PAPER ID: 0416
DOI: 10.18462/iir.compr.2021.0416

CHARACTERIZATION METHODOLOGY FOR VAPOR INJECTION SCROLL COMPRESSORS OF VARIABLE SPEED

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ABSTRACT

Scroll compressor with vapor injection (SCVI) is one of the most used technologies in refrigeration systems and heat pumps that work with high pressure ratios. Nevertheless, the characterization standard for this type of compressors is not system independent and lacks of generality. In this work, a methodology for the characterization of this type of compressors is presented. This methodology allows the compressor characterization using a calorimetric test bench and independently of the used injection system. The methodology is based on the development of a correlation for the intermediate conditions as a function of the injection mass flow and the compressor speed. This correlation was obtained with an SCVI using R-407C as a refrigerant. In order to evaluate the confidence of the obtained results a set of tests was performed with a variable speed scroll compressor with vapor injection (VS-SCVI) working with R-290 as a refrigerant. Finally, an experimental analysis of the intermediate conditions for VS-SCVI is presented.

Keywords: Characterization, Methodology, Compressors, Scroll, Vapor-injection, Variable speed

1. INTRODUCTION

In Europe, manufacturers characterize single-stage compressors based on Standard EN 13771-1 (2017). The standard proposes several procedures for testing compressors, which requires the definition of three external conditions: evaporating pressure, condensing pressure, and superheat at the compressor inlet. In these conditions, the mass flow rate and the power consumption have to be measured. The characterization of vapor-injection scroll compressors (SCVI) is more complex because there are two additional degrees of freedom, the intermediate pressure, and the injection temperature. These parameters depend on the system design, that is, how the injection is performed (economizer, flash tank, liquid injection, etc.). Moreover, for a full characterization of these compressors, the injection mass flow rate must be measured.

For a given test matrix, when including the two additional parameters in the system, the number of experimental points increases considerably because the intermediate pressure can take several values for each operating point. However, not all points of the resultant test matrix describe the behavior of the compressor working in real operating conditions, since the compressor only works with a single intermediate pressure when the injection mechanism is set (injection cycle and control algorithm). Figure 1 shows one of the most typical vapor-injection cycles. The system uses an internal heat exchanger (economizer) to vaporize the injection mass flow rate. The intermediate conditions are set from the economizer size and the chosen mechanism of control, which is usually a thermostatic expansion valve.

Therefore, in this configuration, for each compressor size, a determined heat exchanger size has to be selected to define the different operating points of the compressor. According to the standard EN 13771-1 (2017), the vapor-injection compressors are characterized by considering a superheat at the compressor inlet of 5K; an injection superheat of 5K and a temperature approach in the economizer (T_6 -T_7 in Figure 1) of 5K. Nevertheless, in real applications, the temperature approach in the economizer is varied for different T_e and T_c. By fixing a $\Delta T_{6\text{-}7}$, the compressor work with a unique P_{int}. Moreover, to maintain a constant $\Delta T_{6\text{-}7}$ in the operating conditions, many heat exchangers are needed, hence the cost of the test bench increases dramatically. Therefore, this characterization methodology is not general, it does not allow knowing how the compressor will work in a real installation and it is dependent on the economizer size.

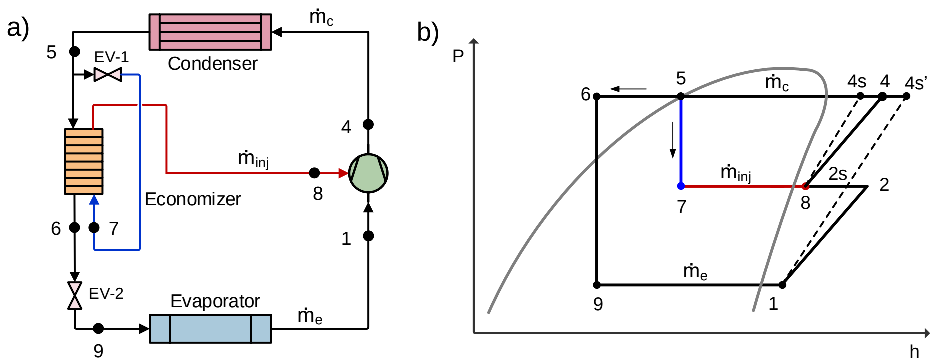

Figure 1: Vapor injection cycle with economizer of the SCVI. a) Schematic of the cycle. b) P–h diagram.

