COB-2021-1170

THERMODYNAMIC SIMULATION OF AN ELECTRIC VARIABLE SPEED SCROLL COMPRESSOR FOR AUTOMOTIVE AIR-CONDITIONING

Vinicius Pereira Dall'Agnol Alves
Ernane Silva
TEG Thermofluids Engineering Group, Universidade Federal de Santa Catarina, 89219600, Joinville, SC, Brazil
ernane.silva@teg.ufsc.br (corresponding author)

Abstract. *Nowadays, electric vehicles are seen as an alternative to reduce greenhouse gas emissions and as such it is expected that at least 20% of the whole world's road transportation will be electrified by 2030. However, there are still many technological challenges to overcome in this field with the need to increase mileage as one of the most significant, requiring the development of novel materials and a more efficient use of energy. In this sense, it is important to look at the vehicle subsystems and identify opportunities to reduce energy consumption. The air-conditioning system, for instance, is of particular importance given that it is generally the largest subsystem of a vehicle and responsible for a significant amount of the energy consumption. Currently, electric vehicle manufacturers adopt electric variable speed scroll compressors in such systems due to their high efficiency and low noise. Understanding how this component is affected by different physical phenomena, such as leakage and heat transfer, according to the operating condition is of paramount importance to further improve the efficiency of electric vehicles. This paper describes the thermodynamic simulation of an electric scroll compressor used for automotive air conditioning applications using a comprehensive compressor simulation model. The numerical model is based on the conservation of mass and energy inside the compression chamber with correlations for leakage and heat transfer. The mass flow rates from the suction plenum and through the discharge orifice are treated as isentropic flows with adjustment parameters to better describe the real condition. The results include predictions of mass flow rate, discharge temperature and indicated power for different operating conditions and different speeds. The results show that an increase in discharge pressure increases the discharge temperature and decreases the mass flow rate. Different rotational speeds also had a great impact in mass flow rate and discharge temperature results. A comparative analysis including instantaneous leakage and heat transfer rates is also provided. The numerical model is able to make predictions at low computational cost, which makes it useful for optimization purposes.*

Keywords: *automotive air-conditioning, scroll compressor, thermodynamic analysis*

1. INTRODUCTION

Nowadays, electric vehicles are seen as an alternative to reduce greenhouse gas emissions and as such it is expected that at least 20% of the whole world's road transportation will be electrified by 2030 (COP21, 2015). However, there are still many technological challenges to overcome in this field with the need to increase mileage as one of the most significant, requiring the development of novel materials and a more efficient use of energy. In this sense, it is important to look at the vehicle subsystems and identify opportunities to reduce energy consumption. The air-conditioning system, for instance, is of particular importance given that it is generally the largest subsystem of a vehicle and responsible for a significant amount of the energy consumption. Currently, electric vehicle manufacturers adopt electric variable speed scroll compressors in such systems due to their high efficiency and low noise. Understanding how this component is affected by different physical phenomena, such as leakage and heat transfer, according to the operating condition is of paramount importance to further improve the efficiency of electric vehicles.

The thermodynamic modelling of scroll compressors follows the same approaches adopted for other positive displacement machines. In this sense, comprehensive models are normally preferred in the preliminary design stages, when optimization routines and sensitivity analyses are required. This stems from the fact that these models provide a reasonable accuracy for mass flow rate and power consumption, comparable to those found in manufacturers' datasheets, at low computational cost. Besides, such models allow a geometric characterization of the machine including all physical aspects of interest and can be seen as an alternative in-between the extremely simple polynomial compressor maps (AHRI, 2020) that rely exclusively on experimental data and the complex high-fidelity CFD analyses (Pereira and Deschamps, 2017; Pereira and Deschamps, 2020).

