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3 - DIMENSIONAL SIMULATION FOR OBTAINING THE HEAT TRANSFER CORRELATIONS OF A THERMAL NETWORK CALCULATION FOR A HERMETIC RECIPROCATING COMPRESSOR

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ABSTRACT

A 3-dimensional simulation of the hermetic reciprocating compressor is still limited by the computer capacity. The 1-dimensional simulation provides a useful result as long as the thermal boundary conditions are well-known. This is the reason to apply a thermal simulation of the whole compressor, which can be done by using a Thermal Network (TNW) calculation. One problem for the TNW is the deduction of the heat transfer correlations between the individual masses. In this paper the heat transfer correlations for the piston-cylinder section are elaborated. The investigation comprises a comparison of a full 3-dimensional simulation with a TNW calculation. The spatial resolution in a TNW depends on the number of mass elements. A method is proposed which divides the domain in non–overlapping geometrically well-defined volumes. Using the results from the 3-dimensional simulation the heat fluxes between these mass elements have been evaluated. Then the heat transfer functions $\left(HTF = \partial \dot{Q} / \partial \Delta T\right)$ are calculated and applied in a TNW calculation. The TNW results show a good agreement compared with the 3-dimensional output.

1. INTRODUCTION

In order to increase the efficiency of a hermetic piston compressor for household refrigeration there are several options. Beside an improvement of the efficiency rates, like volumetric efficiency, mechanical efficiency and electric efficiency, the reduction of heating and pressure drop in the suction gas and the pressure drop in the discharge system are important. Another important issue is the temperature development of the gas during suction, compression, discharge and re-expansion in the cylinder. In order to study the energy fluxes for this complex process in the compressor, the temperature distribution in the solid parts is an important boundary condition. This boundary condition can either be assessed by measurements or by calculation. There are many papers presenting simulations done for temperature distributions of individual compressor parts e.g. Perez-Segarra *et al.* (2005), Rigola *et al.* (2005), Longo (2002). A smaller number of papers are dealing with calculation and analysis of the overall energy balance e.g. [4] Oio (2003), Abidin *et al.* (2005). The papers show that the shell of a hermetic piston compressor forms an additional thermodynamic system, where all energy fluxes interact. The *Thermal Network* approach (TNW), which is also well known under the term *Thermal Mapping* is the tool to analyze the energy fluxes. The result of a TNW calculation gives the temperature of the individual mass elements. TNW uses the Lumped Conductance Method to represent the heat transfer between distinct mass points representing the compressor. Nevertheless the reduction of geometrical information leads to an uncertainty in the values of lumped conductance for almost all heat transfers. Main difficulties are the representation of the heat fluxes due to transient 3d flow phenomena in front of and in the suction muffler, in the discharge line and in the shell. The lumped conductance values are also uncertain for cast parts like the cylinder-crankcase part or the cylinder head. As these parts have irregular forms and therefore the segmentation into mass points and their representation in the TNW is not straightforward. Knowing the problems concerned with the generation of a TNW, it is important to validate the

TNW. Experiments provide temperatures for distinct measurement points, for which it is not clear whether they are reflecting the mean temperatures of the corresponding masses in the TNW. The comparison of temperatures implies another problem concerning the varying values of the lumped conductance for different heat bridges. For the heat transfer in a gray cast iron the lumped conductance is typically 100 to 1000 times higher than the heat transfer on a surface to the gas. Therefore small temperature differences in cast parts result in big changes of the heat flux values. The validation measurements are finally often used to “tune” the TNW to get well fitting results. This is reasonable as long the uncertainties of the lumped conductance values can not be evaluated in any other way. As a result the heat fluxes calculated in the TNW can be different from reality although the temperatures fit well to the measurement.

Many measures for the improvement of a compressor do not change only one heat flux in the TNW but all, according to the strong interdependency in the shell. In order to study the actual influence of a change in design on the heat fluxes, the original TNW has to be as accurate as possible. In the following chapter the concept for a simulation of the TNW of a well investigated hermetic piston compressor is discussed. This is followed by the deduction of a method to get better predicted values for complex segmented cast parts from CFD simulations. The method is finally applied to the cylinder of the hermetic piston compressor.

