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PULSATING FLOW AND HEAT TRANSFER IN A SIMPLIFIED SUCTION SYSTEM OF RECIPROCATING COMPRESSOR

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Abstract. *One of the main sources of thermodynamic inefficiency in compressors is associated with heat transfer that takes place as the gas flows throughout the suction system. This process is usually referred to as superheating and its main effect is the decrease of both the volumetric efficiency, due to reduction of the gas density, and the isentropic efficiency, since the specific work of compression becomes greater as the gas temperature is increased. Since a pulsating flow condition is present in such systems, it is important to verify to what extent the transient flow regime affects this phenomenon. The present paper reports numerical predictions of fluid flow and heat transfer in a simplified geometry of suction system for transient and steady state regimes, considering the compresssor under three operating conditions. The results reveal that heat transfer associated with the transient flow condition is higher than that which would occur in the case of a steady flow regime.*

Keywords*: reciprocating compressor, superheating, pulsating flow.*

1. INTRODUCTION

Hermetic reciprocating compressors are the most common choice for household refrigeration, due to a number of advantages: small volume, absence of leakage and low levels of noise and energy consumption. In hermetic compressors, motor and compressor are directly coupled on the same shaft and the assembly is installed inside a welded steel shell. Reed valves of hermetic compressors are called automatic because they open and close depending on the pressure difference between the cylinder and the suction/discharge chamber, established by the piston motion.

Figures 1 and 2 present a schematic view of a reciprocating compressor and the indicator diagram for a typical compression cycle. When the piston moves downwards, it reaches a position in which low pressure vapor is drawn in through the suction valve, which is opened automatically by the pressure difference between the cylinder and the suction chamber. The vapor keeps flowing in during the suction stroke as the piston moves towards the bottom dead center, filling the cylinder volume with vapor at suction pressure, p_S. The suction process is represented by curve B-C in the indicator diagram of Fig. 2. After reaching the bottom dead center, the piston starts to move in the opposite direction, the suction valve is closed, the vapor is trapped, and its pressure rises as the cylinder volume decreases. Eventually, the pressure reaches the pressure in the discharge chamber, p_D, and the discharge valve is forced to open. After the opening of the discharge valve, the piston keeps moving towards the top dead center, represented by point A.

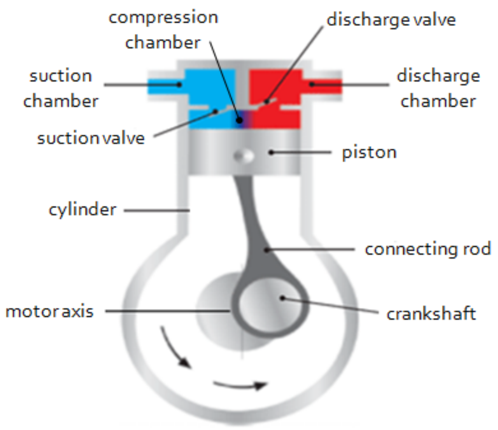


Figure 1. Schematic of reciprocating compressor.

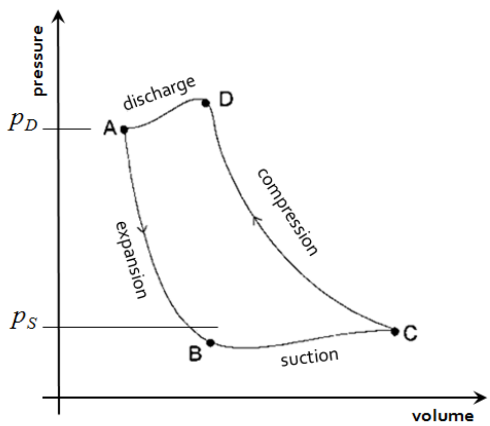


Figure 2. Pressure-volume diagram of a compression cycle.

Recent figures show that approximately 8% of the residential electrical energy consumption in the United States is due to refrigerators and freezers. This is one of the main reasons behind the increasingly demand for high-efficiency cooling systems. Among the components of a vapor-compression refrigeration system, the compressor has a key role in its energy consumption. The overall efficiency of a compressor can be understood as being the result of three aspects: i) electrical efficiency, associated with the driving motor and its startup auxiliary device; ii) mechanical efficiency, related to the bearing system; iii) thermodynamic efficiency, due to irreversibilities in the suction, compression and discharge processes. According to Ribas *et al.* (2008), the thermodynamic efficiency is not as high as the other two efficiencies. It is worth mentioning that superheating may account for almost 50% of the thermodynamic losses.

