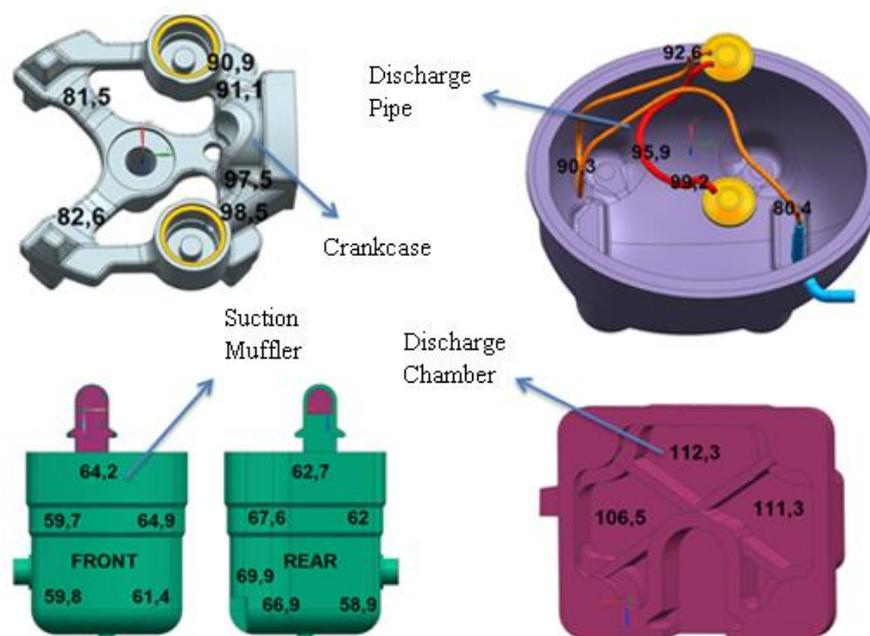


Figure 1. Temperature values on crankcase, discharge pipe, suction muffler and discharge chamber surfaces.

It is seen that the cylinder head has the highest temperature compared to other components of the compressor. Besides the cylinder head, the crankcase and discharge pipe are other heat sources for inner ambient of reciprocating compressors. With respect to rising temperature of the inner gas, heat transfer to the suction muffler by means of convection increases. The suction muffler also gains heat from the valve plate and cylinder head by conduction and the stator of the motor by radiation. The measured temperature values on the refrigerant path are indicated on a CAD model in Figure 2. The measurements show that the temperature of the refrigerant increases approximately 46 °C from the suction muffler inlet to the suction chamber. Thus, the density of the refrigerant decreases due to rising temperature which results in decreased mass flow rate and volumetric efficiency. It is clear that in addition to the acoustic damping, the suction muffler and its interaction with surroundings play an important role on the performance of the compressor.

