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PREDICTING LEAKAGE OF REFRIGERANT IN THE PISTON-CYLINDER CLEARANCE OF RECIPROCATING COMPRESSORS

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Abstract. *Leakage of refrigerant through the piston-cylinder clearance of small reciprocating compressors can significantly reduce the mass flow rate made available to the refrigeration system. This paper assesses three approaches to predict the leakage of refrigerant in a reciprocating compressor adopted in household refrigeration systems: (i) Poiseuille-Couette model for incompressible fluid flow; (ii) Reynolds equation for compressible fluid flow; (iii) correlations developed for radial leakage in scroll compressors. The effects of the operating condition, clearance dimension, compressor speed and compressibility are also included in the analysis. The results show that the compressible fluid flow formulation is required to predict the leakage and that the piston motion has negligible effect on the results.*

Keywords: *reciprocating compressor, piston-cylinder leakage, leakage modelling.*

1. INTRODUCTION

According to Dupont *et al.* (2019), the refrigeration sector was responsible for 20% of the worldwide total electricity consumption in 2019, with approximately two billion cooling devices being used for domestic refrigeration. Therefore, even small improvements in the design of these devices have significant economic and environmental benefits.

The mechanical compression of vapor is adopted in domestic refrigeration systems, being formed by a reciprocating compressor, an expansion device and two heat exchangers (condenser and evaporator). The clearance between the piston and the cylinder in reciprocating compressor is necessary to reduce friction and wear. On the other hand, this clearance gives rise to leakage of refrigerant from the compression chamber to the compressor internal environment, decreasing the mass flow rate and increasing power consumption. Braga and Deschamps (2018) demonstrated through simulations that the leakage can reduce the volumetric and isentropic efficiencies of the compressor by up to 8% and 22%, respectively, in applications of domestic refrigeration. Hence, the understanding of the effect of different parameters on the leakage through the piston-cylinder clearance is important for the optimization of reciprocating compressors used in small capacity refrigeration systems.

Some studies in the literature focus on the numerical and analytical characterization of leakage through small clearances in compressors. For instance, Ferreira and Lilie (1984) proposed an analytical model to evaluate leakage considering incompressible fluid flow formulation. More recently, Braga and Deschamps (2017) implemented a numerical model based on the Reynolds equation to assess the leakage through the piston-cylinder clearance. It is also worthwhile mentioning the correlations developed by Bell *et al.* (2013) and Pereira and Deschamps (2020) to predict the radial leakage of gas in scroll compressors, which can in principle be extended to reciprocating compressors. These models were adopted to investigate the effect of different parameters (clearance dimension, compressor velocity and operating condition) on the leakage and also to assess their adequacy to predict this phenomenon.

2. LEAKAGE MODELS

Ferreira and Lilie (1984) proposed an analytical model to assess the leakage in the piston-cylinder clearance of a reciprocating compressor based on the balance of pressure and viscous forces. The model adopts the incompressible fluid flow formulation and neglects inertial forces, allowing the prediction of the instantaneous leakage and viscous dissipation at each crank angle. This model will be referred to hereafter as PC model (Poiseuille-Couette model).

Braga and Deschamps (2017) predicted the leakage in the piston-cylinder of a reciprocating compressor by coupling a model for the leakage based on the Reynolds equation and a model for the compression cycle. The following hypotheses were adopted in the leakage model:

- Piston and cylinder are concentric and of rigid walls;
- The clearance is formed by two parallel flat plates, given the small dimension of the clearance;
- Negligible pressure radial variation;
- Temperature and dynamic viscosity are uniform within the clearance for each crank shaft increment;
- Subsonic compressible fluid flow;
- Negligible inertia effects, with viscous and pressure forces being in equilibrium.

The aforementioned hypotheses yield the following simplified form of the Reynolds equation,

$$\frac{\delta^3}{12\mu} \frac{d}{dx} \left(p \frac{dp}{dx} \right) = \frac{\delta}{2} \frac{d}{dx} (pV_p) \quad (1)$$

where p corresponds to the local static pressure, δ is the clearance dimension and x , the direction of the flow. Moreover, μ , ρ and V_p represent the fluid dynamic viscosity, fluid density, and piston velocity, respectively. The finite volume method is employed to solve Eq. (1) and obtain the pressure field. Two boundary conditions are required to solve Eq. (1), pressure inside the compression chamber for the inlet boundary and pressure in the compressor internal environment for the outlet boundary. Therefore, the compression cycle model is solved in a coupled manner with the leakage model in order to determine the boundary condition associated with the compression chamber. A lumped formulation is employed to simulate the compression cycle and details can be found in Braga and Deschamps (2017).