In this regard Chen *et al*. (2002a) described a thermodynamic model for the compression process of scroll compressors, which was based on the solution of the mass and energy conservation equations in the suction, compression and discharge chambers. Sub-models for the flow of gas during the suction and discharge processes and to account for leakage and heat transfer were also considered. A thermal model to predict the temperature of the compressor internal components based on the lumped capacity method was coupled later (Chen *et al*., 2002b). The authors concluded that the model was capable of predicting the mass flow rate, power consumption and discharge temperature very close to measured data. Bell *et al*. (2012a) extended this model for compressors and expanders with liquid flooding by including the treatment of mixture properties and two-phase flow pressure drop. The model was validated against experimental data with good agreement for both the compressor and expander (Bell *et al*., 2012b). Diniz *et al*. (2015) adopted a one-dimensional finite volume model to describe the conduction heat transfer through the scroll wraps and found that this effect reduces slightly the discharge temperature. Pereira and Deschamps (2017, 2020) proposed new correlations for heat transfer and leakage in scroll compressors based on numerical analyses.

Given that comprehensive models are widely used for scroll compressor simulations and provide accurate results, this paper describes the use of such a tool for the thermodynamic simulation of an electric scroll compressor used for automotive air conditioning applications. Results of mass flow rate, discharge temperature and indicated power for different discharge pressures and speeds are compared and instantaneous heat transfer and leakage rates are also provided.
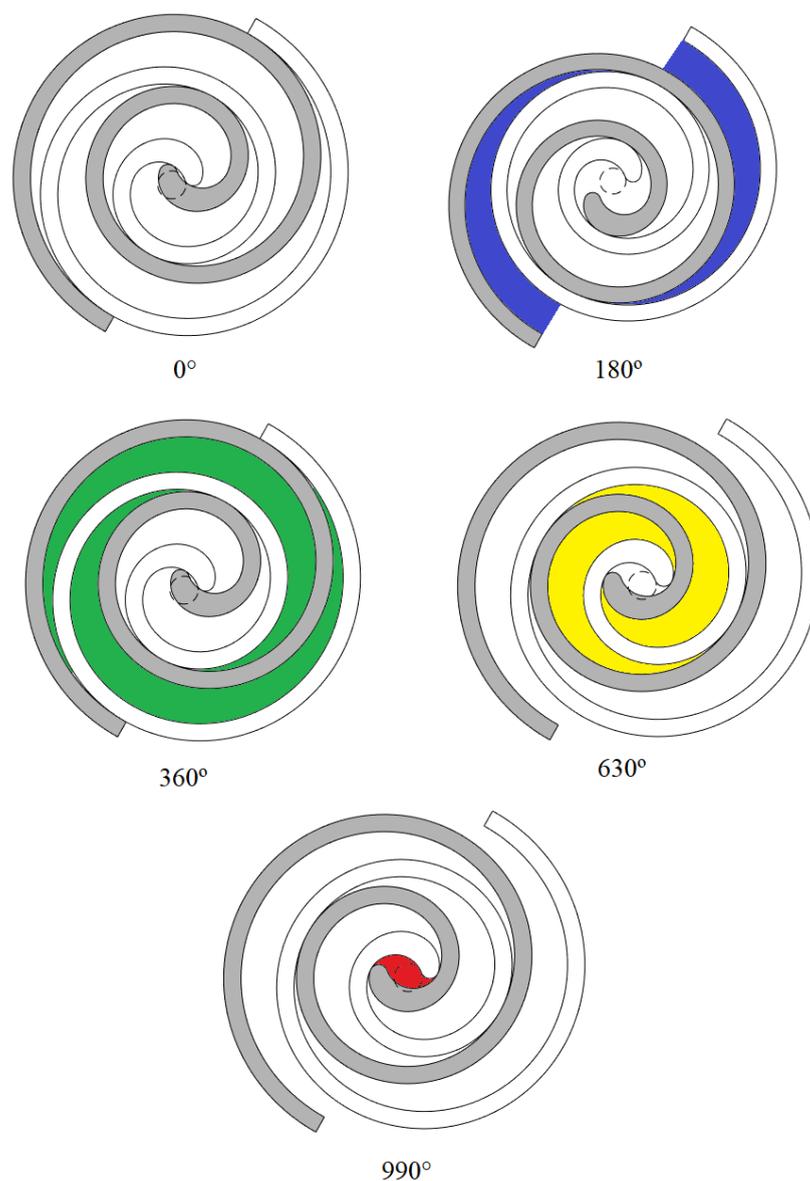

Figure 1. At 0° the suction process starts. At 360° the suction chamber is closed and the compression process starts. At 990° the chamber is open to the discharge plenum, characterizing the discharge process.

