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ABSTRACT

Gas leakage through the clearance between piston and cylinder is a major source of thermodynamic inefficiency in reciprocating compressors, therefore, any simulation model should accurately predict its effect on the overall performance. Factors like misalignment between piston and cylinder and components geometric errors are not taken into account in the simpler numerical models usually adopted to estimate the gas leakage. This paper aims to analyze the impact of such simplifications using a three-dimensional computational fluid dynamics (CFD) model, including transient effects resulting from the piston movement as well as actual geometric errors characteristic of the usual manufacturing processes adopted for the household compressor industry. The results are compared to numerical predictions of simpler models and its benefits are emphasized.

1. INTRODUCTION

Gas leakage through the clearance between piston and cylinder is a major source of thermodynamic inefficiency in reciprocating compressors, especially in small and/or variable speed compressors operating at low speeds, in which the cooling capacity is low.

Besides the nominal clearance between piston and cylinder, geometric characteristics resulting from the manufacturing process, as roundness and cylindricity errors, and the dynamics of the piston as well, are factors that can significantly impact the gas leak through the piston-cylinder gap.

Many of these factors are not considered in the numerical models commonly used to estimate the leakage through the piston-cylinder clearance. Analytical models are usually too simplified, while the computational cost of more complex differential models including these effects is still too high. From the experimental point of view, the large number of parts, the high testing time and the experimental uncertainties make this kind of analysis very expensive.

This paper aims to analyze the impact of some numerical simplifications on the leakage prediction using a three-dimensional CFD model. Moreover, an analytical model is used to evaluate the effect of some errors in manufacturing process of cylinder and piston on the efficiency of reciprocating compressors. To accomplish this, two analytical models are evaluated in terms of leakage predictions, comparing to more complex differential CFD models. Using the most appropriate model, the method of Monte-Carlo is used to predict the influence of design specification limits and manufacturing process capability on the variation of compressor cooling capacity and efficiency. Features like piston recess, entrance effects and the presence of oil are not considered at this stage of the study.

2. NUMERICAL MODELS

The gas leakage through the piston-cylinder gap has been numerically analyzed in several studies with different levels of complexity. In the simpler cases, an average leakage is estimated based on the evaporation and condensation pressures (Hatzikazakis and Xin, 2000). In many other works the instantaneous gas leak is calculated throughout the compression process by simplified models. Some of these works ignore the viscous terms, characterizing the leakage as an isentropic, fully developed flow in a duct (Manepatil and Tiwari, 2006). In others, the inertial forces are ignored and the model for viscous flows between two parallel plates is used to estimate the leakage (Ferreira and Lilie, 1984). There are also studies that take into account both the inertial and viscous terms, showing good agreement with experimental data for rolling piston compressors (Yuan et al., 1992). Furthermore, the works mentioned before assume the piston is centered with respect to the cylinder. The work of Prata et al. (1998) demonstrates a significant piston tilt during compressor operation, raising doubts about the parallel plate assumption for the gas leakage modeling in the piston-cylinder gap.

In this paper two analytical models were evaluated. The first, described in Ferreira and Lilie (1984), assumes a steady, fully plates, as

$$\dot{m} = \pi.D.h.\rho_1\left[V_p\frac{1-K^2+2K^2.\ln(K)}{2.\ln(K).(1-K^2)} + \frac{(P_1-P_2)(D/2)^2}{8\mu L}\left(\frac{1-K^4}{1-K^2}+\frac{1-K^2}{\ln(K)}\right)\right] \quad (1)$$

where,

$$K = \frac{D}{D+2.h} \quad (2)$$

The second is presented in details in Zuk and Smith (1969) and assumes the flow between flat plates as compressible, viscous and isothermal:

$$\dot{m} = \frac{\pi.D.h^3.\rho_1.P_1}{24.\mu.L}.\left(1-\frac{P_2^2}{P_1^2}\right) \quad (3)$$

In the equations above, D is the piston diameter, h is the piston-cylinder clearance, ρ_1 is the gas density, V_p is the instantaneous piston velocity, P_1 is the pressure inside the cylinder, P_2 is the housing pressure, μ is the fluid viscosity and L is the piston sealing length.