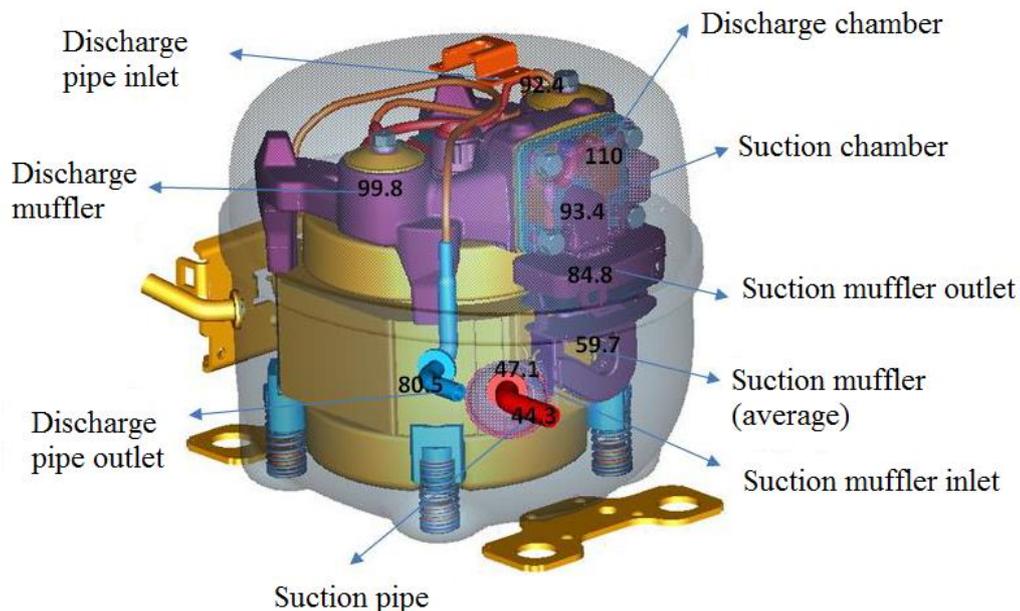


Figure 2. The measured temperature values on the refrigerant path of the compressor.

2.2. PV Measurements

Time-dependent pressure values in the suction and discharge chambers and inside the cylinder are obtained with pressure transducers. An optical encoder was instrumented on top of the crankshaft. The optical encoder generates a signal per shaft angle and another signal per cycle. With this test setup, crankshaft angle and pressure values can be measured in a coupled manner during the operation of the compressor. Locations of the pressure transducers and the optical encoder are given in figures 3 and 4, respectively.

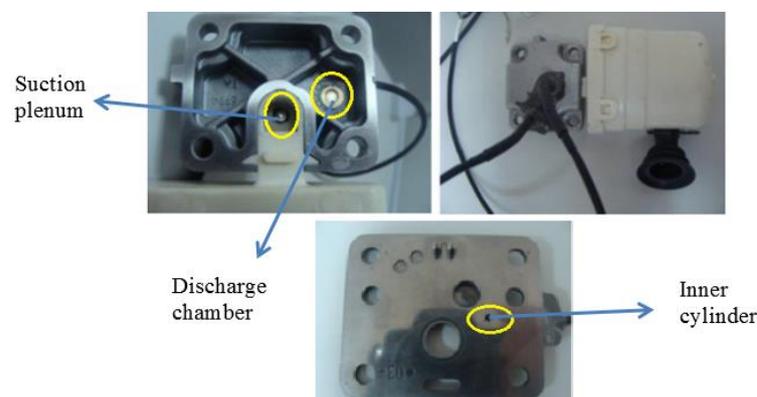


Figure 3. Locations of the pressure transducers.

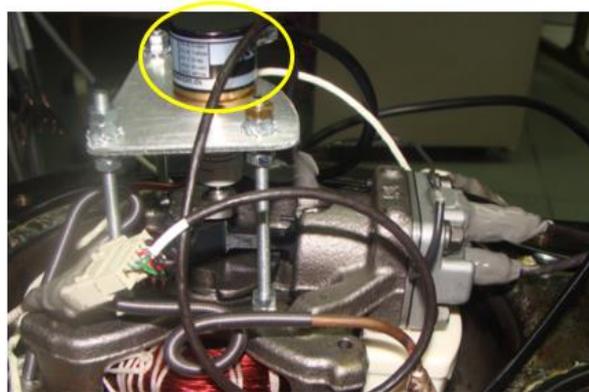


Figure 4. Location of the optical encoder.