Once the pressure field is known, the mass flow rate through the piston-cylinder clearance is obtained from

$$\dot{m}_l = \pi D \left(-\frac{\rho\delta^3}{12\mu} \frac{dp}{dx} + \frac{\rho V_p \delta}{2} \right) \quad (2)$$

The first term inside the brackets corresponds to the leakage promoted by the pressure difference while the second term represents the contribution of the piston motion. This model will be further referred to as the RL model (Reynolds leakage model).

Bell et al. (2013) proposed a correlation to predict refrigerant leakage in scroll compressors based on the isentropic compressible flow through a convergent nozzle. A correction term was then derived for this correlation by solving a one-dimensional adiabatic compressible flow with friction, area variation and real gas properties. The correlation was developed for a range of pressure conditions, geometrical parameters and working fluids. Even though developed for scroll compressors, Bell et al. (2013) pointed out that their model can be used to predict leakage in other positive displacement compressors, such as rolling-piston and reciprocating compressors. This model will be labeled herein as the BL correlation.

Pereira and Deschamps (2020) developed a correlation to estimate the leakage through radial and axial clearances of scroll compressors based on numerical simulation and dimensionless analysis, varying the operating conditions, clearance geometry and refrigerant fluid. The numerical simulations of the compressible turbulent flow were carried out with the commercial code ANSYS Fluent. Their correlation for the leakage through the radial leakage (PDR correlation) can be easily adapted for reciprocating compressors.

3. RESULTS

The present analysis considered the effect of the clearance dimension, compressor speed and pressure difference on leakage of refrigerant R600a in a reciprocating compressor with swept volume of 3.16 cm³. As shown in Table 1, the pressure difference was varied by keeping the condensing pressure constant (7.62 bar) and changing the evaporating pressure according to the so-called LBP, MBP and HBP operating conditions, established by ANSI/ASHRAE Standard 23.1 for rating the performance of positive displacement compressors used in refrigeration systems.

Figure 1 presents the instantaneous leakage during the compression cycle obtained with the Poiseuille-Couette (PC) model and Reynolds (RL) model for a radial clearance of 5 μm under the LBP operating condition. It is worth mentioning that positive values imply that the refrigerant is leaving the compression chamber, and otherwise in the case of negative values. Despite showing similar trends, the leakage values predicted by the PC model are much higher than those obtained with the RL model. In fact, despite much uncertainty associated with the presence of oil and refrigerant in the clearance, the pressure difference of approximately 7 bar in the case of the LBP condition is likely to bring about compressibility effects on the fluid flow. Therefore, the RL model is considered more suitable than the PC model for the present analysis.

The effect of the compressor speed on the leakage was the next aspect considered. Figure 2 shows the predictions obtained with the RL model for three situations: (i) negligible velocity, corresponding to Eq. (1) with $V_p = 0$; (ii) 3600

rpm; (iii) 5400 rpm. As can be noticed, during the compression process ($0^\circ \leq wt \leq 150^\circ$) and discharge process ($150^\circ \leq wt \leq 180^\circ$), the piston drags refrigerant into the compression chamber through viscous effects, decreasing the leakage. During the expansion process ($180^\circ \leq wt \leq 250^\circ$) and suction process ($250^\circ \leq wt \leq 360^\circ$), the piston motion is in the opposite direction and the leakage is increased. However, the overall effect of the compressor speed on the net leakage in a compression cycle is very small and for the conditions of no velocity, 3600 rpm and 5400 rpm, are equal to 3.69, 3.56 and 3.52 g/h, respectively, a maximum difference of 4.5%. Thus, the effect of the piston velocity can be neglected. The correlations proposed by Bell *et al.* (2013) and Pereira and Deschamps (2020) are possible alternatives to predicting leakage in reciprocating compressors.

Figure 3 shows the net leakage obtained with the RL model and the correlations BL and PD for the LBP, MBP and HBP operating conditions. Despite being developed to predict the radial leakage in scroll compressors, the results of the PD correlation are close to the analytical solution of the RL model. On the other hand, the BL correlation underpredicts considerably the leakage, regardless the operating condition (Fig. 3) or radial clearance of $\delta = 5$ and $13 \mu\text{m}$ (Fig. 4).