2. THERMAL NETWORK CONCEPT AND SIMULATION TOOLS

The following concept deals with the thermodynamic analysis of an existing compressor, which is available in a CAD-Digital Mock Up (CAD-DMU). The compressor for R600a (isobutane) is shown in figure 1 with its main parts. The displacement is 12 ccm and the COP is approx. 1.6 for the ASHREA test case shown in figure 2. From experiments the temperature levels and flow characteristics are well known. The thermodynamic analysis has been carried out using these experimental data and simulation tools for the fluid flow and for the heat transfer in the compressor. As a full 3-dimensional simulation of all processes in the compressor can not be carried out up to now, the investigation has been divided into three parts, using simplified sub-models. The three tasks are the analysis of (a) the fluid flow, (b) the heat transfer in the structure including the cylinder-piston system and finally (c) the overall thermal analysis.

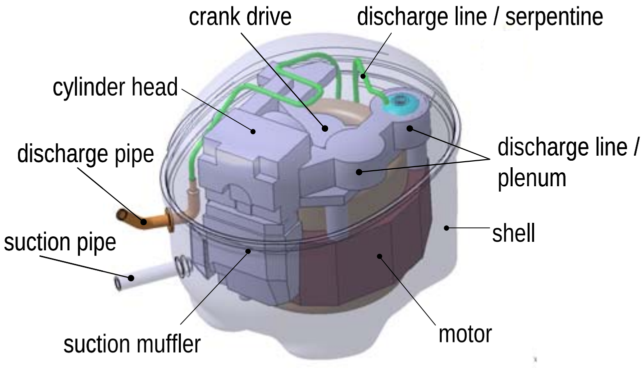

Fig. 1: Schematic view of a hermetically sealed reciprocating compressor

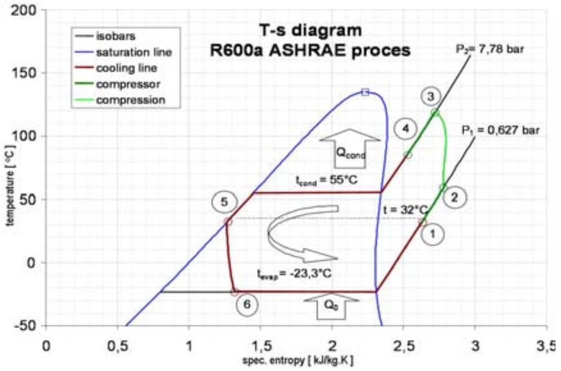

Fig. 2: Schematic T,s - diagram for isobutane for ASHRAE process

2.1 Fluid Flow Analysis

The fluid flow simulation has been carried out using a commercial CFD tool. The model solves the conservation equations for mass, momentum and energy for a 1-dimensional transient flow using a Finite Difference Method. The model allows a representation of the main geometrical features of the compressor including the valve and piston movement. The gas properties are implemented. The simulation provides compression work, velocity and pressure distribution over the gas path, heat transfer fluxes for all surfaces etc. For the calculation of heat transfer the wall temperatures must be given as a boundary condition.

According to the reduction of the 3-dimensional phenomena to a 1-dimensional representation in the model, not all details can be resolved. A more precise description of the model is given in Almbauer *et al.* (2005).

2.2 Thermal Network Analysis

For the thermal investigation the steady state case is taken. Based on a “Lumped Parameter Formulation” the balance of the heat fluxes is calculated. The approach starts from the segmentation of the whole compressor into mass elements. Each of the mass elements is surrounded by a defined closed surface. So every mass element represents a thermodynamic system with its system boundaries. The heat flux between two mass elements exists only if there is a common surface. The choice of the mass elements should provide an overview about all thermal bridges, the directions and the values of heat fluxes. For every mass element the energy balance is solved (eq.1). For steady state case the sum of all heat fluxes together with the heat sources has to be balanced.

$$\sum_{j=1}^{n} HTF_{i,j} \cdot \Delta T_{j,i} + S_i = 0 \tag{1}$$

The heat sources are inner sources (e.g. in the electric motor). All other heat fluxes are over the surfaces of the mass elements. All heat transfers can be modeled using the following equations: heat transfer function (HTF) multiplied by the temperature difference. The thermal network is solved using a Visual Basic code. The numerical effort for the solution is small compared to the fluid mechanics part.