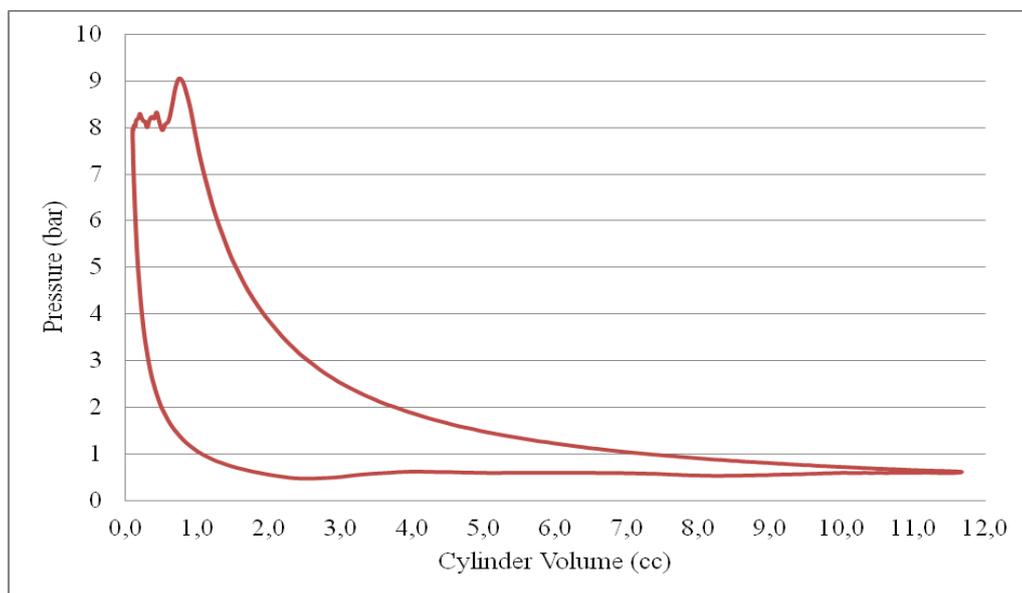


Figure 5. The PV (indicator) diagram of the compressor.

The PV diagram of the compressor is given in Figure 5. Compression work is calculated from this diagram and it will be used in deciding thermal boundary conditions of the cylinder bore. Experimentally obtained pressure profiles are used as boundary conditions in order to simulate transient fluid flow on suction and discharge lines in numerical studies as appropriate.

3. Numerical studies

Numerical studies will be discussed in three sub-sections which are the pure heat conduction model (consisted of the compressor solid parts only), the steady conjugate heat transfer model (includes both solid-fluid domains) and finally the transient conjugate heat transfer model. The CAD model of the hermetic reciprocating compressor is obtained with the commercially available software (NX 7.5). The mesh consisting of approximately 5 million elements is obtained with ANSYS meshing software. As it can be seen in Figure 6, all components of the compressor are included in the numerical model. Fluid domain and mesh structure are also given in Figure 6. Note that the refrigerant gas inside the compressor shell and the compressor oil do not exist in the solution domain. In addition, the expansion and the compression processes of the refrigerant inside the cylinder are not taken into account. The experimentally obtained transient pressure data of the suction chamber and the cylinder is used as boundary conditions. A commercially available CFD code (ANSYS Fluent v14.5) is used

for the analyses. Momentum and energy equations are discretized with second order upwind approximation. Realizable k-epsilon is used as turbulence model.

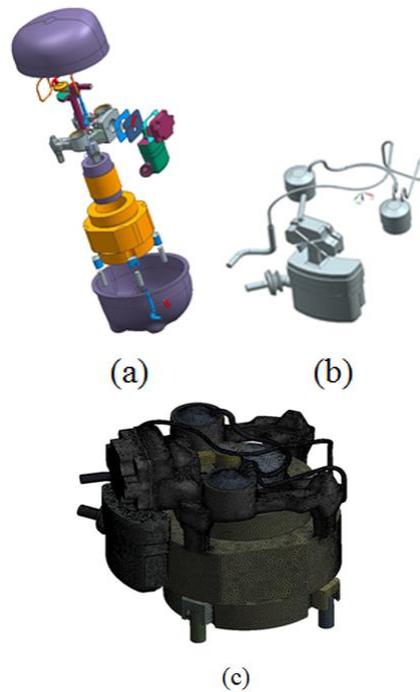


Figure 6. (a) Solid parts, (b) fluid domain (refrigerant), (c) mesh structure

3.1. Pure Heat Conduction Model

In this model, the refrigerant domain was deactivated, so the pure heat conduction analysis was performed for the solid components of the compressor. The measured temperature values from the refrigerant flow path are used as boundary conditions and the experimental temperature distribution on the solid parts are compared with numerical results obtained with the pure heat conduction model while optimizing the local heat transfer coefficients on the outer surfaces of the components. Previous to this study mechanical and electrical losses of the compressor were measured experimentally. In the numerical model, the mechanical losses and electric motor losses are assumed to be converted into heat and integrated into the model as a heat generation (source) term for the corresponding component volume. The difference between real and isentropic compression work is assumed to be converted into heat. The heat generation due to compression process inside the cylinder is simulated by the heat flux boundary condition on the cylinder surface. Prescribed heat sources in the numerical model are given in Table 1.

