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Experimental analysis of the intermediate conditions of a variable speed vapor-injection scroll compressor working with R-410A

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ABSTRACT

This paper presents an experimental analysis of the intermediate conditions for a variable speed (VS) vapor-injection scroll compressor (SCVI) under several working conditions and speeds.
A set of experimental tests was conducted for a VS-SCVI working with R-410A as a refrigerant. From the experimental data and based on previous correlations obtained for constant speed SCVI, a correlation for VS-SCVI was obtained to estimate the injection ratio depending on the compressor speed with an error lower than 10%. Results showed differences in the intermediate conditions of the compressor for low and high compressor speeds.
Keywords: Variable speed, Vapor-injection, Scroll compressor, Correlation, Experimental, Optimization.

1. INTRODUCTION

Nowadays, scroll compressors are widely used in residential and commercial air-conditioning, refrigeration and heat pump applications as well as in automotive air conditioning. This kind of compressor technology is orbital motion, positive-displacement machines that compress with two inter-fitting, spiral-shaped scroll members. They have no dead space, the contact between the flanks of scrolls and in their bases and upper edges is almost perfect and constant; therefore, it has very good axial and radial compliance. Consequently, scroll compressors present advantages such as high compressor and volumetric efficiencies, low vibrations and noise, low torque variations and leakage (ASHRAE Handbook, 2008). Several advanced technologies have been studied in order to enhance the compressor performance and save energy. One of these technologies is the vapor-injection and the other is the use of the variable speed motor.
Vapor-injection technic in scroll compressors has rapidly developed in recent years. The refrigerant injection can either increase the capacity and performance efficiency of the system or decrease the discharge temperature of the compressor to extend the working envelope, especially for refrigeration and heat pump systems working with low evaporating temperatures or high condensing temperatures.
The efficiency of a variable speed compressor with refrigerant injection depends on ambient conditions and compressor frequency as well. Therefore, characterization analysis of a variable speed compressor with refrigerant injection should include the effects of compressor frequency on the performance. This analysis should lead to find a fitting equation that help designers to calculate the compressor performance in a vapor compression cycle in a simple way.
Several researchers studied this problem and tried to develop a correlation to predict compressor performance.
Park et al. (2002) developed a model of a variable speed scroll compressor with vapor-injection working with R22.

The model was validated considering only the no injection condition showing deviations of the predicted compressor capacity and electrical power lower than 10 % with respect 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. An optimal configuration leading to an increase of COP equal to 12 % COP was found.

Dardenne et al. (2015) developed a semi-empirical model of a hermetic, variable-speed vapor-injected R-410A scroll compressor 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 discharge port. The model includes the leakage in the compression process and 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) for validate its own characterization models.

Lumpking et. Al. (2018) 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 in the 63 data points obtained by Dardenne et. Al (2015) and predicts the injection ratio with an average error of ±9.8% and a RMSE of ±6.7%.

Sun et al. (2018) presented a theory based explicit compressor model that consists in a series of models for the suction and injection mass flow rate, total power input and outlet enthalpy. The model needs 26 fitting parameters. Model is validated against experimental data by Dardenne et al. (2015). Predicted injection mass flow rate can describe 83% of the experimental data within deviation of ±10 %.

Authors of this papers presented previous studies in this field. Tello-Oquendo et. al. (2018a) studied the set of equations in two stage vapour compression cycles with economizer to conclude that there are three degrees of freedom namely injection superheat, injection ratio and injection pressure. These parameters are fixed in the cycle by using an injection valve, economizer size and injection compressor characteristics. In case that economizer is replaced by a flash tank, the only degree of freedom is the injection pressure that is determined by the compressor characteristics.

