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CFD SIMULATION OF PRESSURE LOSSES IN DISCHARGE SIDE OF COMPRESSOR WITH COMPARATION OF REAL GAS EQUATIONS

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In this paper different models of equations of state in CFD simulation through discharge channels of valve plate in reciprocating compressor with carbon dioxide as a refrigerant are compared. First, mathematical formulations of cubic equations of state are described. Then CFD simulations based on experimental data are compared to measured values to choose the most suitable model of real gas equation of state for modeling pressure losses in the carbon dioxide flow through discharge valve plate in compressor.

Keywords: carbon dioxide, pressure losses, CFD simulation

1. Introduction

Nowadays, the requirement for the supply of energetically, environmentally and economically most effective solution of cooling circuit is already becoming matter of course. Therefore, care must be taken to select appropriate accessories of cooling system and proper sizing of each component of the cooling circuit, since they may produce undesirable pressure losses, which can affect the operation of the circuit and thus the mentioned economic and energy aspect. One of the most important component of the cooling circuit is the compressor, in which lot of pressure losses can be created, for example in suction filter, in the valve plate, in the inlet channels to the cylinder heads, etc. It is necessary to minimize these losses, for example with appropriate geometry of valve plate, valves, channels and so on. This would achieve lower power consumption to drive the compressor, which can increase the overall energy efficiency of cooling circuits.

Moreover, in recent years the question about full restriction of high GWP refrigerants is more and more discussed because of their affect to global warming. And here we can see the growth of using natural refrigerant in cooling circuits, for example carbon dioxide, which has good thermodynamic properties and is friendly to the environment. Using carbon dioxide as a refrigerant in cooling circuits due to its physical properties and pressure conditions, reducing the pressure losses at the lowest possible values is required. To achieve low pressure losses it is necessary to know the behaviour of the refrigerant in circuit, especially its flow through different parts of the compressor. Using appropriate software, such as ANSYS CFX, FLUENT, it is possible to achieve sufficiently precise simulation of refrigerant flow.

Aim of this work is to measure the pressure losses through the discharge side of the valve plate of compressor and compare them to CFD simulation where different equations of state of refrigerant (carbon dioxide) will be used. There are many equations of state which are devided into two basic groups. In the first group there are relatively simple cubic equations. Their solution is simple, derivation of constants is not difficult, because they are dependent on the critical parameters. This group includes Redlich-Kwong (RK) equation of state, which was designed in 1949. The second group consists of the so-called BWR (Benedict-Webb-Rubin) equations of state or equations derived from them. The advantage of BWR equation is the

ability to customize settings for desired area of pressures and temperatures. Constants for BWR equation are calculated from the known experimental data, which have been tested and verified. In this paper cubic equations of state will be shown.
There will be two different conditions of discharge pressure, 50 bar (subcritical cooling circuit) and 80 bar (transcritical cooling circuit).

2. Cubic Equations of State

The Redlich Kwong variants of cubic equation of state are written in *Tab. 1*, where p_c means critical pressure, T_c is critical temperature, v_c is critical specific volume. The standard Redlich Kwong (RK) model sets the parameter *c* to zero and parameters *n* is equal 0,5. The Aungier form (RKA) differs from the original by a non-zero parameter *c* which is added to improve the behavior of isotherms near the critical point, as well as setting the exponent *n* differently. Peng Robinson (PR) equation of state extends the ideal equation and also gives pressure as function of temperature and volume.

Tab. 1 Review of cubic equations of state

Equation of State	Formulation	Parameters	
Standard Redlich Kwong	$p = \frac{rT}{v-b} - \frac{a}{v(v+b)T^{0,5}}$	$a_0 = a(T_c) = 0{,}42748\, r^2T_c^2/p_c$	$b = 0{,}08664\, rT_c/p_c$
Aungier Redlich Kwong	$p = \frac{rT}{v-b+c} - \frac{a(T)}{v(v+b)}$	$a = a_0(T/T_c)^{-n}$	$c = \frac{rT_c}{p_c + \left(a_0/v_{c(v_c+b)}\right)} + b - v_c$
Peng Robinson	$p = \frac{rT}{(v-b)} - \frac{a(T)}{v^2 - 2bv + b^2}$	$a(T) = a_0\left[1 + n\left(1 - \sqrt{T/T_c}\right)\right]^2$	$a_0 = 0{,}45724 r^2T_c^2/p_c$ $b = 0{,}0778 rT_c/p_c$