Table 1. Heat sources

Geometry	Heat Flux [W/m ²]	Heat Generation [W/m ³]
Cylinder bore	5546	-
Electric motor	-	23249
Crank bearing clearance	-	1,44x10 ⁸

Figure 7 shows that experimentally measured surface temperatures and the numerical results are in good agreement. The solution of the pure heat conduction model pointed out that the heat transfer coefficients varies between 8 and 40 W/m²K depending on the location of components inside the compressor.

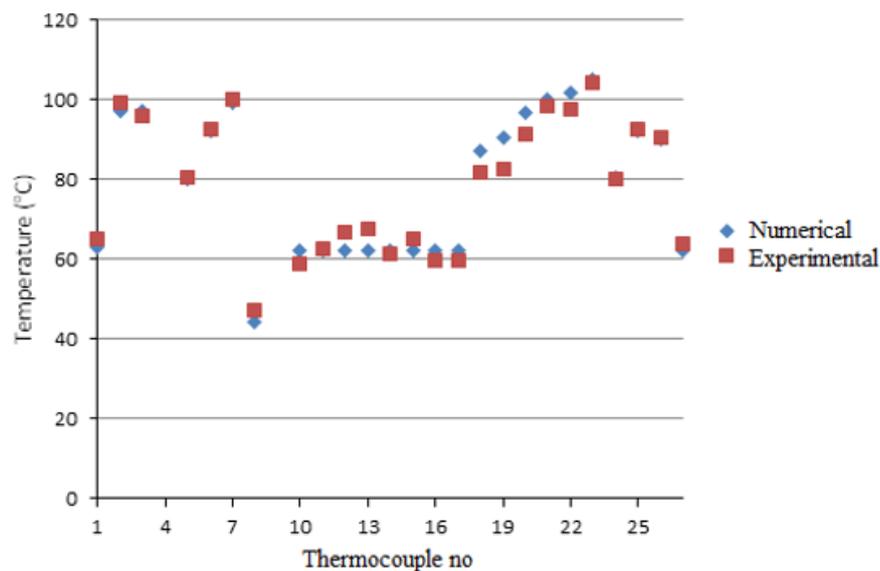


Figure 7. Comparison of experimental and numerical results

3.2. Steady Conjugate Heat Transfer Model

The fluid (refrigerant) domain was activated for this model in order to solve the steady state conjugated heat transfer problem employing the heat transfer coefficients obtained in the pure heat conduction model as discussed previously. The boundary conditions at inlet and outlet of the suction and discharge lines are given in Table 2.

Table 2. Boundary conditions

	Pressure[bar]	Temperature[°C]	Mass Flow Rate[g/s]
Suction inlet	-	44	0,54
Suction outlet	0,624	-	-
Discharge inlet	-	113	0,54
Discharge outlet	7,6	-	-

Temperature contours of the compressor components at steady state operation are given in Figure 8. The heat generation during the compression process inside the cylinder causes the heat transfer between the crankcase, the valve plate and cylinder head. This region attains the highest temperatures inside the compressor. Nearly all hermetic reciprocating compressor designs require suction muffler to be located in this high temperature region. As a result, the suction muffler gains heat from these hot components. This fact will also be discussed when the results of the transient conjugate heat transfer model are shown with figures taken from different phases of a compression cycle.

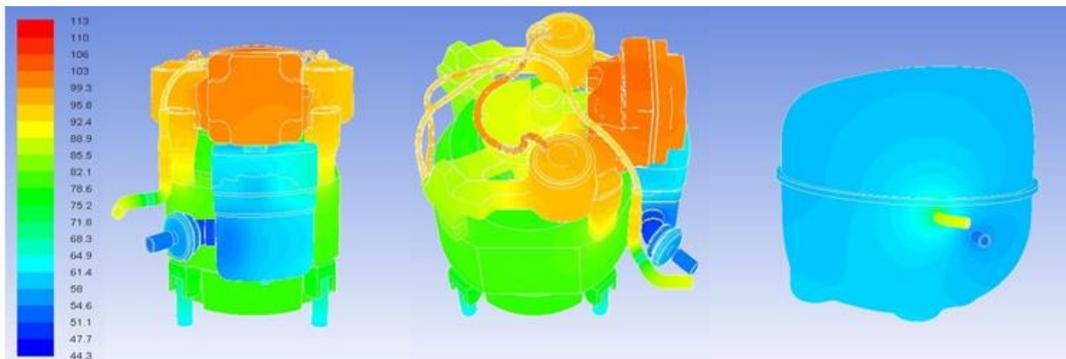


Figure 8. Temperature contours of the compressor components and shell.