2. **NUMERICAL MODEL**

2.1 Geometrical Model

A scroll compressor is made, primarily, by a fixed spiral wrap and an orbiting wrap which rotates around the fixed one and touches it in a set of conjugation points. The area bounded by the fixed and orbiting wraps is the scroll compressor working chamber. As can be seen in Figure 1, as the crank angle increases, a suction chamber is created in the external portion of the scroll compressor. After a complete revolution of the orbiting scroll, the suction chamber is closed to the suction plenum, creating a compression chamber. As the orbiting process continues, the size of the chamber decreases and the fluid is compressed. When the working chambers open to the discharge plenum, the discharge process initiates.

To simulate the compressor, geometric characteristics of the working chambers need to be calculated for the suction, compression and discharge processes. These characteristics are calculated by approximating the compressor wraps by a set of line segments, finding the intersection points between these line segments and calculating the area and the perimeter of the working chambers base. The area is calculated through the use of Green's Theorem and the perimeter is calculated as the sum of the length of each line segment that bounds the working chamber. The base area and perimeter can then be used to calculate the volume and wall area of the working chamber.

Two other main geometric characteristics need to be calculated: the leakage clearances and the discharge port uncovered area. The leakage from the working chamber can occur in two manners: through the clearance between the tip of a wrap and the base of the other, which is called radial leakage, and through the clearance in the conjugation points between two wraps, which is called flank leakage. Both types of leakage can be seen in Figure 2. The flank leakage area can be calculated as the height of the wrap multiplied by the clearance width. The radial leakage area is calculated similarly.
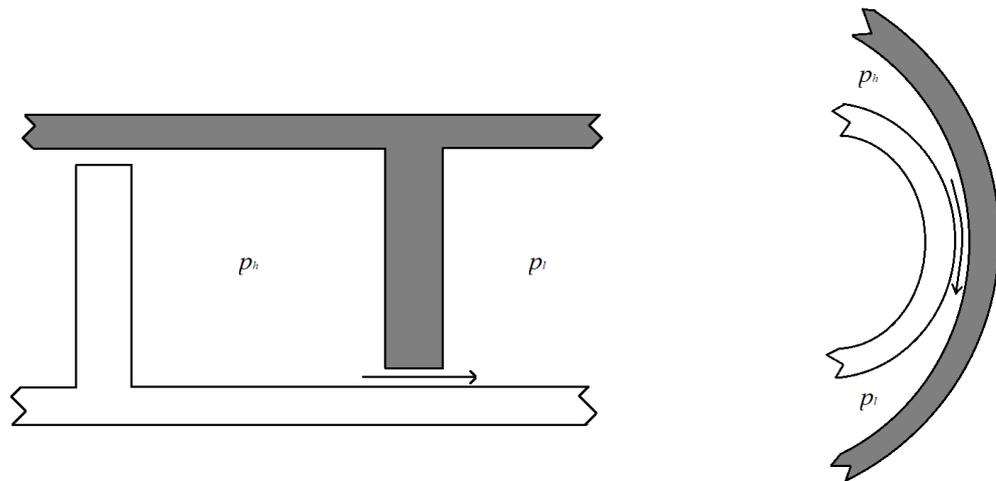

Figure 2. Representation of the radial leakage, on the left, and the flank leakage on the right. The leakage occurs from the high pressure chamber, p_h, to the low pressure chamber, p_l.

2.2 Lumped Model

The model adopted simulates a single working chamber from the beginning of the suction process until the end of the discharge process. The temperature, the mass and the pressure of the fluid are calculated through conservation equations:

$$\frac{\partial m}{\partial t} = \Sigma \dot{m}_{in} - \Sigma \dot{m}_{out},\tag{1}$$

$$\frac{\partial E}{\partial t} = \dot{Q}_{in} + \dot{W}_{in} + \Sigma \dot{m}_{in} h_{in} - \dot{Q}_{out} + \dot{W}_{out} + h_c \Sigma \dot{m}_{out},\tag{2}$$

where m is the mass of the fluid in the working chamber, $\dot{m}$ are the mass flow rates, E is the total energy of the fluid in the working chamber, $\dot{Q}$ is the rate of heat flow, $\dot{W}$ is the work done by the compressor per unit of time and h is the specific enthalpy of the fluid. The subscripts in and out denote quantities that enter and leave the working chamber, respectively. Subscript c designate a property of the fluid inside the working chamber. The mass flow rates that leave and enter the compression chamber are given by the following equations:

$$\Sigma \dot{m}_{out} = \dot{m}_{disc} + \dot{m}_{leak,out} , \tag{3}$$

$$\Sigma \dot{m}_{in} = \dot{m}_{suc} + \dot{m}_{leak,in} + \dot{m}_{backflow} , \tag{4}$$

