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SURFACE OF FLOW AND FORCE EFFECTIVE AREAS APPLIED TO DEVELOPMENT OF RECIPROCATING COMPRESSORS

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ABSTRACT

The concept of flow and force effective areas is extensively used to simulate the pressure-volume diagram helping to calculate the thermodynamic power consumption of the discharge process. The main advantage is to permit analysis in different application conditions in few seconds. Commonly, the discharge flow and force effective areas are evaluated in CFD steady state analysis with different discharge valve positions resulting in curves relating effective areas with valve displacement.

This work presents a detailed study of the discharge process and proposes the use of response surfaces methodology to represent the discharge effective areas indicating a better reproduction of the physical phenomena, mainly in the region of the end of discharge process. The proposed method was compared simultaneously with the curve's effective area and experimental results.

1. INTRODUCTION

The increasing demand by reducing energy consumption promotes a great challenge to the researchers responsible for the development of reciprocating compressors: to understand increasingly the physical phenomena that governs the compressor operation, and thus reduce energy losses continuously.

The simulation of reciprocating compressors is one of the most used tools in the process of optimization of the valve system. Several methods use the concept of flow and force effective areas to determine the mass flow through the discharge and suction orifices, as well as forces acting on the valves. Initially, the effective areas were obtained empirically. Schwerzler *et al.* (1972) developed an analytical method to obtain the effective areas, through the use of equations that depended only on the geometry of the valves. Driessen (1986) examined experimentally the influence of the geometry of valves and orifices on the effective areas. Ribas (2004) developed a differential model to calculate the fluid properties inside the cylinder of reciprocating compressors during the compression, when the piston is close to the valve plate. Pereira (2006) developed a computational model using the finite volume method to analyze the discharge system of a reciprocating compressors. In most studies the values of effective areas are only plotted as a function of the valve opening.

In this study, a detailed analysis of the discharge process was carried out and it was represented by the concept of flow and force effective areas obtained by using of software Ansys CFX Version 12.0.1 (2009) and equations (1) and (2), respectively. The use of statistical tools showed the importance of the position of the piston on the results of effective areas. Finally, the differences between effective areas obtained in the form of curves and surfaces were compared by simulating the p-V diagram of a compressor.

$$FwEA = \frac{\dot{m}}{P_{us} \cdot \sqrt{\frac{2\gamma}{(\gamma-1)RT_{us}}} \cdot \sqrt{\left(\frac{P_{ds}}{P_{us}}\right)^{\frac{2}{\gamma}} - \left(\frac{P_{ds}}{P_{us}}\right)^{\frac{(\gamma+1)}{\gamma}}}} \quad (1)$$

$$FcEA = \frac{F_v}{\Delta P} \quad (2)$$

2. CURVE EFFECTIVE AREAS

The effective areas can be obtained by CFD simulations in steady state and incompressible flow considering various valve openings. The simulations are performed until larger valve openings do not result in significant variations in the flow effective area as shown in Figure 1. In the present study a compressor, named compressor A, was modeled with cylinder diameter of 22.5mm and discharge orifice diameter input of 5mm and output of 6mm, operating condition at -23.3^{0}C / 40.5^{0}C (evaporation temperature/condensation temperature). All dimensionless numbers were obtained by dividing them by the maximum value of each variable.

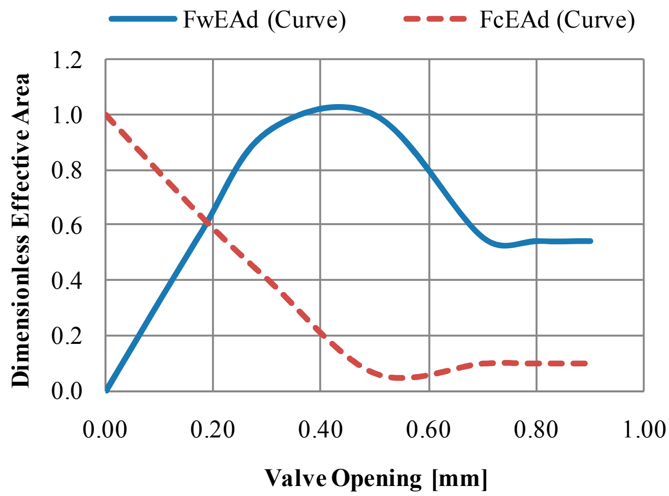


Figure 1: Curves of dimensionless flow and force effective areas as a function of crank angle

Using experimental values of the dynamics of the discharge valve, it is possible to graph the flow and force effective areas as a function of crank angle, as shown in Figure 2.