A section view of the temperature contours is given in Figure 9. It is seen that the suction muffler is heated by the valve plate and cylinder head especially from the contact surfaces. This rises the temperature of the refrigerant at the start of the compression process. In order to keep the refrigerant at lower temperatures, the materials of selected components are replaced and CFD analyses are repeated for each case. Materials of the crankcase, valve plate and cylinder head are replaced with aluminium, POM (Polyoxymethylene) and PBT (Polybutylene terephthalate) respectively. The valve plate, cylinder head and the suction muffler temperatures are compared for each case with the original case.

The material of the crankcase was changed from cast iron to aluminium at first case. Temperature contours of original situation (cast iron) and aluminium crankcase is given in Figure 10. This case leads to a more homogenous temperature distribution on the crankcase and lower temperature values were obtained around the cylinder region. As the average temperature of the crankcase decreases, the inner ambient of the compressor, which is a common heat source for suction muffler, remains at lower temperatures.

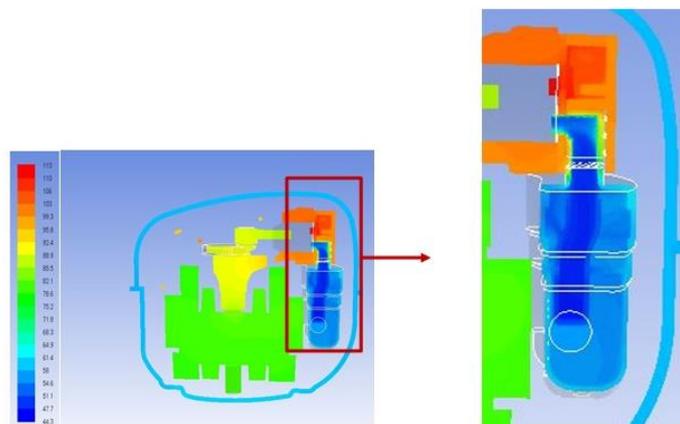


Figure 9. A section view of temperature contours.

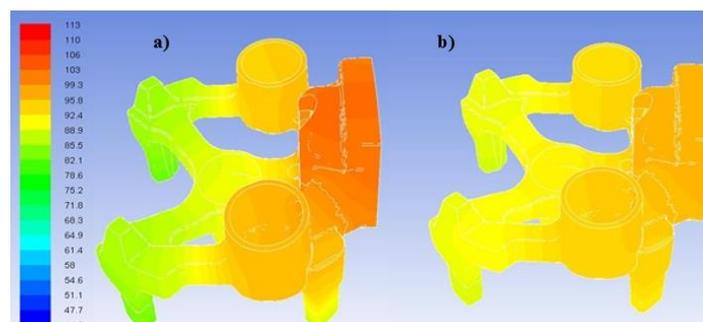


Figure 10. Temperature distribution of crankcase a) Original (cast iron) b) Aluminium

Comparison of the valve plate temperature contours for different circumstances are given in Figure 11. Using an aluminium crankcase lowers the average temperature of valve plate. Replacing the material of the valve plate to an insulative (POM) reduced heat conduction from cylinder region to the suction muffler, thus the refrigerant temperature inside the suction muffler is reduced. The average temperature of the valve plate increases, in the case of changing the material of the cylinder head from aluminium to PBT.