Navarro et al. (2013) presented a test campaign for an SCVI of an air-to-water refrigerant injection circuit installed in a climatic chamber. The refrigerant injection was made through an economizer. The intermediate conditions were fixed by the control of the injection expansion valve and by the economizer size (UA). However, this kind of characterization was performed with a defined economizer size; it means that the results of the characterization also depend on the characteristics of the heat exchanger used on the test bench. In conclusion, none of these procedures involves an intrinsic characterization of the compressor because they considered external parameters such as the economizer size, temperature approaches, or other injection mechanisms.

On the other hand, the efficiency of a variable-speed compressor with refrigerant injection depends on ambient conditions and compressor frequency as well. Therefore, the characterization analysis of this kind of compressor should include the effects of compressor frequency on the performance. This analysis should lead to finding a fitting equation that helps designers to calculate the compressor performance in a vapor compression cycle in a simple way. Several researchers studied this problem and tried to predict the compressor performance. Park et al. (2002) developed a model of a variable speed scroll compressor with vapor-injection (VS-SCVI) working with R-22. The model was validated considering only the no injection condition showing deviations of the predicted compressor capacity and electrical power lower than 10 % respecting to the experimental ones. The model was then used to investigate the influence of geometrical (injection hole diameter and position) and thermodynamic (refrigerant pressure and quality or superheat) injection parameters on compressor working parameters as a function of rotational frequency.

Dardenne et al. (2015) developed a semi-empirical model of a hermetic VS-SCVI working with R-410A, based on the semi-empirical model of a fixed speed scroll compressor presented by Winandy and Lebrun (2002). The model was validated using 63 experimental test conditions. The model requires 10 parameters fitted from experimental data to simulate the process that the refrigerant undergoes from suction and injection ports to the discharge port. The model computes the suction and injection refrigerant mass flow rates, the compressor power, and the discharge temperature within ±5 %, ±10 %, ±5 %, ±5 K, respectively. Lumpking et al. (2018) and Sun et al. (2018) used experimental data from Dardenne et al. (2015) to validate its characterization models. Lumpking proposed a correlation for the calculation of injection mass flow rate that uses 10 fitting exponents of dimensionless group numbers derived by the Buckingham-PI theorem. The proposed correlation was validated based on the 63 data points obtained by Dardenne et al. (2015). Sun et al. (2018) presented a theory based explicit compressor model that consists of a series of models for the suction and injection mass flow rate, total power input, and outlet enthalpy. The model needs 26 fitting parameters. The model is validated against experimental data by Dardenne. Predicted injection mass flow rate can describe 83% of the experimental data within a deviation of ±10 %. Recently, Dechesne et al. (2019) presented an experimental study of a residential heat pump working with a variable speed scroll compressor with refrigerant injection and R-410A as the working fluid. They performed an experimental campaign for investigating the performance of the scroll compressor under different evaporating and condensing temperatures and rotational speeds. Based on that, an empirical model of the compressor was proposed. The model is based on five dimensionless relations namely: the volumetric efficiency, the isentropic efficiency, the variable speed drive efficiency, the injection ratio (ratio between the injection and the suction mass flow), and the ambient losses ratio (ratio between the compressor ambient losses and the electrical consumption of the compressor).

Nevertheless, in none of the studies described above is a procedure established that allows systematically characterizing the compressor and considering the effect of compressor speed in intermediate conditions such as injection pressure and superheat. The present paper presents a methodology for the characterization of vapor-injection compressors using a calorimetric bench. To do so, an SCVI was tested using R-407C as refrigerant. The dependence of the injection mass flow rate with the intermediate pressure is analyzed and an empirical correlation of the injection ratio was identified. Also, a VS-SCVI was characterized by several working conditions and 4 different frequencies. From the experimental data of the compressor, a correlation of the intermediate conditions of the compressor is obtained based on the previous correlation obtained for constant speed SCVI. The correlation is checked with other sources of data available in the public literature.

2. MAIN SECTION

2.1. Experimental setup

Figure 2 shows the scheme of the test bench used for testing scroll compressors with vapor-injection. A calorimetric test bench was used which has an additional line for the refrigerant injection (Tello-Oquendo et al., 2017). The calorimetric bench was designed to control the operating conditions of the vapor-injection compressor at the suction, discharge, and injection ports. The compressors testing procedure was performed based on the European Standard EN 13771-1 (2017). According to this standard, the refrigerant mass flow rate is the determining parameter to be measured, and primary and confirming measurements have to be made. The primary test procedure chosen is the secondary refrigerant calorimeter method. A Coriolis-type mass flow meter was used as the confirming test method.