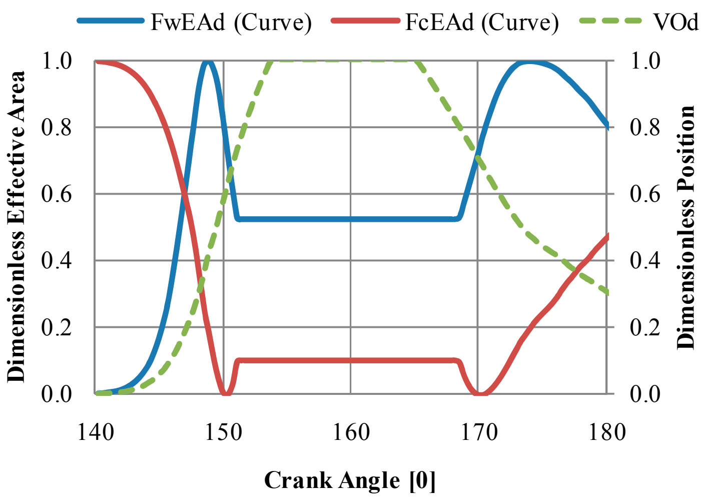


Figure 2: Curves of flow and force effective areas as a function of crank angle

The behavior of the flow effective area may be divided into 4 stages: (i) 140-150^0 > FwEA increased as a result of opening the discharge valve, (ii) 150^0 > FwEA reduction due to the recirculation caused by large valve openings and the restriction of the flow at the entrance of the orifice caused by the proximity of the piston, (iii) 150-170^0 > the discharge valve remains opened limited by the presence of a stopper and the values of flow effective area remains constant and (iv) 170-180^0 > the valve begins to close with an increase and subsequent decrease of the flow effective area. From the moment the piston starts to move away from the upper piston position, no longer makes sense to evaluate the behavior of the flow effective area, but the behavior of the backflow effective area. The subject of backflow will not be addressed in this study. The last two steps seem inconsistent, since even though the discharge valve is opened, the flow effective area should decrease due to the restriction of the approach of the piston and until the closing of the discharge valve.

3. SURFACE EFFECTIVE AREAS

Aiming to identify what the relevant parameters are on the discharge effective areas, a statistical experiment known as central composite design was used. According to Montgomery (1997), CCD is the most commonly used experiment to generate response surfaces by means of second order models. The great advantage of the CCD experiment instead of the full factorial one is the amount of required runs, reducing a case of 3 factors in 3 levels from 27 to 15 configurations, i.e., a reduction in computational time by 44%.

The three factors analyzed were the discharge valve opening, the chamber height (distance of the piston from the valve plate) and speed of the piston. To define the maximum and minimum levels of each of the three factors above, we used experimental data from compressor A, shown on Figure 3.

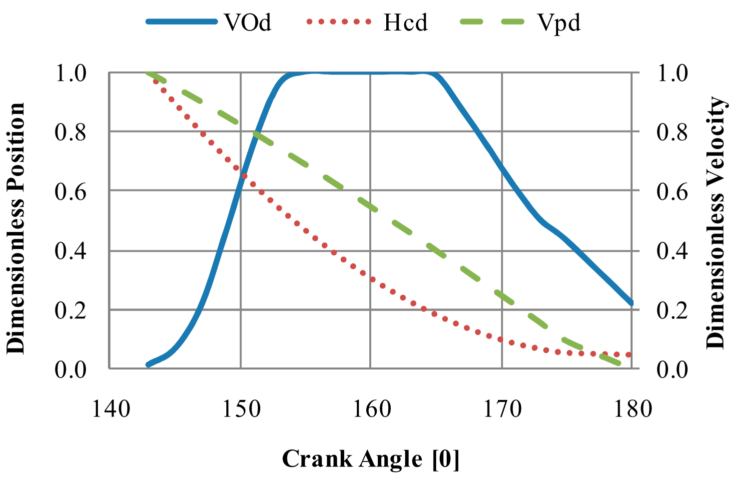
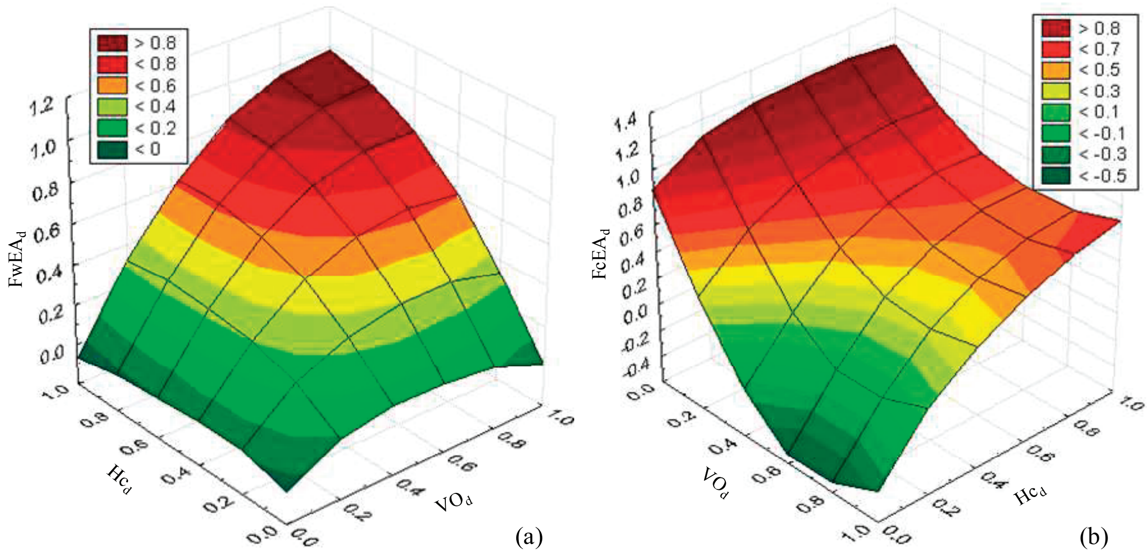