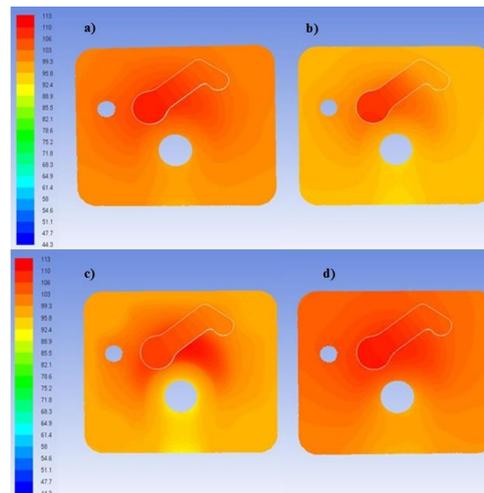


Figure 11. Temperature distribution of the valve-plate a) Original b) Aluminium crankcase c) POM valve-plate d) PBT cylinder head

Temperature distributions on cylinder heads for all cases are given in Figure 12. The effect of aluminium crankcase on the cylinder head is similar to the valve plate. POM valve plate avoids heat conduction from crankcase to the cylinder head and the suction muffler. Plastic based cylinder head shows a significant change on the suction chamber wall temperature. In virtue of the low thermal conductivity of the material, the suction chamber region remains at lower temperatures.

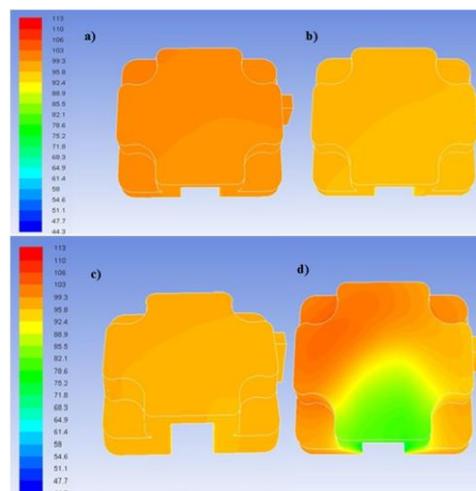


Figure 12. Temperature distribution of the cylinder a) Original b) Aluminium crankcase c) POM valve-plate d) PBT cylinder head

Temperature contours of the suction muffler are given in Figure 13. Variations between temperature distributions of the suction muffler on different cases are specified especially on the suction chamber region. Aluminium crankcase and POM valve plate provide a better result for the

purpose of reducing wall temperatures of the suction chamber. On the other hand, PBT originated cylinder head shows the highest impact on the suction chamber wall temperature with 10°C decrease.

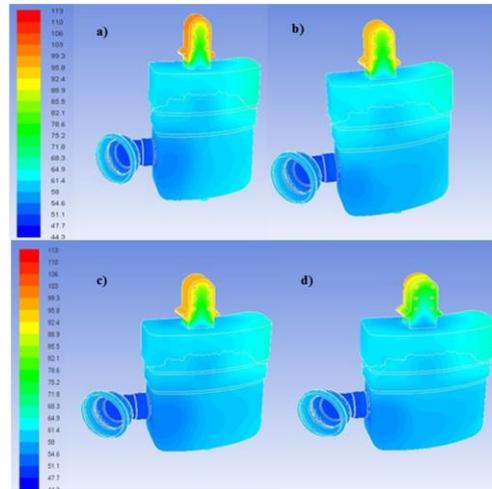


Figure 13. Temperature distribution of suction muffler a) Original b) Aluminium crankcase c) POM valve-plate d) PBT cylinder head

3.3. Transient Conjugate Heat Transfer Model

Transient non-isothermal CFD analysis is performed in order to reveal the fluid flow and its influence on superheating of the refrigerant. Time-dependent pressure profiles, which were obtained experimentally, are used as boundary conditions at the inlets of suction and discharge lines. Constant pressure outlet boundary conditions are used at the outlets of suction and discharge lines. Time step is 0,00005 seconds and calculations are performed for 400 time steps which corresponds to 0,02 seconds total cycle time of a compressor running at 50Hz. Figure 14 shows instantaneous views of streamlines corresponding to the discharge phase, the beginning of suction phase, the last phase of suction and the compression phase respectively. It is seen that refrigerant is heated by convection inside the suction muffler during the periods in which the suction valve is closed. Refrigerant which exists inside the suction muffler at higher temperature enters the cylinder at the beginning of the suction period. Fresh refrigerant replaces the heated refrigerant and fills the cylinder volume as suction process continues. Refrigerant starts to gain heat beginning from the suction chamber during the compression process.