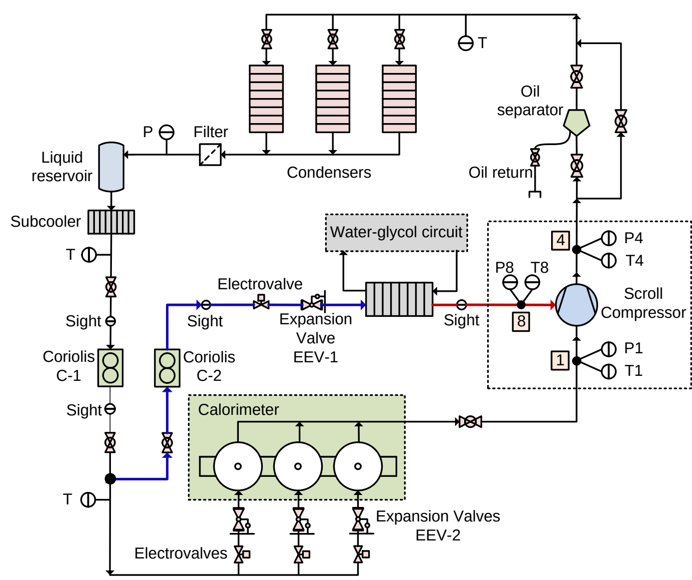

Figure 2: Scheme of the calorimetric test bench.

The condenser mass flow rate is directly measured using a Coriolis-type (Fisher–Rosemount Micro-Motion CMF025M), C-1 in Figure 2. Several PID control loops adjust the refrigerant conditions at compressor inlet (evaporating temperature and superheat) and outlet (condensing temperature) with a precision of 1 kPa. The instrument accuracies of pressure transmitter (Fisher–Rosemount 3051) and temperature transmitter (RTD-PT 100) are 0.02 % and 0.05 ºC, respectively. The injection line (blue line in Figure 2) is separated from the evaporator line to control independently the intermediate pressure and the injection temperature. Part of the liquid (injection mass flow rate) is derived from the condenser outlet and is expanded to the intermediate pressure in an electronic expansion valve (EEV-1 in Figure 2). After the expansion valve, the injection mass flow rate is vaporized in a heat exchanger using a secondary circuit of a water-glycol mixture. Electric resistors control the temperature of the water-glycol mixture to fix the injection superheat as intermediate pressure is controlled by expansion valve EEV-1. The injection line is also equipped with a Coriolis-type mass flow meter with an uncertainty of ±0.025 g s-1 (C-2 in Figure 2), a pressure transducer with a precision of 0.2 %, an RTD with a precision of 0.1 K, an electrovalve located before the expansion valve (EEV-1), and an electrical power meter with a precision of 0.1 %.

The evaporator mass flow rate is calculated as the difference between the condenser mass flow rate and the injection mass flow rate. The testing procedure begins with the setting of the condensing pressure, evaporating pressure and the superheat at the compressor inlet acting on the flow rate of the water condenser, valves EEV-2, and resistors of the calorimeter, respectively. The electronic expansion valve (EEV-1 in Figure 2) regulates the intermediate pressure. Once the system is in equilibrium, the total mass flow rate ($\dot{m}_c$), the injection mass flow rate ($\dot{m}_{inj}$), and the compressor power input are measured. Also, the injection temperature (T_{inj}), and the condenser outlet temperature are registered. The compressor used for the characterization was an SCVI of 17.1 m^3/h (swept volume) working with R-407C as refrigerant. The laboratory tests were performed according to the following parameters: suction superheat of 5 K, injection superheat of 5 K and 5 K of subcooling at the condenser outlet. On the other hand, a VS-SCVI of 17.28 m^3/h was tested with R-290 as refrigerant. The laboratory tests were performed according to the following parameters: suction superheat of 10 K, injection superheat of 5 K and 5 K of subcooling at the condenser outlet. Figure 3 shows the working envelope of the compressors and the test matrix.