3. Measuring line

The measuring line consists of two sections (see *Figure 2*). First section is the measuring station used by Emerson Climate Technologies for performance testing of compressors (Performance Test Stand - PTS) and second section is the tested section, where the pressure losses are measured and which contains only the body of compressor with valve plate, while the other parts are disassembled. Performance test stand consists of oil separator, Coriolis mass flow meter, plate heat exchanger (gas cooler), control valves, shut-off valves, temperature and pressure sensors (*Figure 1*). Compressor 4MTL-30X in the PTS is used for compressing the refrigerant to the circuit, ensuring stationary flow of carbon dioxide with required pressure through the tested section. Refrigerant enters the compressor at pressure p_1 and temperature T_1, where is compressed to pressure p_2 and temperature T_2. Then the refrigerant in high pressure part of the circuit enters the oil separator, which is used to separate the oil from the refrigerant. After separation of oil, the refrigerant enters the tested section, where the pressure losses through the valve plate on discharge side are measured, while the suction valves are fixed. After passing through tested section refrigerant flows through Coriolis flow meter which is used for measuring the mass flow rate of refrigerant in the system. Subsequently carbon dioxide in the form of gas flows into the plate heat exchanger (gas cooler), which ensures cooling of the refrigerant to the suction temperature T_1. Required suction pressure p_1 before entering the compressor is achieved by a pair of control valves. Also the pressure p_2 before entering the gas cooler is achieved by a pair of control valves. Scheme of measuring line can be seen in *Figure 1*. CO_2 as the refrigerant operates at high operating pressures and it is necessary to ensure maximum safety. As can be seen from *Figure 2*, both sections were limited with the safety cage.

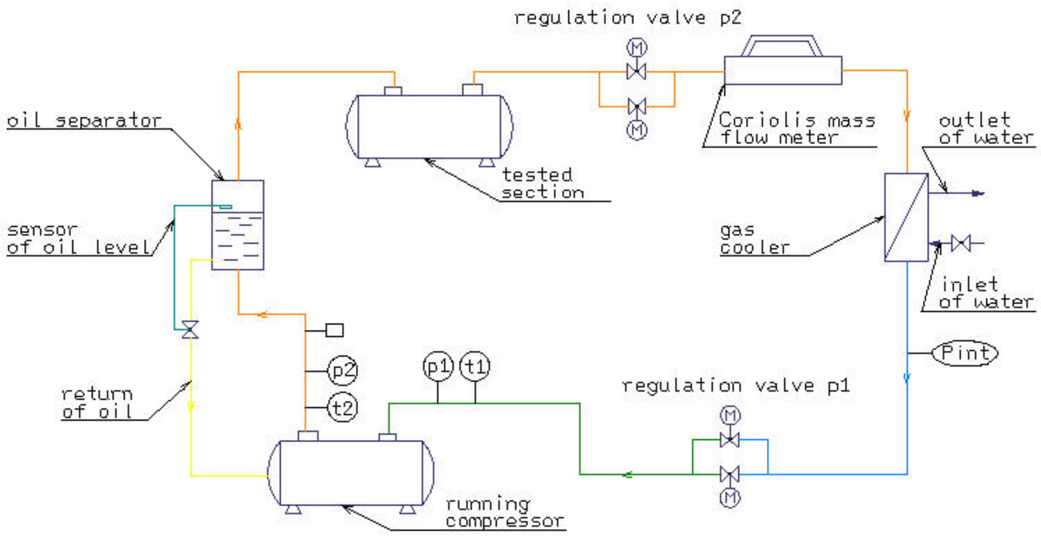

Fig. 1 Scheme of the measuring line

Fig. 2 Measuring line

As it was mentioned before, there were investigated two different pressure levels through the valve plate in tested section (50 and 80 bar). The valves on the suction side were fixed to prevent back flow of refrigerant to the body of compressor. Evaporating temperature was -10°C. The values of the temperature and pressure on the suction side of running compressor were $t_1 = 2°C$ and $p_1 = 26{,}5\, bar$. In *Figure 3* can be seen operating envelope of compressor (4MTL-30X in the PTS) with denoted points of measurement.