Where $\dot{m}_{disc}$ represents the mass flow rate through the discharge port, $\dot{m}_{leak,out}$ refers to the mass flow that leaks out of the chamber, $\dot{m}_{suc}$ is the suction mass flow rate, $\dot{m}_{leak,in}$ represents the mass flow rate leaking into the chamber from the posterior chamber and $\dot{m}_{backflow}$ refers to the backflow through the discharge port. Moreover, an equation of state for the pressure inside the working chamber is required to completely determine the thermodynamic properties in the chamber, in the form:

$$p = p(E, \rho) , \tag{5}$$

where p is the pressure and ρ is the density of the fluid inside the working chamber. The thermodynamic relations in the model were calculated using the CoolProp library developed by Bell et al. (2014). In addition, equations for the convective heat transfer, internal leakages and suction and discharge mass flow rates are needed.

For the heat transfer, the correlation developed by Pereira and Deschamps (2017) was used, together with the calculated values of the compressor wall area. The temperature of the wrap was assumed to vary linearly from the temperature of the fluid in the suction plenum at the outermost section of the scroll to the discharge temperature of the fluin at the inner tip. The heat transfer between the fluid and the scroll wrap was then calculated as:

$$\dot{Q} = h_{conv} (T_w - T) A_w , \tag{6}$$

Where A_w is the area of the chamber walls, T_w is the temperature of the scroll wrap, T is the fluid temperature and h_{conv} is the convective heat transfer coefficient. For the internal leakages, the correlations developed by Pereira and Deschamps (2020) were used. The suction and discharge mass flow rates were estimated by equations for the isentropic compressible flow through a convergent nozzle, and are given by:

$$\dot{m} = C_c A \sqrt{2 p_h \rho_h} \sqrt{\frac{\gamma}{\gamma-1} \left[\left(\frac{p_l}{p_h} \right)^{\frac{2}{\gamma}} - \left(\frac{p_l}{p_h} \right)^{\frac{\gamma+1}{\gamma}} \right]} , \tag{7}$$

where C_c is a contraction coefficient that corrects the flow, A is the inlet or outlet area, γ is the specific heat ratio of the fluid, and subscripts h and l refer to properties in the high and low pressure chamber, respectively. The contraction coefficient for the suction flow rate used was equal to 1, and for the mass flow through the discharge port, the contraction coefficient used was 0.59. These values were obtained from numerical simulations.

Equations (1) and (2) were solved numerically. At each instant of the compression process, the mass and internal energy of the fluid inside the chamber were calculated as:

$$m = m_o + \frac{\partial m}{\partial t} \Delta t , \tag{8}$$

$$E = E_o + \frac{\partial E}{\partial t} \Delta t , \tag{9}$$

where Δt is the time step between each instant and subscript o refers to properties in the previous step.

3.   **RESULTS AND DISCUSSION**

The compressor analyzed has a displacement of 33 cc and rotational speed from 700 rpm to 8500 rpm. Three operating conditions were simulated for refrigerant fluid R134a, as can be seen in Table 1. Cases 1 and 2 have the same rotational speed but different discharge pressures, while Case 3 has the same discharge pressure as Case 2 but at a higher speed.. For the cases with the same rotational speed, as the pressure ratio increased from 3.0 to 5.0, the mass flow rate fell 7.7%. The effect of the increase in pressure ratio affected to a greater extent the discharge temperature, which had a substantial increase of 56.55°C, and the indicated power, which increased by 37.1%. As the rotational speed was increased by a factor of 2.3, the mass flow rate and indicated power increased significantly, 81.7% and 57.2% respectively. The discharge temperature, however, decreased 20°C.