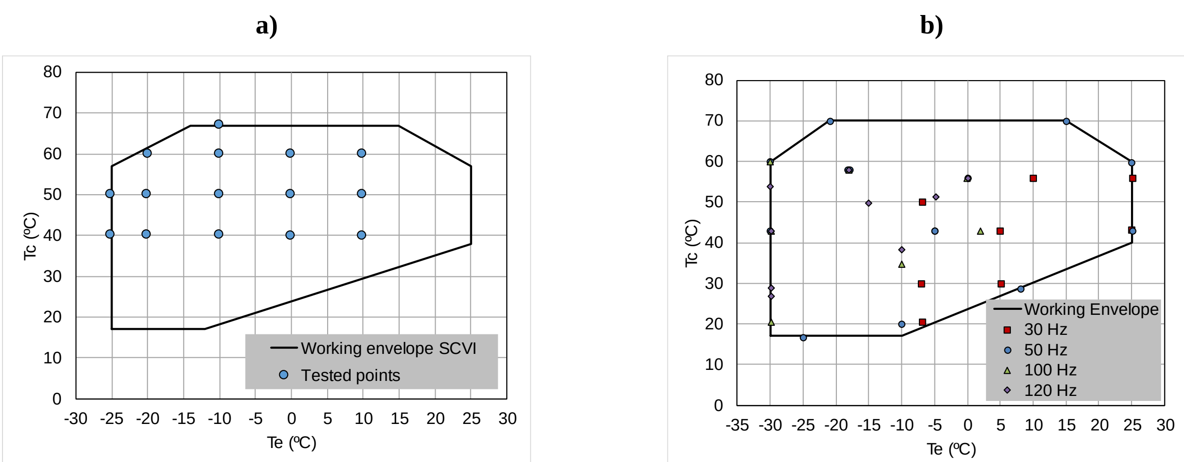

Figure 3: Working envelope and tested points of the compressors. a) SCVI. b) VS-SCVI.

The volumetric efficiency is defined by the Eq. (1), where the number 1 is located at the compressor inlet. The overall compressor efficiency is defined by Eq. (2). This expression represents a ratio between the ideal isentropic power consumption and the real indicated work for the compressor.

$$\eta_v = \frac{\dot{m}_e}{\dot{V}_1\, \rho_1} \qquad \text{Eq. (1)}$$

$$\eta_c = \frac{\dot{m}_e\,(h_{4s'} - h_1) + \dot{m}_{inj}\,(h_{4s} - h_8)}{\dot{E}} \qquad \text{Eq. (2)}$$

where h_{4s}' represents the enthalpy at the discharge pressure considering an isentropic compression from the inlet condition (see point 1 in Figure 1), h_{4s} represents the enthalpy at the discharge pressure considering an isentropic compression from the intermediate injection condition (see point 8 in Figure 1) and $\dot{E}$ represents the compressor power input. The evaporating and condensing temperatures are dew point temperatures. The thermophysical properties of the refrigerant at the different points are calculated with the NIST REFPROP database (Lemmon et al., 2010).

2.2. Results and discussion

2.2.1. Fixed speed SCVI

Figure 4 depicts the compressor and volumetric efficiency of the SCVI as a function of the pressure ratio for several condensing temperatures. At lower condensing temperatures, the compressor efficiency, and volumetric efficiency are higher. The SCVI presents high volumetric efficiency values (above 0.8) for any operating point because the compressor doesn´t have undesirable dead space and no inlet and outlet valves, the contact between the flanks of scrolls and their bases and upper edges is almost perfect and constant; thus, it has very good axial and radial compliance. The compressor efficiency varies from 0.5 to 0.62.

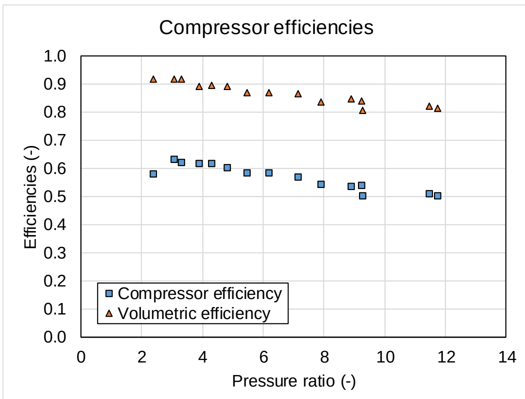

Figure 4: Compressor efficiency and volumetric efficiency of the SCVI as a function of pressure ratio.