Table 1. Operating conditions considered in the simulations for refrigerant fluid R600a.

Operating condition	Evaporating temperature	Evaporating pressure	Suction line vapor density ⁽¹⁾	Condensing temperature	Condensing pressure
LBP	-23.3°C	0.629 bar	1,463 kg/m ³		
MBP	-6.7°C	1.229 bar	2.902 kg/m ³	54.4°C	7.62 bar
HBP	7.2°C	2.011 bar	3.849 kg/m ³		

⁽¹⁾ The suction line temperature is assumed to be 32°C

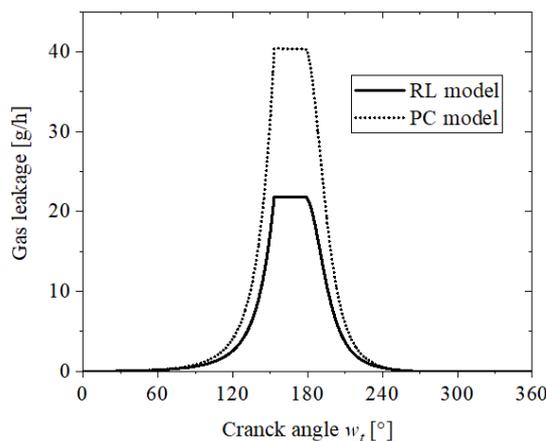


Figure 1. Predictions of leakage following compressible and incompressible fluid flow formulations ($\delta = 5 \mu\text{m}$).

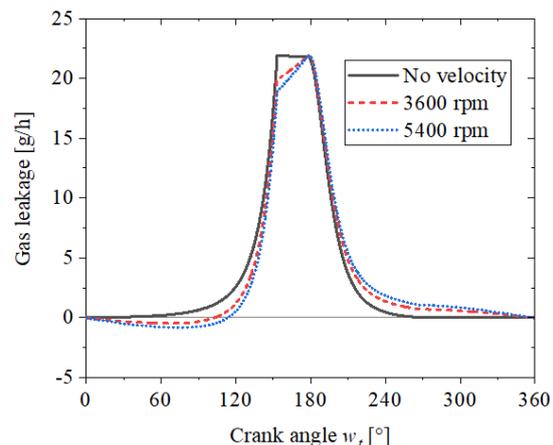


Figure 2. Effect of the piston motion on the leakage ($\delta = 5 \mu\text{m}$).

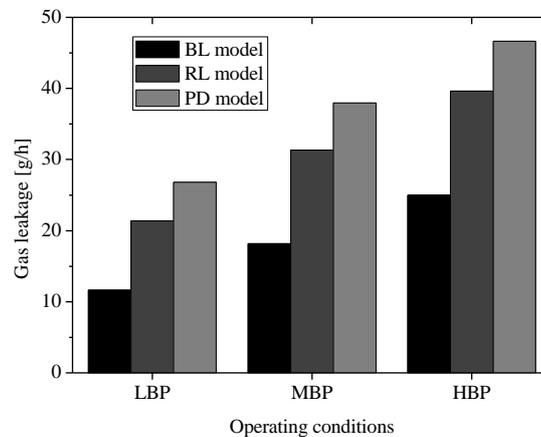


Figure 3. Leakage mass flow rate in relation to the operating conditions ($\delta=9\mu\text{m}$)