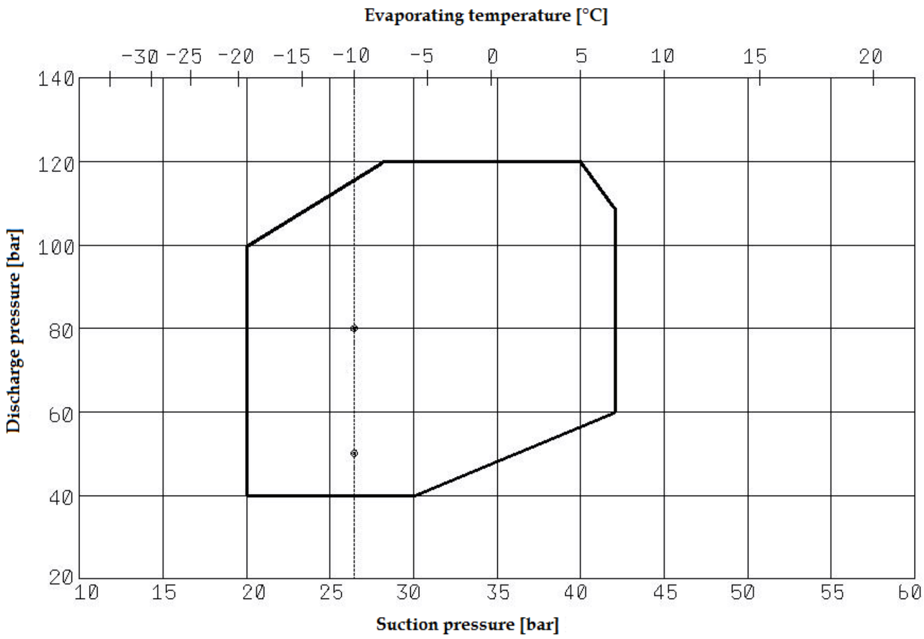

Fig. 3 Operating envelope of compressor with measured conditions

For measuring the pressure losses it is necessary to connect the differential pressure sensor to the tested section. First reference point was connected to the compressor body, just before the refrigerant enters the cylinder head cover through the valve plate. The second reference point was set behind shut-off valve on the discharge side of the compressor, as shown in *Figure 4*.

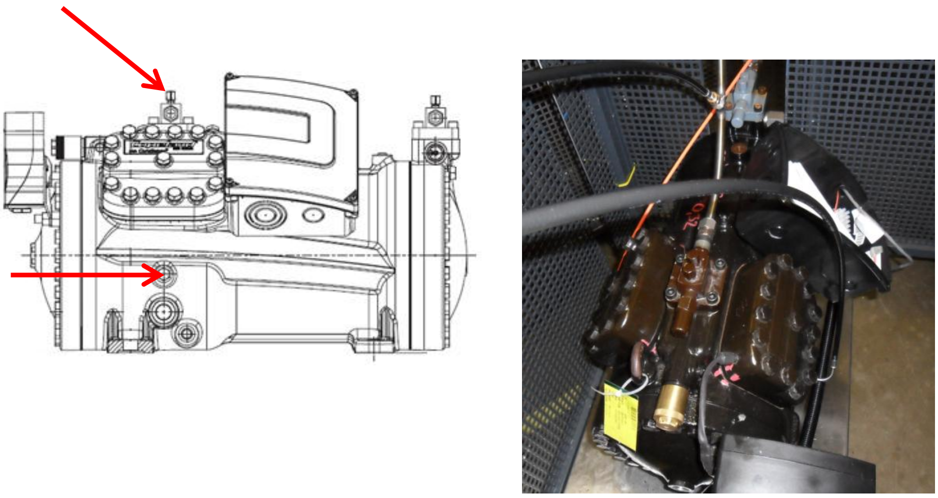

Fig. 4 Reference points of differential pressure sensor

4. Results

First, the pressure losses through valve plate on the discharge side of compressor were measured (these results were required for CFD simulation of refrigerant flow). Then CFD simulation of pressure losses with different equations of state in refrigerant flow of carbon dioxide through discharge side of valve plate of reciprocating compressor were investigated. For this simulation was used ANSYS CFX. Boundary conditions for refrigerant flow were defined with pressure for inlet and with mass flow for outlet. The refrigerant carbon dioxide was defined as a model of an ideal gas, as a model with Redlich-Kwong (RK) equation of state and as a model of Peng Robinson (PR) equation of state. In the *Table 1* is shown the comparison of the measured value of pressure losses with the simulation data with different gas equation models.