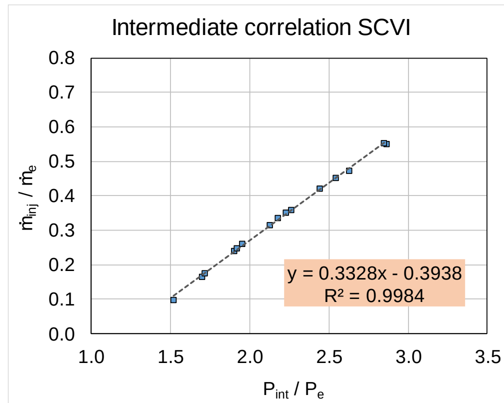

Figure 5: Injection ratio ($\dot{m}_{inj}/\dot{m}_e$) as a function of the intermediate pressure ratio (P_{int}/P_e).

Figure 5 represents the evolution of the injection ratio ($\dot{m}_{inj}/\dot{m}_e$) to the pressure ratio (P_{int}/P_e). This figure shows a direct dependence between intermediate pressure and injection ratio as stated by Tello-Oquendo et al. (2017). Based on Figure 5, the injection mass flow rate can be correlated with the intermediate pressure. The correlation is presented in Eq. (3). By linear regression, the coefficients A and B are obtained with a correlation factor higher than 0.99. The fitted coefficients are A=-0.383 and B=0.329.

$$\frac{\dot{m}_{inj}}{\dot{m}_e} = A + B\frac{P_{int}}{P_e} \qquad \text{Eq. (3)}$$

Once the correlation (3) is identified, the injection mass flow rate of a determined system with a concrete injection strategy can be calculated directly for each working condition. The Eq. (3) is an additional AHRI polynomial required to characterize vapor-injection scroll compressors. The correlation supplies a tool to the compressor manufacturers in order to provide compressor data independently of the heat pump or refrigeration system in which the compressor will be installed. It must be emphasized that it was not necessary to test the SCVI in more points than the required ones for the single-stage compressor characterization in order to obtain the correlation of the intermediate compressor conditions. The SCVI was tested in only a single intermediate pressure for each working condition.

2.2.2. Variable speed SCVI

Figure 6a depicts the compressor and volumetric efficiency of the VS-SCVI as a function of the pressure ratio for several frequencies. The compressor efficiency presents a maximum for pressure ratios around 3, that correspond to the building volume ratio of the compressor at the nominal frequency (50 Hz). The compressor efficiency decreases as the pressure ratio increases due to the under-compression effect, in all frequencies. The lowest compressor efficiency is achieved at 30 Hz. The volumetric efficiency also decreases as the pressure ratio increases due to the higher influence of the internal leakage at high-pressure ratios. Moreover, the volumetric efficiency decreases rapidly at 30 Hz due to the higher relative influence of the internal leakage at lower frequencies.

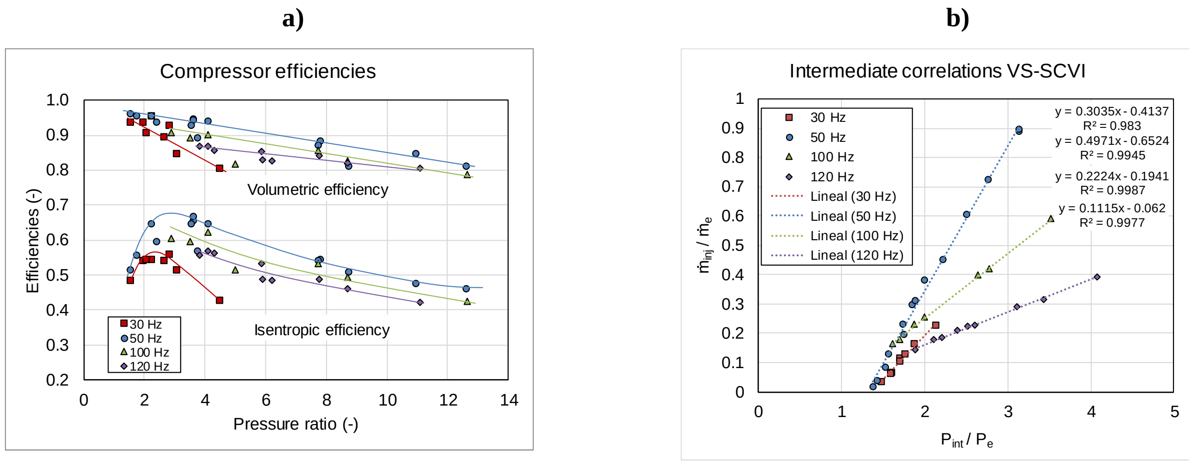

Figure 6: a) Compressor efficiencies of the VS-SCVI as a function of pressure ratio at several frequencies. b) Injection mass flow rate correlation at different frequencies.