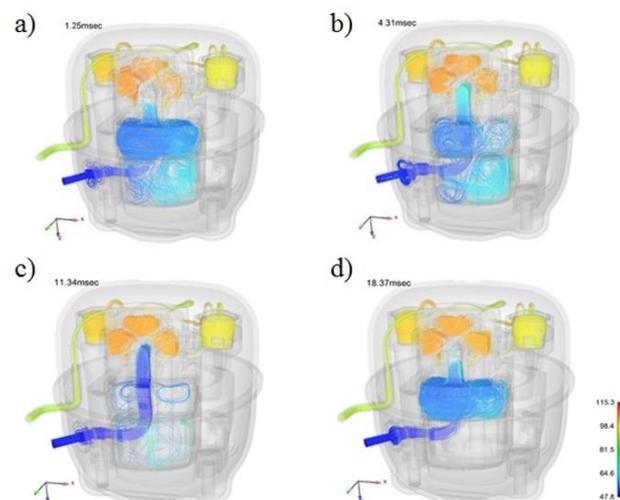


Figure 14. Temperature coloured streamlines of refrigerant at different phases of a compression cycle.

4. Conclusion

Effects of using different materials on the temperature distribution of selected key components such as the crankcase, cylinder head and the valve plate are investigated. The material of the crankcase was changed from cast iron to aluminium at first case. This case lead to a nearly homogenous temperature distribution on the crankcase and lower temperature values around the cylinder region. The other modification was changing the material of the valve plate to an insulative. This change reduced heat conduction from cylinder region to the suction muffler. In the last case, a plastic based material for the cylinder head was used which resulted in a significantly decreased wall temperature of suction chamber. In virtue of the low thermal conductivity of the material, the suction muffler was remained at lower temperatures. The transient conjugate heat transfer analysis showed that refrigerant is heated by convection inside the suction muffler especially during the periods in which the suction valve is closed. Temperature of the refrigerant at the start of the compression process is critical for the thermodynamic efficiency of the compressor. The temperature distribution on the components of the compressor determines the heat gain of the refrigerant until the beginning of the compression. The numerical model presented in this study is used for analysing the effects of component materials of the compressor on its temperature distribution and the results are in good agreement with the experimental studies. The model also provides information, before prototyping, for structural changes on compressor components from the thermodynamic efficiency perspective.

References

- [1] Raja B., Joseph Sekhar D., et al. (2003). Numerical Model for Thermal Mapping in a Hermetically Sealed Reciprocating Refrigerant, Compressor International Journal of Refrigeration.
- [2] Pereira E.L.L., Santos C.J., (2012). A Simplified CFD Model for Suction Process of Reciprocating Compressor, Compressor Engineering Conference, Purdue.
- [3] Nakano A., Kinjo K., (2008). CFD Applications for Development of Reciprocating Compressor, Compressor Engineering Conference, Purdue.
- [4] Kara S., Oğuz E., (2010). Thermal Analysis of a Small Hermetic Reciprocating Compressor, Compressor Engineering Conference, Purdue.
- [5] Morriesen A., Deschamps C.J. (2012). Experimental Investigation of Transient Fluid Flow and Superheating in the Suction Chamber of a Refrigeration Reciprocating Compressor, Applied Thermal Engineering,41 (Sf.61-70)
- [6] Sarıoğlu K., Özdemir A.R., (2012) An experimental and numerical analysis of refrigerant flow inside the suction muffler of hermetic reciprocating compressor, Compressor Engineering Conference, Purdue.
- [7] Kawai H., (1982). The Development of High Efficiency Compressor by Reducing Suction Gas Temperature, Compressor Engineering Conference, Purdue.
- [8] Padhy S.K., (1992). Heat Transfer Model of a Rotary Compressor, Compressor Engineering Conference, Purdue.
- [9] Almbauer, R.A., (2006). 3-Dimensional Simulation for Obtaining the Heat Transfer Correlations of a Thermal Network Calculation for a Hermetic Reciprocating Compressor, Compressor Engineering Conference, Purdue.
- [10] Dutra, T., Deschamps, C.J., (2010). Experimental Investigation of Heat Transfer in Components of a Hermetic Reciprocating Compressor, Compressor Engineering Conference, Purdue.
- [11] Deschamps, C.J., (2012). A Heat Transfer Model Combining Differential and Integral Formulations for Thermal Analysis of Reciprocating Compressors, Compressor Engineering Conference, Purdue.