Tab. 2 Results from CFD simulation compared with experimental measurement

Condition (bar)	**t_1 (°C)**	**p_1 (bar)**	**$\dot{m}$ (kg/s)**	**Δp measurement (bar)**	**Δp Ideal gas (bar)**	**Δp Redlich (bar)**	**Δp Peng (bar)**
50	2	26.5	0.27	**2.298**	**1.973**	**1.985**	**1,994**
80	2	26.5	0.27	**1.319**	**1.124**	**1.13**	**1.141**

As we can see from *Table 2*, using the Peng Robinson equation of state is the best solution of three compared models because of closest results to experimental data. The biggest difference arises by using Ideal gas model. Differences between real gas, Redlich-Kwong and Peng Robinson models are relatively small, so it is acceptable to use ideal gas model to CFD simulations.

In the *Figures 5-8* can be seen the CFD simulation of refrigerant flow through valve plate (specifically through discharge channels of valve plate) using Peng Robinson model as an example. In the *Figures 5* and *7* are displayed the velocity fields in the discharge channels with different pressures (50 and 80 bar) and in the *Figures 6* and *8* we can see the total pressure fields in the discharge channels.

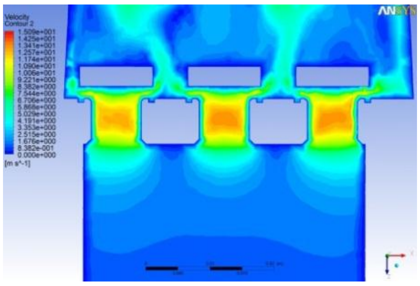

Fig. 5 Displaying of velocity field in the discharge channels (50 bar)

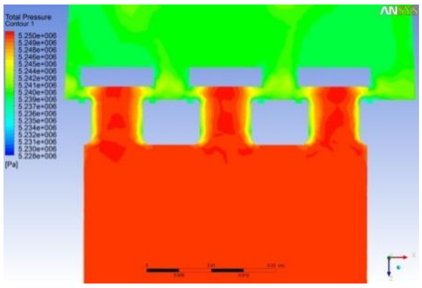

Fig. 6 Displaying of total pressure field in the discharge channels (50 bar)

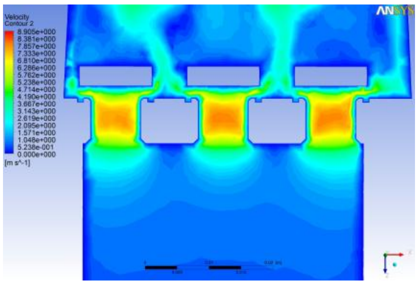

Fig. 7 Displaying of velocity field in the discharge channels (80 bar)

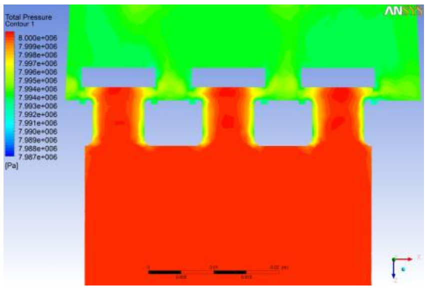

Fig. 8 Displaying of total pressure field in the discharge channels (80 bar)

Conclusion

The aim of this paper was to analyze the pressure losses in the discharge channels of valve plate of reciprocating compressor with carbon dioxide as a refrigerant using different equations of state models in CFD simulation (ideal gas, Redlich-Kwong and Peng Robinson). These data were compared to experimental values. The best model of dofferent equations of state used in simulation and compared to experimental data is Peng Robinson model. Difference between investigated real gas and ideal gas models was not very significant so it is acceptable to use ideal gas model for simulations. Also an example of refrigerant flow through discharge channels of valve plate were shown.

Literature

[1] KIM, Y. 2007. Equation of state for carbon dioxide. In *Journal of Mechanical Science and Technology*. 2007, vol. 21, p. 799-804.

[2] MASARYK, M. – FERSTL, K. 2011. *Heat transfer*, Bratislava: Slovak University of Technology, 2011, 424 p. ISBN 978-80-227-3534-6.

[3] SPAN, R. – WAGNER, W. 1996. A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. In *NIST, American Institute of Physics and American chemical society, J. Phys. Chem. Ref. Data.* 1996, vol. 6.

[4] BUKAC, H., *Understanding Valve Dynamics*. International Compressor Engineering Conference (2002). Paper 1564.

[5] ANSYS CFX Solver Theory Guide, Release 12.0 [online] Available on internet: http://www1.ansys.com/customer/content/documentation/120/cfx/xthry.pdf

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