The analysis of the intermediate conditions of the VS-SCVI was performed considering the intermediate pressure ratio (P_{int}/P_e) and the injection ratio ($\dot{m}_{inj}/\dot{m}_e$). Figure 6b shows the injection ratio as a function of the intermediate pressure ratio for all frequencies. Both plotted ratios show a linear dependence between them for each frequency. This dependence corresponds to the expression (3) identified in previous work Tello-Oquendo et al. (2017), for constant speed SCVI. Hence, Eq. (3) is fitted for each frequency, and results are shown in Figure 6b. Equations fit perfectly data for each frequency obtaining R-squared values between 0.98 and 1. Figure 7a shows the dependence of intercept (A factor in equation (3)) and slope (B factor in equation (3)). Both factors show the same behavior: two straight lines with the common point centered in the nominal frequency of 50Hz.

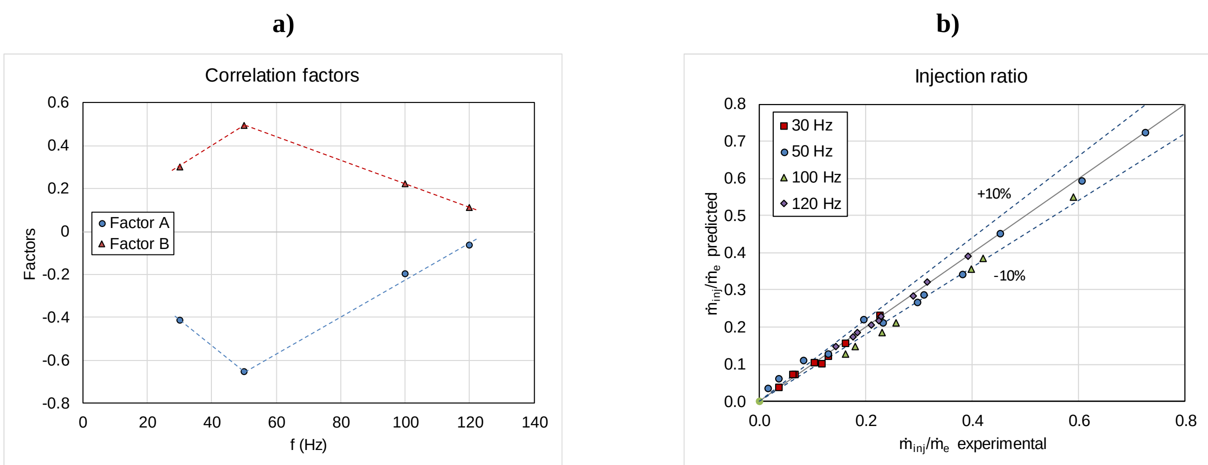

Figure 7: a) Slope and intercept dependence on frequencies. b) Comparison of the experimental and predicted injection mass flow ratio for a VS-SCVI working with R-290.

Based on the experimental results, Eq. (4) is proposed to estimate the injection mass flow rate of the compressor, where coefficients are given in Table 1. The analysis of the intermediate conditions of the VS-SCVI was verified with the experimental data published by Dardenne et al. (2015) and Dechesne et al. (2019). Figure 8 represents the comparison of the experimental and predicted injection ratio ($\dot{m}_{inj}/\dot{m}_e$) for the compressors. The Eq. (4) provides accurate results in the prediction of the injection ratio as a function of the intermediate pressure ratio and the frequency. The main advantage of the present correlation is the simplicity and accuracy to estimate the intermediate conditions of the VS-SCVI. This correlation can be used in a cycle model to predict the injection mass flow rate and the intermediate pressure for a given injection mechanism and compressor frequency.

$$\frac{\dot{m}_{inj}}{\dot{m}_e} = (A_0 + fA_1) + (B_0 + fB_1)\frac{P_{int}}{P_e} \qquad \text{Eq. (4)}$$

Table 1. Coefficients fitted for Eq. (4).