Table 1. Operating conditions and obtained results for the simulated scroll compressor

Case	Rotational Speed (rpm)	Suction Pressure (bar)	Discharge Pressure (bar)	Mass Flow Rate (kg/h)	Discharge Temperature (°C)	Indicated Power (W)
1	3015	3,00	15,0	69,7	115,9	1014,2
2	3015	3,00	25,0	64,4	172,4	1613,3
3	4995	3,00	25,0	117,0	152,4	2535,6

The leakage rates from the compression chamber increase slowly from the beginning of the compression process until the beginning of the discharge process, as can be seen in Figure 3. When the crank angle reaches an angle over $\theta = 700°$, the chamber opens up to the discharge plenum and the pressure inside the chamber quickly equalizes with the pressure of the plenum. This raise in pressure creates an increase in the leakage rate, as seen in Figure 3. Between the operating conditions with the same rotational speeds, the case with the largest pressure ratio presents a greater leakage rate after the pressure equalization with the discharge plenum. This is true in both absolute and relative terms: the mean leakage rate for the second case reaches 14.8% of the value of the compressor mass flow rate for that case, while for the first case the mean leakage rate reaches only 8.8% of the value of the mass flow rate of the compressor. The leakage rate for the case with a higher rotational speed is very similar to that of the second case, even though its mass flow rate is higher. Thus, the mean mass leakage rate reaches only 8.4% of the mass flow rate for this case. Before the pressure equalization with the discharge plenum, the leakage rates of the three cases are similar.

Table 2. Geometric characteristics of the simulated scroll compressor

Involute base circle radius	2,77 mm
Scroll thickness	4,16 mm
Discharge port radius	3,37 mm
Scroll number of turns	2,17
Scroll height	20 mm
Flank leakage width	10 μm
Radial leakage width	12 μm

The instantaneous heat transfer rate for the three cases can be seen in Figure 4. In the beginning of the operation cycle, as the temperature of the scroll wrap is higher than the temperature of the fluid, the fluid is heated. This heating phase is very similar for both cases with low rotational speed, but is more intensive for the third case. In the second half of the operating cycle, the fluid reaches higher temperatures than the scroll wrap, which makes it lose heat to the walls.

As seen in Figure 4, the three cases lose heat at different rates, with the first case having the smallest values of heat transfer rate, the third case having the greatest values and the second case in the middle of them.
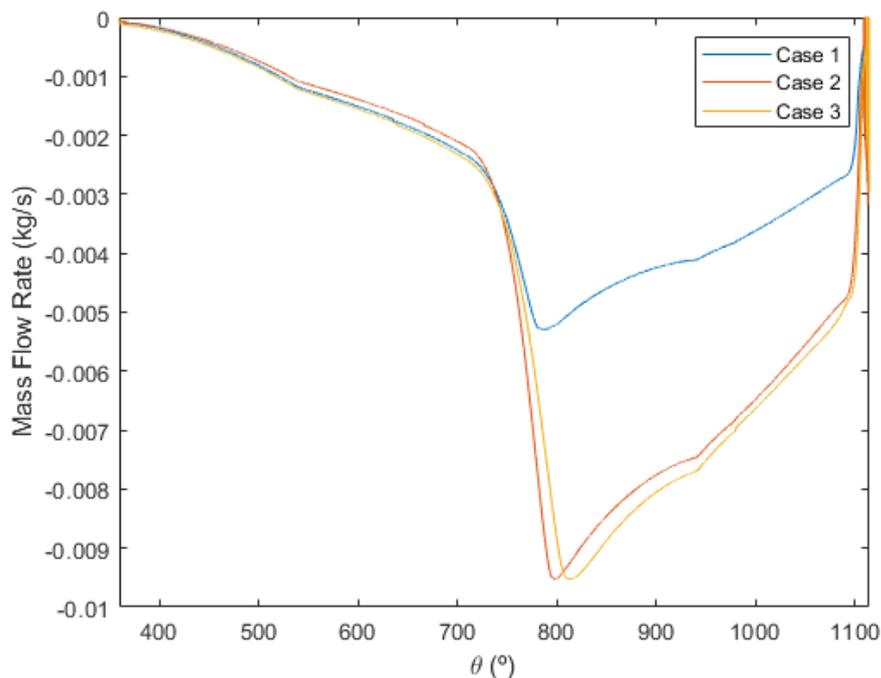