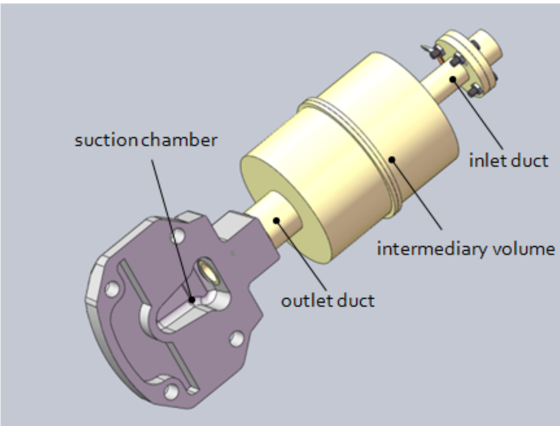
Superheating is associated with heat transfer that takes place as the gas flows throughout the suction system and enters the compression chamber. Some superheating is desirable to avoid liquid entering the compression chamber, but excessive superheating can considerably decrease both the volumetric efficiency, due to reduction of the gas density, and the isentropic efficiency, since the specific work of compression becomes greater as the gas temperature is increased.

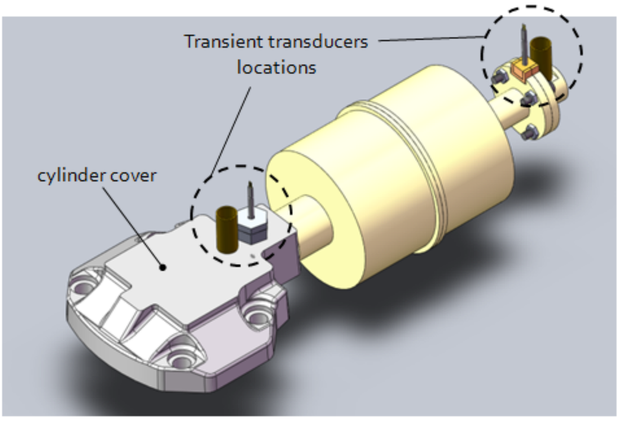
The opening and closure of the suction valve induce a pulsating flow in the system suction. One of the main functions of the suction system is to reduce the undesirable effects of this flow condition, such as vibration and noise. However, it is not clear how pulsating flow affects heat transfer in the suction system. In fact, this phenomenon is not even clear for simple geometries such as straight ducts (Wang and Zhang, 2005; Blel *et al*., 2009). Bauer *et al.* (1998) discuss the pulsating flow and heat transfer in the suction system of an internal combustion engines based on experimental data. More recently, Morriesen and Deschamps (2011) presented measurements of temperature transients in the suction chamber of a reciprocating compressor. The main goal of this paper is report the results of a numerical analysis of transient fluid flow and heat transfer in a suction system under different operating conditions.

2. SUCTION SYSTEM GEOMETRY

Figure 3 shows a schematic view of the simplified geometry of suction system adopted in the present analysis. As can be seen, the geometry has a straight inlet duct, an intermediary volume and a straight outlet duct connected to the suction chamber.

The cylindrical suction system was experimentally tested in a dedicated compressor facility in which the suction and discharge pressures can be adjusted according to required operating condition. The compressor is tested inside a box with controlled ambient temperature. Measurements of velocity, temperature and pressure were carried out at the inlet and outlet of the suction system (Fig. 3b) and used to validate the numerical model.





(a) (b)

Figure 3. Cylindrical suction system.

3. NUMERICAL MODELING

The Reynolds averaged Navier-Stokes (RANS) equations were solved with a commercial code (FLUENT, 2010) and the RNG k-ε turbulence model was selected to account for turbulent transport of momentum and energy. An enhanced wall-treatment was adopted to take into account the effect of solid surfaces. In this respect, the solution domain was discretized with a mesh resolution to guarantee that $y^+ < 5$ for the cell adjacent to the wall. Fluid flow properties in the solution domain were interpolated with a second order upwind scheme and the coupling between the pressure and velocity fields was achieved with the SIMPLEC scheme. A temperature boundary condition was prescribed at the external surface with reference to experimental data and heat conduction through the wall was modeled via a one-dimensional thermal resistance. The Redlich-Kwong gas real model was adopted to characterize the refrigerant R404a.