Figure 3: Experimental data of compressor A

In both analysis of variance the relevant factors were the valve opening, the chamber height and the interaction between them. The piston speed showed no significant influence on the effective areas. This result may be due to the steady state analysis and incompressible flow. The opening of the discharge valve is the most important factor, followed by the chamber height and then by the interaction between them.

Since two factors are important for the behavior of discharge effective areas, it was necessary the visualization by the use of response surfaces. Figures 4(a) and 4(b) present the response surfaces obtained through the CCD experiment for the flow and force effective area, respectively. The piston speed was kept constant at its mean value, 0.80m/s.

Looking at Figure 4, it is possible to verify that for small values of chamber height, independent of the discharge valve opening, the values of flow effective area are generally low. Since this same behavior is observed for small valve openings, the conclusion is that the valve dominates the beginning of the discharge process and from certain values of chamber height, the piston (chamber height) begins to dominate the pressure drop in the discharge process.

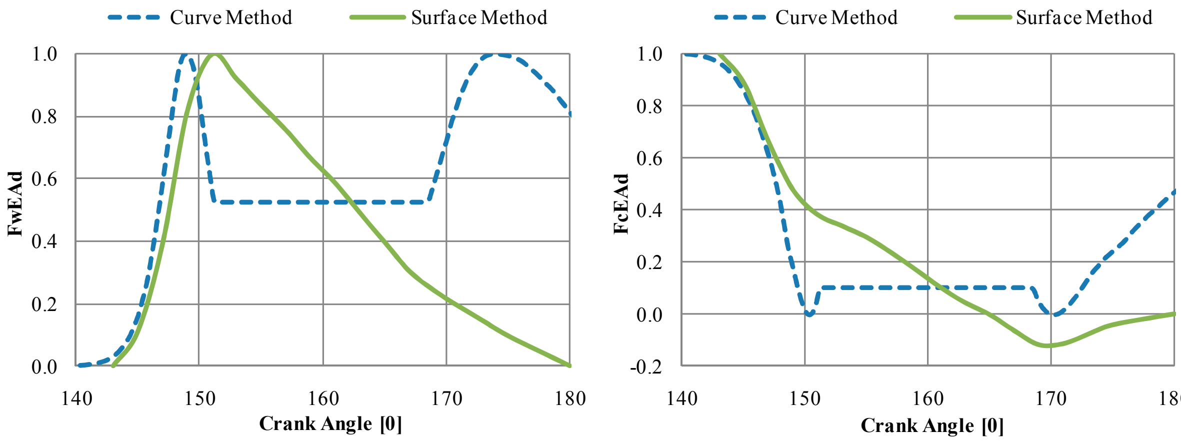


(a) (b)

Figure 4: Surface Flow (a) and Force (b) Effective Area

4. COMPARISON: CURVE AND SURFACE EFFECTIVE AREAS METHOD

In Figure 5 it is possible to compare the results of flow and force effective areas of compressor A plotted as a function of crank angle using the methods of curve and surface. The difference between the two methods starts soon after the flow effective area reaches its highest value, where the method of curve indicates a rapid decline followed by a plateau and presents another elevation posteriorly. The surface method shows that after its maximum value, the discharge flow effective area decreases until zero when the piston reaches its upper position.