The geometrical simplifications in the TNW result in similar problems as they occur in the fluid flow. Full information about the conductive heat transfer can only be obtained from 3d simulations. Therefore a 3-dimensional study has been carried out for the following part of the compressor shown in figure 3: the cylinder, the valve plate and the cylinder head together with a small part of the stator have been simulated using the CFD-code FLUENT. For this application FLUENT solves only the conduction terms of the conservation equation for heat. The simulation provides the steady state 3-dimensional temperature distribution. The boundary conditions for the simulation are achieved from measurements and from the cycle-averaged heat flux from the fluid flow simulation. For all surfaces, which are in contact with the gas in the shell the heat transfer has been calculated according to equation (2).

$$\dot{Q}_{i,shell} = \alpha \cdot A_{i,shell} \cdot (T_i - T_{shell}) \tag{2}$$

The heat transfer from the gas inside the cylinder and the cylinder head have been given as heat sources. The grid for the 3d simulation includes approx. 520.000 Finite Volumes (tetrahedrons with a typical size 0.2-0.3 mm) for the whole geometry (figure 3).

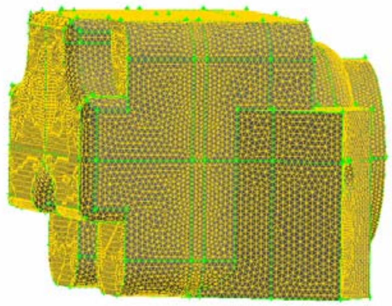

Fig. 3: 3-dimensional simulation grid

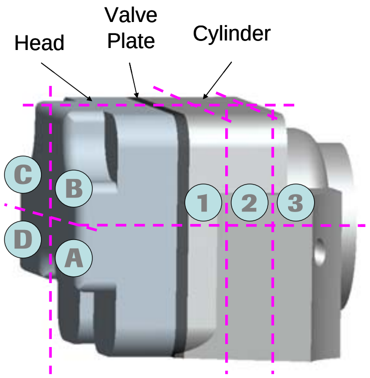

Fig. 4: Segmentation of cylinder, valve plate and cylinder head for the TNW

The results are shown for two parts of the investigated structure (figure 5a and 5 b). The first part is the cylinder head, where the hot compressed gas heats the inner surfaces. This leads to hot temperatures on the upper surfaces. The second part is the upper part of the cylinder, where the discharge pipe enters from the cylinder head. The influence of the hot gas in the discharge passage can be seen in form of an area of hot temperatures.

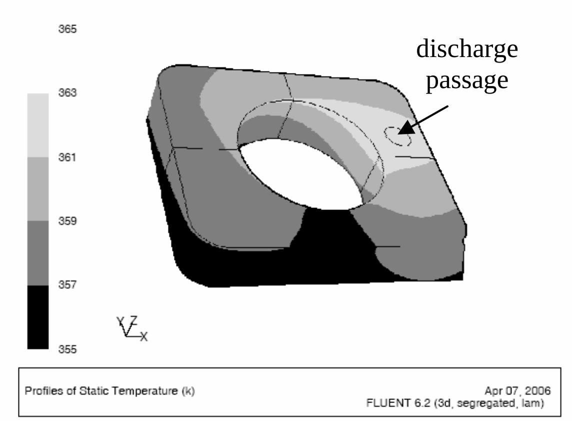

Fig. 5a: 3-d temperature distribution of upper cylinder

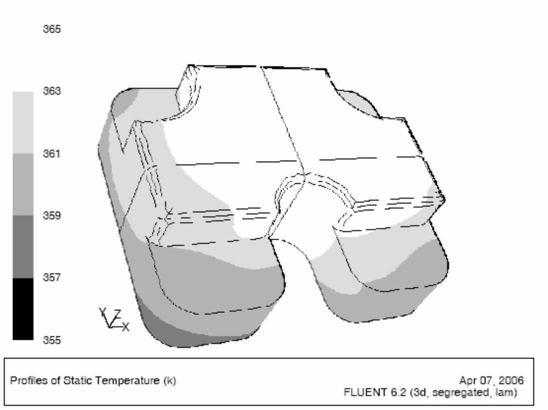

Fig. 5b: 3-d temperature distribution of cylinder head

2.3 Mapping of the 3-d method into the TNW

In order to map the thermal behavior of the 3-dimensioanl structure on the TNW a segmentation of the structure into mass elements has to be chosen. There is no general rule on the method concerning the number and shape of mass elements. In addition there is no perfect way to get the lumped conductance between the two mass elements. We propose the following method, which should represent the influence of the 3-dimensional geometry in the TNW.