The indirect suction system of the compressor considered in the analysis implies that the gas from the suction line reaches the internal volume of the compressor shell before entering into the suction system. This design is usually used for cooling the electric motor and also to avoid the possibility of liquid refrigerant reaching the compression chamber. The numerical model considers just 25% of the shell internal volume around the suction system inlet (Fig. 4). At the open surfaces of the solution domain, total pressure and temperature were prescribed with reference to experimental data. At the outlet boundary in the suction chamber, the instantaneous mass flow rate obtained from an auxiliary simulation code of reciprocating compressors was imposed for the transient simulation. On the other hand, the average value of the mass flow rate was prescribed when the flow was analyzed for a steady state condition.

As shown in Fig. 4, a plane of symmetry was adopted to reduce the size of the solution domain. After tests for the assessment of truncation error in the numerical solution, the final mesh was developed with 2.3 million cells. Numerical results for pressure and temperature in the suction system were compared to experimental data for different operating conditions and a reasonable agreement was found (Palomino, 2012).

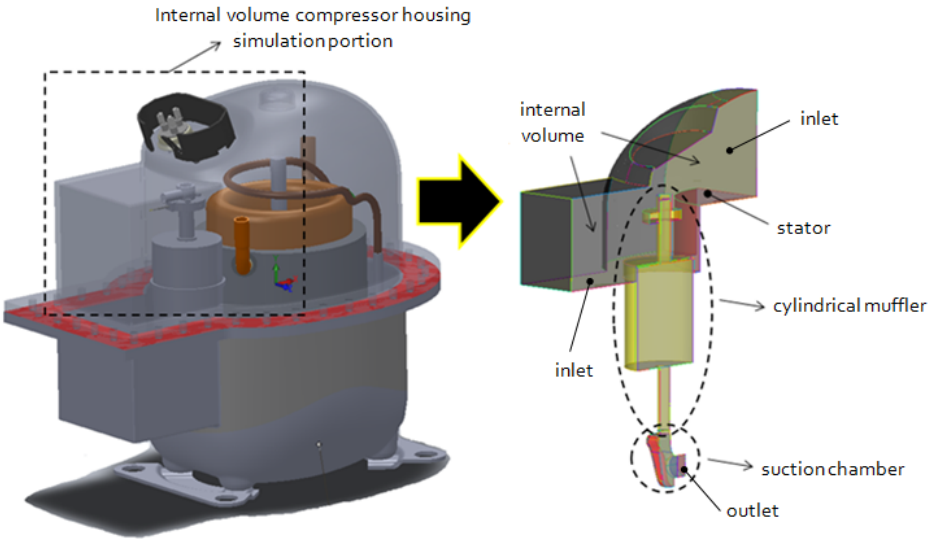


Figure 4. Simulation geometry.

4. RESULTS AND CONCLUSIONS

The compressor was tested under three operating conditions established by changing the pressure in the suction line, resulting three levels of mass flow rate: low mass flow rate (LMF), medium mass flow rate (MMF) and high mass flow rate (HMF). Each operating condition was tested three times and the averaged results for pressure and mass flow rate are shown in Table 1.

Table 1. Compressor operating conditions.

	LMF	**MMF**	**HMF**
Suction pressure [bar]	4.737	5.922	7.423
Discharge pressure [bar]	25.721	25.729	25.359
$\dot{m}$ [kg/h]	**53.4**	**80.6**	**112.4**