By means of a commercial CFD package (Ansys CFX, 2014), two- and three-dimensional models are employed to verify the ability of analytical models in estimating the gas leakage through piston-cylinder clearance. Compressibility and unsteady effects as well as piston lateral motion and piston tilt are the main effects hereafter analyzed. The computational domain includes only the region of the gap. Representative values of gas pressure and gas temperature inside the cylinder during the compression process are prescribed at the gap entrance. The evaporation pressure is prescribed at the gap outlet. The flow is considered laminar due to the small clearance. It is assumed that the refrigerant behaves as a real gas and its properties are calculated via Aungier Redlich-Kwong equation of state. Moreover, a high-resolution spatial interpolation scheme and a Second Order Backward Euler method for unsteady cases are used. Tests were carried out to determine the appropriate mesh refinement and time advance in terms of computational cost and accuracy.

3. RESULTS AND DISCUSSIONS

The following analyses were carried out for a variable speed compressor, typically applied in household refrigerators. The compressor has 9cm³ displacement and is designed to operate with R600a in a speed range from 1200 to 4500rpm. All results are for an operating condition of -23.3ºC/38.0ºC.

Firstly, effects of compressor speed, piston lateral motion and piston tilt are assessed using two- and three-dimensional models previously detailed. Finally, the impact of piston and cylinder dimensional variability on the compressor cooling capacity and efficiency is analyzed in function of the capability of the manufacturing process and roundness errors.

3.1 Analytical models: compressibility effects

The first analysis consists in comparing the analytical and CFD models in a steady-state condition, considering that the piston is stationary and centered with respect to the cylinder bore. Hence, the problem is simplified to a two-dimensional flow and the boundary conditions are constant. Just for comparison, CFD solution for incompressible flow is also considered.

As can be seen in Table 1, both analytical models provided results in good agreement with the respective results from two-dimensional models, with differences within 10%. On the other hand, it is clear the impact that incompressible flow assumption can have on gas leakage estimation. Given the nature of the flow, the assumption of incompressibility is not appropriate, and so only the models for compressible flow are considered in the following analyzes.

Table 1: Relative gas leakage in the piston-cylinder clearance estimated by different numerical models.

Model	Gas leakage* [-]
CFD (compressible)	1
CFD (incompressible)	1.87
Analytical (compressible)	1.07
Analytical (incompressible)	1.94

3.2 Piston velocity effects:

The effect of piston movement on the gas leak was initially analyzed via a two-dimensional model assuming a constant speed on one of the walls and fixed pressure difference (steady-state analysis). Figure 1 shows the difference on results of leakage between the analytical and two-dimensional models for different wall velocities. In the coordinate system here adopted, positive wall velocities represent the compression process. In this case, for the compressor and conditions under analysis, the analytical model predicted a gas leakage around 20% lower than the two-dimensional model at velocity of 4m/s. On the other hand, a difference exceeding 30% was observed at the maximum speed when the wall velocity represents the expansion process.

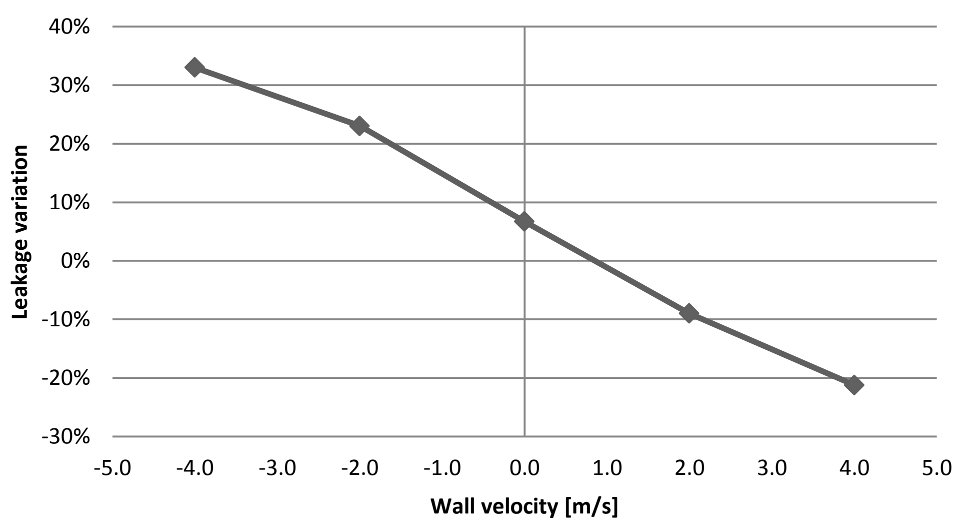


Figure 1: Effect of wall velocity on the gas leak through the clearance.