Tello-Oquendo el al. (2017) presented a new methodology for measuring vapour injection compressors. They observed a linear dependence of the injection ratio with the injection pressure ratio and proposed a simple linear correlation between these variables:

$$\frac{\dot{m}_{inj}}{\dot{m}_e} = A + B\frac{P_{inj}}{P_e} \qquad \text{Eq. (1)}$$

Where $\dot{m}_e$ is the evaporator mass flow rate in $kg\ s^{-1}$, $\dot{m}_{inj}$ is the injection mass flow rate in $kg\ s^{-1}$, P_e is the evaporation pressure in Pa and P_{inj} is the injection pressure in Pa.

The correlation predicts the injection mass flow rate with a maximum error of -1.80% and an average error of -0.79%.

Tello-Oquendo et. al. (2018b) extends the correlation with new data for a variable speed compressor working with propane. Compressor was tested at 3 different frequencies (50 Hz, 100 Hz and 120 Hz) and using the data provided by Dardenne et al. (2015) of the R-410A compressor. Equation 1 is adapted making the lineal coefficients dependent on the frequency in a linear form. Proposed correlation agrees very well with both experimental data sets having a maximum absolute error of 7.36% and a RMSE of 5.6%.

Dechesne & Lemort (2018) developed a model for the whole two-stage cycle that uses an equation of the injection ratio as a logarithmic function of the injection pressure ratio. The compressor model was validated using measurements of an air to water heat pump under different compressor speeds and temperatures of the sink/source. The system model is capable to predict the heating capacity and compressor power input with an error less than 2.6% and 6.8% respectively.

2. EXPERIMENTAL SETUP

A schematic representation of the test bench is given in **Error! Reference source not found.**.
The refrigerant loop is controlled by means of a ModBus Interface, which implies the adjustment of the rotational speed of the air evaporator fan, of the scroll compressor, as well as the openings of the expansion valves. Both expansion valves, evaporator and injection, controls the inlet superheat of evaporator and injection compressor port to 5 K respectively.
The drive cooler is an additional heat exchanger installed to cool down the power electronic used for the variation of the compressor speed.

- Conditions in terms of temperature and absolute pressure are measured at the supply/exhaust of each component of the refrigerant loop. Temperatures are determined by means of sensor pocket (type T thermocouple) with accuracy of ±0.3 K. Used absolute pressure sensors show the following characteristics:Operating range of 0-20 bar for the sensor used at the supply of the compressor with an accuracy of 1% of the full scale range
- Operating range of 0-30 bar for sensors used for measuring the low and intermediate pressure level with an accuracy of ±1% of the full scale range,
- Operating range of 0-50 bar for sensors used for measuring the high pressure with an accuracy of ±0.5% of the full scale range.

The refrigerant flow rate at the exhaust of the liquid receiver is measured by means of a Coriolis flow meter with a relative error of 0.1%. A heat exchanger (subcooler, SC) has been added in order to insure a small degree of subcooling under any working conditions and thus assure a better flow rate measurement. This subcooler is a 10 cm long concentric tube heat exchanger where the refrigerant in the inner tube can be cooled down with tap water.
The relative error related to the use of flow meter used for the determination of the refrigerant flow rate passing through the high pressure side economizer is also equal to 0.1%.