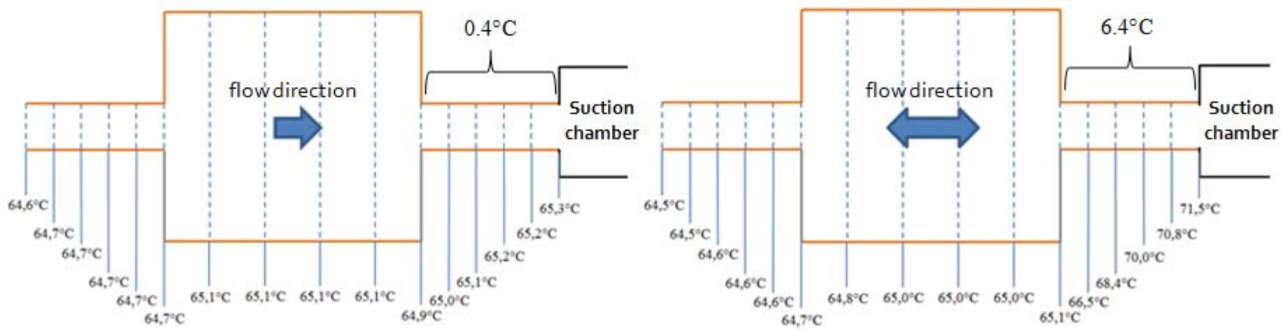
Table 2 shows predictions of heat transfer and temperature variation in the suction system. In addition to the actual transient flow condition, heat transfer was also investigated for the steady state flow regime, established by imposing the average mass flow rate associated with each operating condition. As can be seen in Table 2, heat transfer is slightly increased in the transient situation and the same occurring with the temperature variation between the inlet and outlet of the suction system.

The intensification of heat transfer in the pulsating flow can be associated with two main mechanisms. The first one is related to the flow acceleration field, which makes the thermal boundary layer thinner, and the second is associated with the oscillating flow itself which increases mixing between cold and hot portions of gas in the suction system.

Numerical results for average temperature at several cross sections of the suction system are shown in Fig. 5 for the steady and transient flow regimes (LMF condition). As can be seen, most of the temperature variation occurs along the outlet duct connected to the suction chamber and it is much more significant in the transient flow condition. This is a consequence of the higher wall temperature verified next to the suction chamber.

Table 2. Average heat transfer (Q) and temperature variation ($\mathbf{T_{out} - T_{in}}$) in the suction system.

	Q [W]			**$\mathbf{T_{out} - T_{in}}$ [°C]**	
	Steady	**Transient**	**Variation [%]**	**Steady**	**Transient**
LMF	8.9	9.3	4.5	1.1	6.7
MMF	7.9	8.5	7.6	0.6	5.3
HMF	4.7	4.8	2.1	0.4	4.2



(a) (b)

Figure 5. Temperature variation along the suction system for steady (a) and transient (b) flow regimes; LMF operating condition.

5. REFERENCES

Bauer, W.D., Wenisch, J. and Heywood, J. B., 1998. “Averaged and Time-Resolved Heat Transfer of Steady and Pulsating Entry Flow in Intake of a Spark-Ignition Engine”. Int. J. of Heat and Fluid Flow, v. 19. pp. 1-9.

Blel, W., Le Gentil-Lelièvre, C., Bénézech, T., Legrnd, J. and Legentilhomme, P., 2009. “Application of Turbulent Pulsating Flows to the Bacterial Removal during a Cleaning in Place Procedure - Part 1: experimental analysis of wall shear stress in a cylindrical pipe”. J. Food Engrg., v. 90. pp. 422-432.

Gosney, W.B., 1982. “Principles of Refrigeration”. Cambrige, Inglaterra: Combridge University Press.

Wang, X. and Zhang, N., 2005. “Numerical Analysis of Heat Transfer in Pulsating Turbulent Flow in a Pipe”. Int. J. Heat and Mass Transfer, v. 48, pp. 3957-3970.

Morriesen, A. and Deschamps, C. J., 2011. “Experimental investigation of transient fluid flow and superheating in the suction chamber of a refrigeration reciprocating compressor”. Applied Thermal Engineering, v. 41, pp. 61-70.

Palomino, P. C. R., 2012. “Análise Numérico-Experimental da Transferência de Calor no Escoamento Pulsante em Sistemas de Sucção de Compressores Alternativos”. Master Thesis, Programa de Pós-Graduação em Engenharia Mecânica, Universidade Federal de Santa Catarina, Florianópolis, Brazil.

Ribas Jr, F. A., Deschamps, C. J., Fagotti, F., Morriesen, A. and Dutra, T., 2008. “Thermal Analysis of Reciprocating Compressors: a critical review”. Proc. Int. Compressor Engrg. Conf. at Purdue, West Lafayette, IN, USA, paper 1306.

6. RESPONSIBILITY NOTICE

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