The following analysis includes the effect of transient motion of the piston and the pressure variation inside the compression cylinder. The instantaneous velocity of the piston is calculated as a function of the geometrical parameters of the mechanism and compressor speed. The instantaneous pressure and temperature inside the compression chamber are calculated in advance by a simplified numerical model and thus set as boundary conditions at gap inlet. Pressure is kept constant at outlet. Some compression cycles are simulated until the solution reaches a periodic transient state.

Figure 2 shows the instantaneous gas leak throughout a compression cycle, predicted by the analytical and two-dimensional models at 20 Hz. The analytical model predicts smaller leakage values during the compression of the gas. On the other hand, part of residual gas in the clearance volume returns to the compression chamber during the expansion process. As consequence, higher leakage values are estimated by the analytical model. The results are very close during the suction process when the pressure difference is low. Despite the occasional discrepancies, the integration of mass flow rate reveals a good agreement between the analytical and differential models. As seen in Figure 3, differences are within 12% for the piston-cylinder clearances and compressor speeds considered.

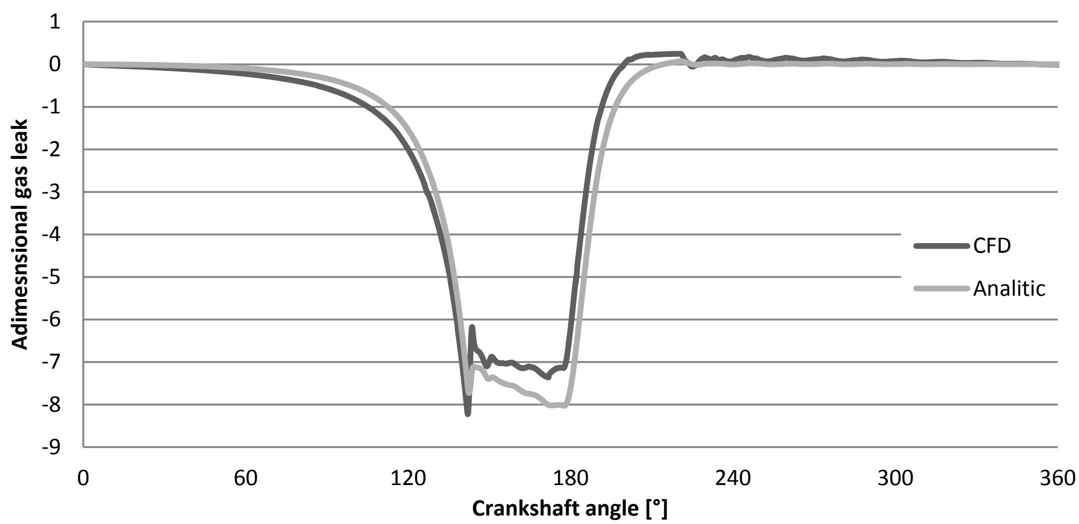


Figure 2: Instantaneous mass flow rate through the piston-cylinder gap.