Table 1: Comparison of 3-dimensional and TNW temperature results

	Case 1			Case 2		
Mass Element Name	3-d Temp. [°C]	TNW Temp. [°C]	Delta Temp. [K]	3-d Temp. [°C]	TNW Temp. [°C]	Delta Temp. [K]
Head A	89.37	89.22	0.15	80.42	80.25	0.17
Head B	90.74	90.49	0.25	81.48	81.03	0.45
HeadC	89.87	89.83	0.04	80.94	80.76	0.18
Head D	88.47	88.53	-0.06	79.87	79.87	0.00
Plate A	87.78	87.64	0.14	78.76	78.82	-0.06
Plate B	90.66	90.41	0.25	80.68	80.93	-0.25
Plate C	89.13	89.09	0.04	79.80	80.07	-0.27
Plate D	86.44	86.56	-0.13	77.94	78.14	-0.20
Cyl A1	84.99	84.89	0.10	76.48	76.58	-0.10
Cyl A2	83.70	83.63	0.07	75.46	75.58	-0.12
Cyl A3	82.84	82.79	0.05	74.84	74.99	-0.15
Cyl B1	86.72	86.57	0.15	77.67	77.77	-0.10
Cyl B2	84.99	84.88	0.11	76.33	76.46	-0.13
Cyl B3	83.33	83.27	0.06	75.08	75.30	-0.22
Cyl C1	84.80	84.79	0.01	76.48	76.66	-0.18
Cyl C2	82.99	83.00	-0.01	75.10	75.29	-0.19
Cyl C3	81.11	81.17	-0.06	73.68	73.94	-0.26
Cyl D1	83.44	83.52	-0.08	75.53	75.71	-0.18
Cyl D2	81.89	81.96	-0.07	74.33	74.51	-0.18
Cyl D3	81.03	81.11	-0.08	73.70	73.90	-0.20

Starting from the CAD data set, the whole structure is divided using geometrically defined intersecting planes, which allow the evaluation of the area and the heat flux passing through the plane. Evaluation of the 3-d results gives heat fluxes in [Watt] for every surface part of each mass element. The mean temperature can be calculated as a volumetric averaged value. Finally we can assume that the heat transfer obeys to the following equation (3) for every conductive heat bridge.

$$\dot{Q}_{i,j} = HTF_{i,j} \cdot \Delta T_{i,j} \tag{3}$$

Dividing the heat flux by the temperature difference results in values for the lumped conductance or heat transfer functions ($HTF_{i,j}$) between two mass elements. This has been done for the shown structure using two intersecting planes aligned with the cylinder axis (sectors A, B, C, and D) and four planes normal to the cylinder axis (cyl. head, valve plate, cyl.1, cyl.2, and cyl.3) (figure 4). This gives 20 mass elements, for which the volumes, the surfaces, the mean temperature and the heat fluxes over the individual surface parts are given. The results are shown in table 1. The evaluated values for the HTF can now be used for the TNW calculation and it is trivial, that the result for the 3d-simulation and the TNW calculation is the same. There is only the small difference according to the slightly different influence of the boundary conditions on the outer surface. Particularly the heat transfer on the outer surface for the 3-dimensional case is calculated using the temperature of each of the Finite Volumes. In contrast to it the TNW uses the mass element temperature to calculate this heat transfer.

3. TNW VALIDATION AND DISCUSSION

Assuming that the proposed method for the derivation of HTF is correct, it must also be valid for other test cases. Therefore a new test case (Case 2) has been set up, with a reduced heat flux in the cylinder head and the discharge pipe. The result of the 3-dimensional simulation has been treated in the same way as for the first test case (Case 1). The result for the HTF is compared for the two test cases only for largest diverting values in table 2. Generally there is a reasonable consistency for almost all lumped conductance values. 25 values out of 36 differ by less than 5 %, another 7 values differ by less than 10 %. There is one value which disagrees with a factor of almost 9.