(a) (b)

Figure 5: Flow (a) and Force (b) Effective Area: Curve x Surface Method

It is expected that the use of response surfaces of effective areas impact on changes in the p-V diagram, especially in the second half of the discharge process, where the curve method does not predict well the pressure drop at the entrance of the orifice. Figure 6 shows the p-V diagram in the region of the discharge process for both methods obtained by simulation of the compressor A in an in-house software that uses the information of effective areas as input to solve the mass flow passing through the holes and the dynamics of the valves.

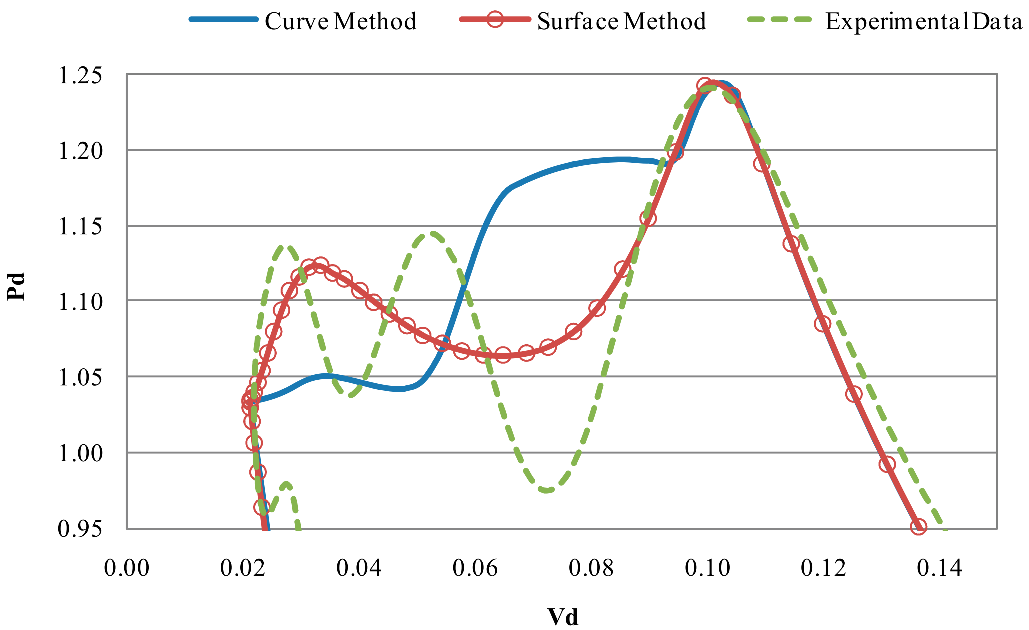


Figure 6: p-V diagram: discharge process

In general, the result of simulation using the method of surface effective areas showed better agreement with experimental data than when using the method of curves, especially from 0.1 to 0.02 of the dimensionless volume, where the dominant restriction on the flow is characterized by small values of chamber height.

5. CONCLUSIONS

The use of discharge effective areas as input for simulations of reciprocating compressors applied in household refrigeration was evaluated using two methods: curve and surface of flow and force effective areas. In the first case, the effective areas are influenced directly only by the discharge valve opening and indirectly by the compression chamber height. In the case of surfaces, the effective areas have direct dependence simultaneously with both the valve opening and the chamber height. In evaluating the results of simulations on p-V diagrams, it was noted that the main differences between the two methods occurred from 0.1 of the dimensionless volume until smaller volumes, which corresponds to 60% of the time of the discharge process for the evaluated condition.

Therefore, the use of surface to evaluate the discharge effective areas proved to be an important tool to enhance understanding of physical phenomena that govern the discharge process of reciprocating compressors.

NOMENCLATURE

CFD	Computational Fluid Dynamics	(-)
FwEA	Flow Effective Area	(m^2)
FcEA	Force Effective Area	(m^2)
$\dot{m}$	Mass Flow	(kg/s)
ρ	Density	(kg/m^3)
F_v	Total Force on Discharge Valve	(N)
ΔP	Upstream-Downstream Pressure Difference	(Pa)
CCD	Central Composite Design	(-)
VO	Discharge Valve Opening	(m)
Hc	Chamber Height	(m)
Vp	Piston Velocity	(m/s)
V	Volume	(m^3)

P	Pressure	(Pa)
γ	Specific Heat Ratio	(-)
R	Refrigerant Gas Constant	(m^3Pa/Kmol)

Subscripts

d	dimensionless
us	upstream
ds	downstream

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