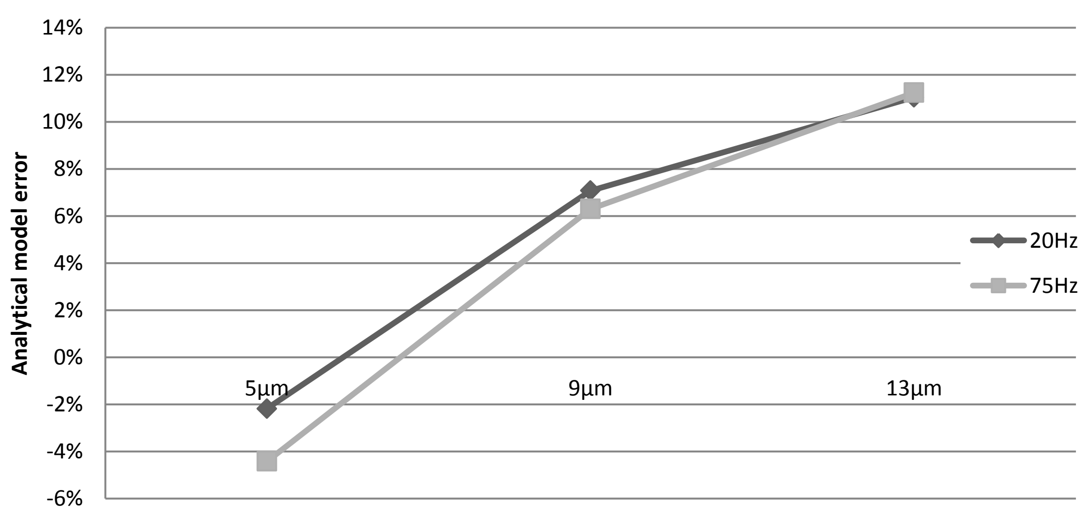


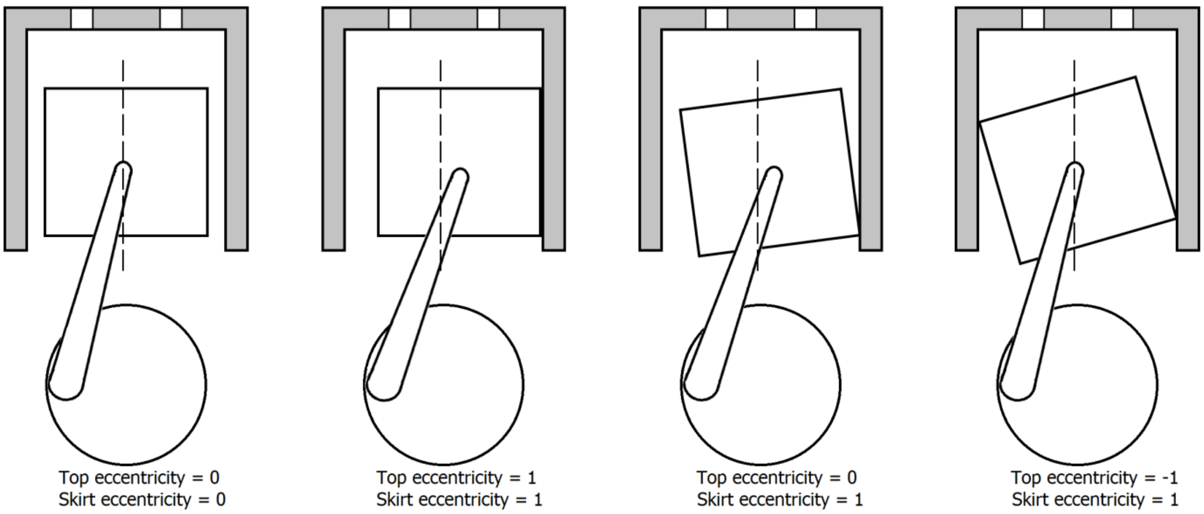
Figure 3: Influence of clearance and compressor speed on the net gas leakage estimation.

3.3 Effect of piston secondary motion:

In the previous analyses, piston was considered aligned and centered to cylinder bore, resulting in a uniform clearance. However, this assumption may result significant errors in the estimation of the gas leakage, due to its cubic dependence on the clearance. The secondary motion of piston is composed by a translation perpendicular to cylinder and piston pin axis (piston lateral motion), and a rotation about piston pin axis (piston tilt).

Due to the geometric characteristics of the problem, a three-dimensional model was adopted assuming a steady-state flow and stationary piston. In these analyses piston tilt and piston lateral motion are characterized by varying the eccentricity of piston relative to the bore separately for top and skirt, as illustrated in Figure 4. Analyses were carried out for three nominal clearances: 5, 9 and 13µm. Leakage was also estimated analytically by integrating equation (1) along the perimeter of the piston:

$$\dot{m} = \frac{\pi.D.\rho_1.P_1}{24.\mu.L}.\left(1-\frac{P_2^2}{P_1^2}\right).\int_0^{2.\pi} h(\theta)^3.d\theta \qquad (4)$$



Case A Case B Case C Case D

Figure 4: Piston positions analyzed.