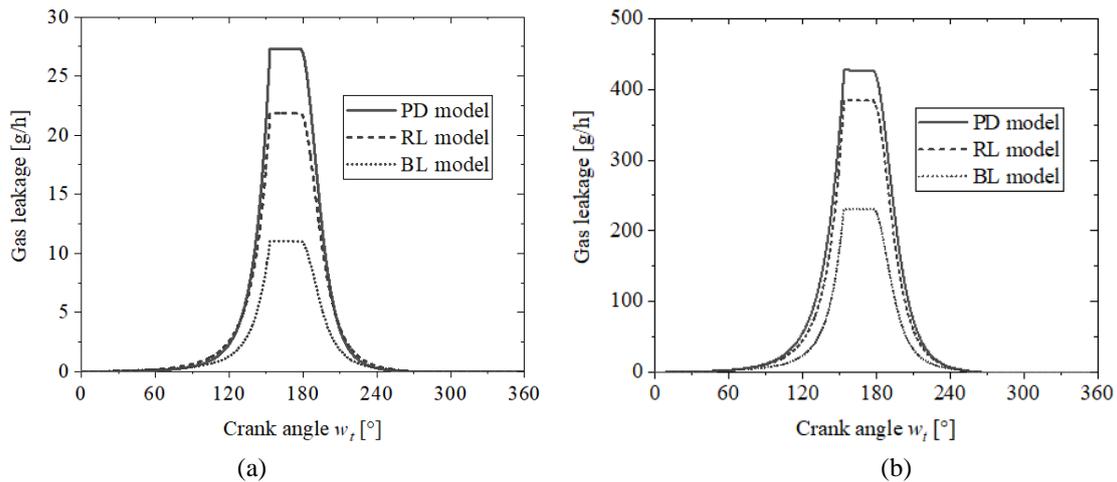


Figure 4. instantaneous leakage mass flow rate in relation to the clearance height (LBP condition):
 (a) $\delta=5\mu\text{m}$; (b) $\delta=13\mu\text{m}$

This shortcoming of the BL correlation is related to the choked flow condition observed by Bell *et al.* (2013) when solving the isentropic flow condition for some working fluids. For instance, the critical pressure ratio of 0.59 is found for the R600a between the crank angles of 130° and 205° . Hence, the mass flow rate in this condition is calculated with reference to the critical pressure ratio for isentropic flow, which is smaller than the actual pressure ratio allowed for the viscous flow in the clearance. As a consequence, the mass flow rate is underpredicted.

As shown in Fig. 3, despite having the lowest pressure difference, the HBP condition gives rise to the highest leakage because the density of the refrigerant inside the cylinder is higher than in the LBP and MBP conditions. In other words, the effect of the density overcomes the effect of the pressure difference. On the other hand, the relative importance of leakage for the three operating conditions can be determined via the ratios between the leakage and the compressor mass flow rate disregarding leakages made available in Fig. 5. It is well known that the volumetric efficiency of reciprocating compressors decreases with the pressure ratio due to the re-expansion of the refrigerant in the clearance volume between the piston head and valve plate. This aspect combined with the fact that the density of the refrigerant in the suction line increases with evaporating pressure results means that leakage is less detrimental when the compressor operates under the HBP condition.

An acknowledged limitation of the models included in this study is that none of them consider the presence of oil in the piston-cylinder clearance. In addition to its lubricating function the oil also contributes to sealing the clearance, therefore, reducing the leakage of refrigerant. It should also be pointed out that the secondary motion of the piston is an important aspect regarding the piston-cylinder leakage and remain to be explored in future studies.

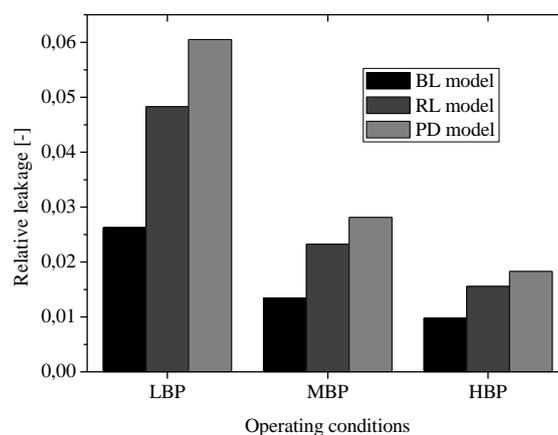


Figure 5 – Relative leakage for in relation to the operating conditions ($\delta=9\mu\text{m}$)

4. CONCLUSIONS

Three approaches were employed to estimate the leakage of refrigerant through the piston-cylinder clearance of a small reciprocating compressor used in household refrigeration systems. One of them is based on the analytical solution of the Poiseuille-Couette fluid flow, whereas in the approach the Reynolds equation is used to take into account fluid compressibility effects. The study also analyzed two correlations (BL and PD) developed for radial leakage in the clearances of scroll compressors, which have been proposed for possible application in the piston-cylinder clearance of reciprocating compressors. Parameters such as the operating condition, clearance dimension, fluid compressibility and compressor speed were analyzed. We found that the compressible fluid flow formulation is required to predict the leakage, whereas the piston motion has negligible effect on the results. Finally, the correlation PD was shown to be the more suitable than the correlation BL for estimates of leakage in the piston-cylinder clearance.

5. ACKNOWLEDGEMENTS

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