Coefficient	Frequency	Frequency
	$f \leq 50$ Hz	$f \geq 50$ Hz
A_0	-5.57E-02	-1.07E+00
A_1	-1.19E-02	8.43E-03
B_0	1.31E-02	7.73E-01
B_1	9.98E-03	-5.51E-03

a) **b)**

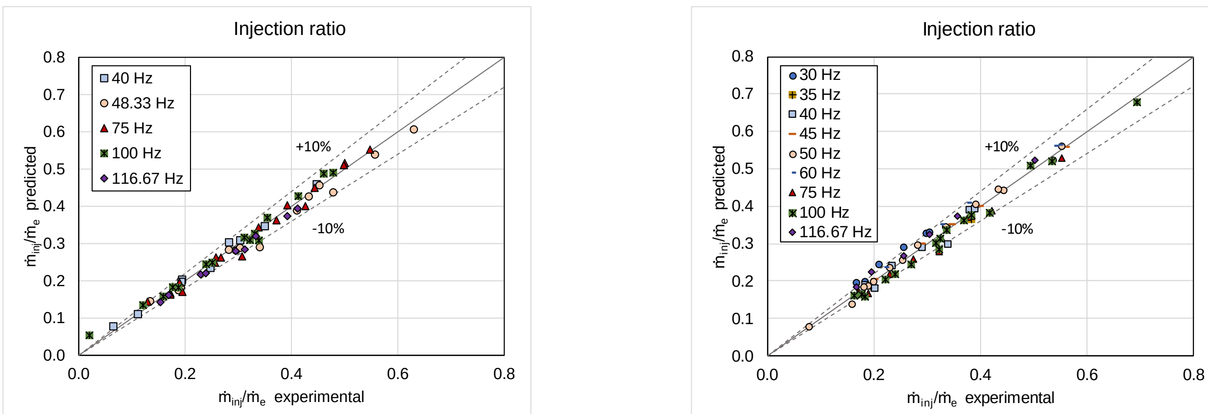

Figure 8: Comparison of the experimental and predicted injection mass flow ratio. a) VS-SCVI working with R-410A from Dardenne et al. (2015). b) VS-SCVI working with R-410A from Dechesne et al. (2019).

3. CONCLUSIONS

This paper presents a characterization methodology for SCVI, and its extension to analyze VS-SCVI. The following conclusions can be drawn from the study:

- The characterization of SCVI is based on the linear correlation between the injection ratio with the intermediate pressure ratio. The correlation was experimentally verified by testing an SCVI using R-407C as refrigerant in a modified calorimetric test bench.

- A VS-SCVI was tested using R-290 as refrigerant in a wide range of operating conditions and frequencies. Based on experimental results, it was identified that the intermediate pressure ratio and injection ratio are linear dependents, for each compressor frequency. Two different compressor performance is detected depending on the frequency range: below or above the nominal frequency of 50 Hz.

- A correlation between the intermediate conditions of VS-SCVI has been obtained from experimental data. The injection ratio was correlated with the injection pressure ratio and frequency. The proposed correlation for VS-SCVI was verified with other compressors and refrigerant (R-410A) from the data of two different authors.

- The proposed characterization methodology allows evaluating the compressor performance independently of the injection mechanism and the system design. This methodology can be a useful tool for compressor manufacturers when providing information about their compressors, to the designers to estimate more reliably the compressor behavior in a particular application and also to implement new control strategies based on the intermediate pressure in order to optimize the system performance.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by the project "ENE2017-83665-C2-1-P" funded by the "Ministerio de Ciencia, Innovación y Universidades" of Spain.

NOMENCLATURE

A_i	parameter	Greek symbols	
B_i	parameter	ρ	density (kg m^{-3})
$\dot{E}$	compressor power input (W)	η_c	compressor efficiency (%)
f	frequency (Hz)	η_v	volumetric efficiency (%)
$\dot{m}$	mass flow rate (kg s^{-1})	Subscripts	
p	pressure (kPa)	c	condenser
SCVI	scroll compressor with vapor injection	e	evaporator
T	temperature (K)	*inj*	injection
VS	variable speed	*int*	intermediate
$\dot{V}$	swept volume (m^{3}h^{-1})	s	isentropic, suction

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