Figure 5 shows the variation of leakage in relation to the reference case, which does not consider the secondary motion of piston (Case A). As it can be seen, piston lateral motion is responsible for a major impact on leak (Case B), increasing it in about 130% when piston lateral surface is in total contact with cylinder bore. Leakage seems to decrease in relation to the worst case as the piston top tilts in the opposite direction. When top piston is centered to the cylinder (Case C) gas leak is 5% higher than the reference case for the conditions here analyzed. When piston top is in contact with the opposite side of cylinder bore, leak is around 30% higher than reference case.

These results show how important the secondary motion of piston can be on the estimative of gas leak through the piston-cylinder clearance. Furthermore, the analytical model here adopted seems to predict leak correctly on the extreme cases (totally centered and totally eccentric), situation in which clearance is constant along the cylinder bore axis.

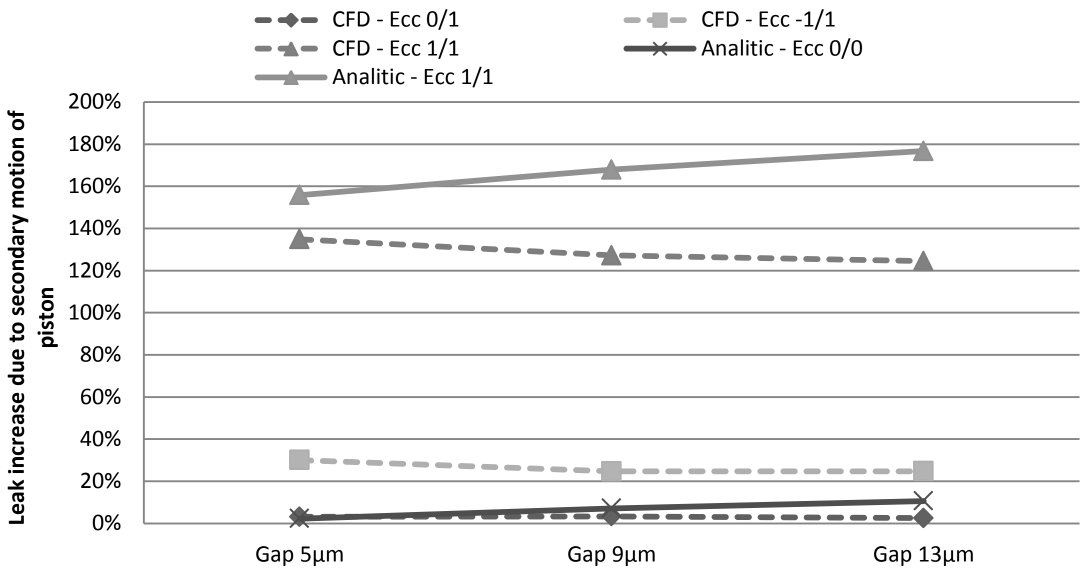


Figure 5: Effect of secondary motion of piston on the gas leak.

3.4 Effect of roundness errors and clearance variation on compressor performance

Although the effect of piston tilt is very important on leak predictions, the analytical model is here used to analyze the impact of piston and cylinder roundness errors as well as clearance variation on the compressor performance in the extreme cases: Case A and Case B.

The clearance between the piston and cylinder varies due to form errors here divided into variation of the average diameter and circularity of the components. In this work, the average diameter of the cylinder and piston are characterized by the manufacturing process capability (Cp), assuming a normal distribution around the nominal design value. The circularity, on the other hand, is characterized by a uniform random distribution. These assumptions are used to assess the numerical analysis methodology, and do not necessarily represent actual or typical manufacturing situations.

The analytical model is coupled to a lumped formulation to calculate the pressure and temperature of the gas during a compression cycle. Hence, the effect of the leak on the capacity and performance of the compressor is assessed. Moreover, the viscous power loss in the piston-cylinder gap is also estimated as a function of the clearance (equation (5)), in which the minimum clearance is characterized by Ra values of the surfaces of the piston and cylinder.

$$F_{visc} = \int_0^{2\pi} \left(\frac{\mu_{oil} V_p}{h(\theta)} \frac{LD}{2} \right) d\theta \tag{5}$$

The results presented hereafter were calculated for a compressor operating at 20Hz. The lower and upper limits for piston-cylinder clearance are 5 and 13µm. Different roundness errors and process capabilities are analyzed. For each analysis, 2000 random samples are generated as a function of process variables to estimate the mean and standard deviation of cooling capacity and COP by the method of Monte-Carlo.