Table 2: Comparison of the four most diverting HTF for Case 1 and Case 2

HTF [W/K]	Plate B Head B	Cyl D3 Cyl C3	Plate C Head C	Cyl B3 Cyl A3
HTF Case 1	24.3050	0.3818	3.6657	0.1815
HTF Case 2	2.4715	0.9453	2.1507	0.2104
DT Case 1	0.080	0.080	0.740	0.490
DT Case 2	0.800	0.015	1.144	0.240

The analysis of the largest discrepancies shows that the values for the temperature difference (volumetric mean value) between the two mass elements in case 1 or 2 are very small. For the value of the HTF between the cylinder head part B and the valve plate part B the actual temperature difference for the Case 1 is 0.08 K. This is also the case for the second discrepant value (Cyl D3 to Cyl C3). The temperature differences for the two other cases are higher. Other facts are that the mass elements have either a complex geometrical form (e.g. one quarter of the cylinder head) and/or an extra heat source (e.g. the discharge pipe passing through the valve plate). Both facts generate a non-uniform temperature distribution, which influences the heat conductance. Finally the HTF values of Case 1 are applied in the TNW to calculate Case 2. The results are shown in table 1 on the right side. The comparison of temperatures shows a good agreement, although the HTF values do not fit to Case 2. The temperature differences are less than 0.45 K. The heat fluxes for the individual heat bridges differ from the 3-dimensional results. This amplifies the assumption that many results from TNW calculation show reasonable agreement in temperatures for solid parts, while the heat fluxes differ from reality. In order to reduce the uncertainties of the HTF a better geometrical representation of the temperature distribution must be achieved. This can be done by an increase of the number of mass elements.

4. CONCLUSION

The temperature increase of the compressed gas has an important influence on the efficiency of a compressor. As it is not straightforward to measure the gas temperatures in highly transient flow conditions, the remedy is the assessment of temperatures using a CFD simulation tool. The 3-dimensional way is still time consuming and needs similar to the 1-dimensional simulation realistic temperature boundary conditions. The shell of a hermetic piston compressor implements an extra thermodynamic system boundary. So all heat fluxes of the compressor like mechanical friction, electrical losses, heat fluxes of the gas etc. interact in the shell. In order to get the correct temperature distribution all heat fluxes have to be modeled. Thermal mapping of the compressor can be done applying a Thermal Network calculation. This Lumped Conductance method suffers from the reduced geometrical information, which can be represented. Especially in the solid structure the heat transfer function HTF depends on the complex geometry of the mass elements. The proposed method uses the 3-dimensional geometry and temperature distribution of a Finite Volume method. The real geometry is available from a CAD-DMU. Dividing the geometrically well defined structure into mass elements has the advantage to get the exact areas between the mass elements. With it the heat flux of a test case over the area between two adjacent mass elements can be evaluated. Using this information the HTF are calculated by dividing the heat flux with the temperature difference. The application of the resulting HTF to a second test cases shows that the method is not universally valid. The HTF depend on the test case. The reasons are manifold: the temperature distribution in the individual mass element is not uniform. This can be the case for mass elements with complex shapes. The same happens for mass elements with asymmetric heat sources. Finally the shape of the mass elements should be close to cubic in order to decompose the 3-dimensional heat transfer into the three Cartesian directions.

NOMENCLATURE

symbol	comment	unit	symbol	comment	unit
$HTF_{i,j}$	heat transfer function between mass elements i and j	$[W/K]$	$A_{i,j}$	area between mass elements i and j	$[m^2]$
TNW	thermal network	$[-]$	T	temperature	$[K]$
$\dot{Q}_{i,j}$	heat flux between mass elements i and j	$[W]$	S_i	heat source of mass element i	$[W]$
ΔT	temperature difference	$[K]$	Δt	time step	$[s]$
η_{el}	electrical efficiency	$[-]$	α	heat transfer coefficient	$[W/m^2K]$
η_{mech}	mechanical efficiency	$[-]$	COP	coefficient of performance	$[-]$
η_v	volumetric efficiency	$[-]$	CAD-DMU	computer aided design digital mock up	$[-]$

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