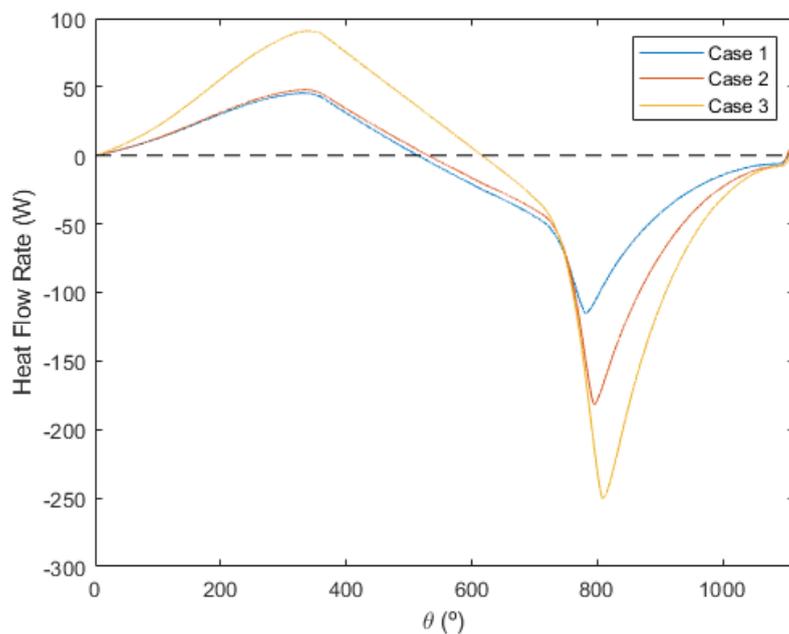Figure 3. Mass leakage rates for the three simulated cases along a single cycle.

Figure 4. Heat transfer rate for the three simulated cases along a single cycle.

Another form of irreversibility in a scroll compressor is the pressure equalization when the compression chamber opens up to the discharge plenum. As seen in Figure 5, in all simulated cases, there was some extent of mass flow from the plenum into the working chamber (positive values). This mass flow rate is greater for the cases with greater pressure

ratios, and persists for longer. This affects mainly the case with the highest rotational speed, which has the higher mass flow rates in this pressure equalization phase.
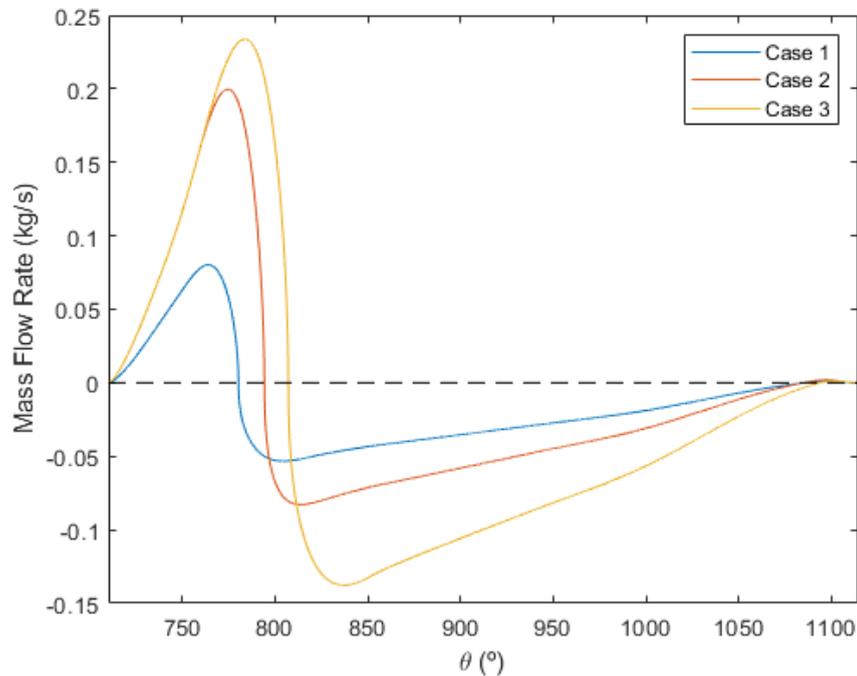

Figure 5. Mass flow rate through the compressor's discharge port for the three cases.