Figure 6 shows the impact of the process capability (Cp) on the capacity and efficiency of the compressor, assuming a normal distribution, centered piston and no roundness errors. As expected, the variability significantly increases as the capability of the manufacturing process decreases. Moreover, it is observed that distributions deviate from a normal distribution, showing a left tail, especially for low Cp. This property is due to the cubic dependence of leakage with the clearance.

Cooling capacity and COP distributions are similar in shape when roundness and piston lateral motion (eccentric piston) are taken into account. Thus, they are here omitted. However, results are summarized in terms of average values and standard deviations.

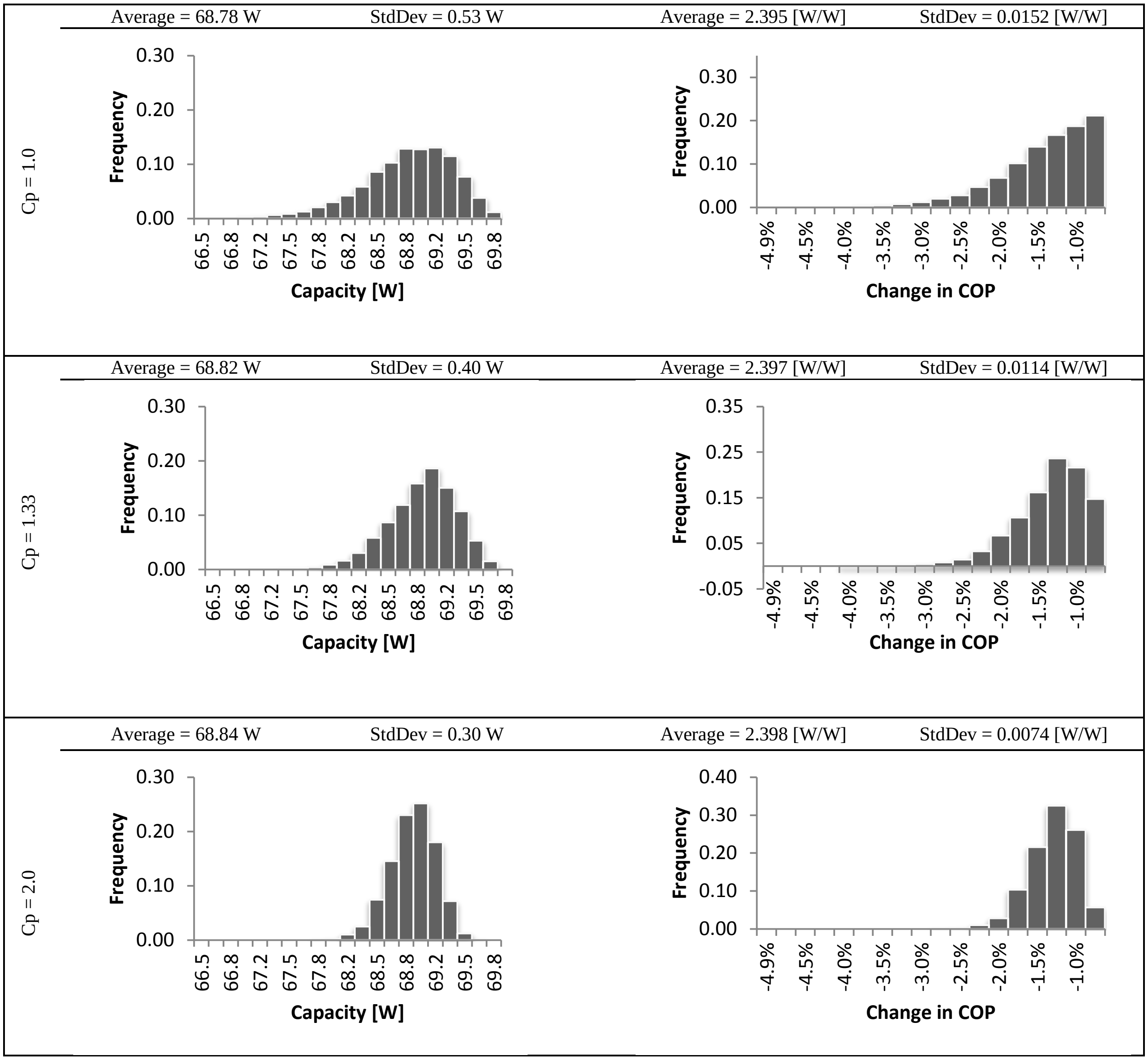


Figure 6: Effect of process capability (Cp) on compressor performance: Centered piston; no roundness errors.

Tables 2 and 3 present the effect of process capability and piston lateral motion on cooling capacity and COP variability, respectively. The process capability seems to have small influence on the average values. As expected, its impact is higher on the standard deviation (variability). Moreover, piston lateral motion decreases both average cooling capacity and average COP by about 3%, increasing variability significantly.

The effect of roundness on compressor performance is shown in Tables 4 and 5. For academic purposes, it is assumed that roundness of piston and cylinder bore are the same but with random uniform distributions. Moreover, piston-cylinder average clearance follows a normal distribution with Cp = 1.33 within the limits of 5 and 13μm. Again, the piston lateral motion presents the major impact on the performance, reinforcing the importance of a good understanding of piston dynamics to the estimative of leakage through the piston-cylinder clearance. For the compressor here analyzed, roundness showed a small impact on cooling capacity and COP, even in terms of variability.

Table 2: Effect of process capability and piston lateral motion on cooling capacity variability.

Cp	Centered piston		Eccentric piston	
	$\overline{Q_e}$ [W]	σ [W]	$\overline{Q_e}$ [W]	σ [W]
1	68.78	0.53	66.94	1.31
1.33	68.82	0.40	67.06	0.98
2	68.84	0.30	67.10	0.63

Table 3: Effect of process capability and piston lateral motion on COP variability.

Cp	Centered piston		Eccentric piston	
	$\overline{COP}$	σ	$\overline{COP}$	σ
1	2.39	0.015	2.32	0.042
1.33	2.40	0.011	2.32	0.032
2	2.40	0.007	2.32	0.020

Table 4: Effect of roundness error and piston lateral motion on cooling capacity variability.

Roundness [μm]	Centered piston		Eccentric piston	
	$\overline{Q_e}$ [W]	σ [W]	$\overline{Q_e}$ [W]	σ [W]
0	68.82	0.40	67.06	0.98
1.5	68.76	0.40	66.97	1.01
3	68.60	0.42	66.87	1.03

Table 5: Effect of roundness error and piston lateral motion on COP variability.

Roundness [μm]	Centered piston		Eccentric piston	
	$\overline{COP}$	σ	$\overline{COP}$	σ
0	2.40	0.011	2.32	0.032
1.5	2.39	0.011	2.31	0.032
3	2.39	0.012	2.30	0.034

These behaviors may be different for other operating conditions and geometries. Table 6, for instance, shows that roundness has a major relative impact on COP variability when piston-cylinder clearance tolerance limits are reduced, although in absolute terms variability increases with the increase of clearance limits. At last, it should be noted that roundness also defines the average clearance between piston and cylinder, having thus an indirect impact on leakage.

Table 6: Effect of roundness error and piston-cylinder clearance tolerance limits on COP variability: Eccentric piston.

Roundness [μm]	5 – 9μm		5 – 13μm	
	$\overline{COP}$	σ	$\overline{COP}$	σ
0	2.37	0.007	2.32	0.032
1.5	2.36	0.010	2.31	0.032
3	2.34	0.017	2.30	0.034

4. CONCLUSIONS

This paper analyzed the impact of some numerical simplifications on the leakage prediction using a three-dimensional CFD model. Moreover, an analytical model was used to evaluate the effect of some errors in manufacturing process of cylinder and piston on the efficiency of reciprocating compressors. The following observations stand out:

- Compressibility effects are important on the modeling of gas leakage through piston-cylinder clearance;
- An analytical model for compressible, viscous and isothermal flow between parallel plates provided good leakage estimative for cases with no piston tilt;
- A good understanding of piston dynamics is necessary to the estimative of leakage through the piston-cylinder clearance, especially the piston tilt movement;
- The process capability seems to have a small influence on the average values of compressor cooling capacity and efficiency; the impact on variability is higher when piston is eccentric to cylinder bore;
- The direct effect of roundness on leakage was small for the compressor analyzed.

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