4. CONCLUSIONS

The present study described a comprehensive compressor simulation model, which is able to predict integrated parameters of the compression cycle such as mass flow rate, discharge temperature and indicated power, but also instantaneous values, such as leakage and heat transfer rates. An electric variable speed scroll compressor with displacement equal to 33 cc used for automotive air-conditioning application was simulated considering different discharge pressures and rotational speeds. The results indicate that the mass flow rate delivered by the compressor decreases and the discharge temperature and indicated power increase as the discharge pressure is increased. On the other hand, the mass flow rate and the indicated power increase and the discharge temperature decreases when the rotational speed is increased. The influence of the discharge pressure and rotational speed on instantaneous values of leakage and heat transfer rates was also assessed and it is clear that while the discharge pressure has a major influence over the instantaneous leakage rate, the rotational speed affects the heat transfer rate considerably. Finally, the instantaneous flow rate through the discharge port is also provided, showing how these operational parameters impact the backflow. Even though the comprehensive compressor simulation models have a low computational cost, they are capable of providing valuable information for the design of compressors, specially during the initial design stages, when sensitivity analyses and optimization procedures are required. Future studies should verify how design changes affect the compressor performance and identify the optimal geometric configuration for a particular application.

5. REFERENCES

AHRI, 2020, AHRI Standard 540 - Performance Rating of Positive Displacement Refrigerant Compressors, Air Conditioning, Heating, & Refrigeration Institute AHRI, Arlington, USA.

Bell, I. H., Lemort, V., Groll, E. A., Braun, J. E., King, G. B., and Horton, W. T., 2012. "Liquid-flooded compression and expansion in scroll machines – part I: model development". *International Journal of Refrigeration*, Vol. 35, No. 7, pp. 1878–1889.

Bell, I. H., Lemort, V., Groll, E. A., Braun, J. E., King, G. B., and Horton, W. T., 2012. "Liquid flooded compression and expansion in scroll machines – part II: experimental testing and model validation". *International Journal of Refrigeration*, Vol. 35, No. 7, 1890–1900.

Bell, Ian H.; Wronski, Jorrit; Quolin, Sylvain; Lemort, Vincent. Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp. *Industrial & Engineering Chemistry Research*, vol. 53, No. 6, p. 2498-2508, 2014.

Chen, Y., Halm, N. P., Groll, E. A., and Braun, J. E., 2002a. "Mathematical modeling of scroll compressors – part I: compression process modeling". *International Journal of Refrigeration*, Vol. 25, No. 6, pp. 731–750.

Chen, Y., Halm, N. P., Braun, J. E., and Groll, E. A., 2002b. "Mathematical modeling of scroll compressors – part II: overall scroll compressor modeling". *International Journal of Refrigeration*, Vol. 25, No. 6, pp. 751-764.

COP21, 2015, Paris Declaration on Electro-Mobility and Climate Change and Call to Action, 21st Conference of the Parties COP21, United Nations Climate Change Conference, Paris, https://newsroom.unfccc.int/media/521376/paris-electro-mobility-declaration.pdf. Acessed 7 June 2021.

Diniz, M. C., Pereira, E. L., and Deschamps, C. J., 2015. "A lumped-parameter thermal model for scroll compressors including the solution for the temperature distribution along the scroll wraps". *International Journal of Refrigeration*, Vol. 53, pp. 184–194.

Pereira, E. L., and Deschamps, C. J., 2017. "A heat transfer correlation for the suction and compression chambers of scroll compressors". *International Journal of Refrigeration*, Vol. 82, pp. 325–334.

Pereira, E. L., and Deschamps, C. J., 2020. "Numerical analysis and correlations for radial and tangential leakage of gas in scroll compressors". *International Journal of Refrigeration*, Vol. 110, pp. 239–247.

6. **RESPONSIBILITY NOTICE**

The authors are the only responsible for the printed material included in this paper.