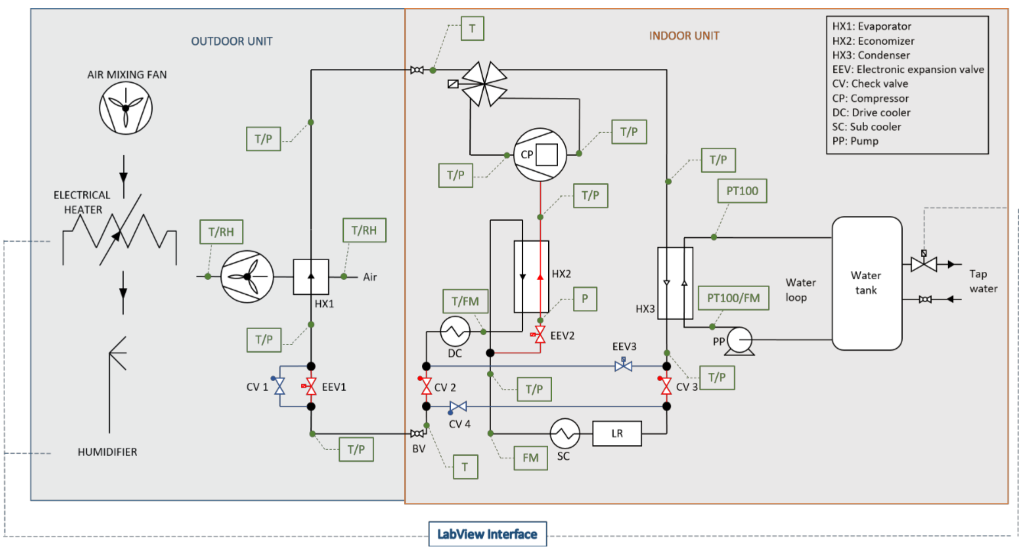

Figure 1: Experimental setup

Water flow rate passing through the condenser is controlled by adjusting the rotational speed of the water pump. The water temperature at the supply of the condenser is adjusted by a PID controlling the opening of a valve on the tap water loop. This latter is used to cool down the water tank that acts as a buffer and helps to maintain steady conditions at the inlet of the condenser. This water tank is thus used as a heat sink that can be either cooled continuously by means of tap water or heated up via variable electrical resistances. Given the low temperature difference between the supply and the exhaust of the condenser (between 3 and 10K), PT100 with accuracy of ±0.1 K have been preferred instead of type T thermocouple. Water flow rate is determined by means of an impulse water meter (4 pulses per litter).

3. TEST CAMPAIGN

Compressor tested is the Copeland model ZHW08 with a swept volume of $2.8\ m^3/h$ at $50\ Hz$ working with the refrigerant R-410A.
Compressor is tested in the experimental setup with and without injection in the operation points shown in Figure 2 and Figure 3. A total number of 68 points are tested in the central operation points of the compressor. For each operation point, 7 different frequencies are tested ranging from 30 Hz to 120 Hz.

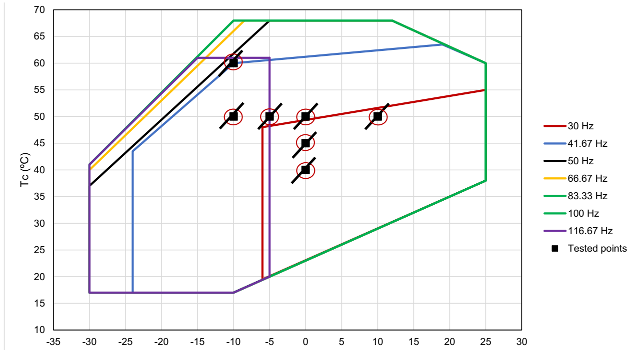

Figure 2: Tested points with injection

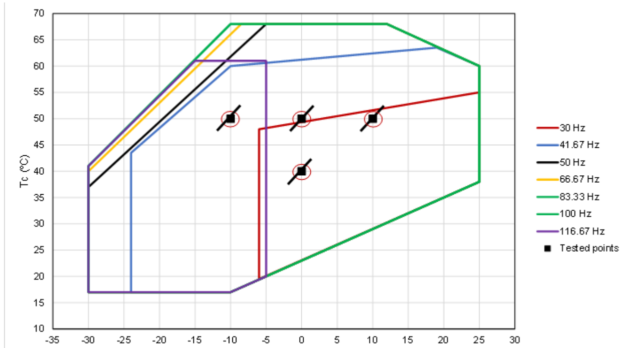

Figure 3: Tested points without injection

After testing, values of volumetric efficiency and isentropic efficiency are calculated.
Volumetric efficiency is defined in the following way:

$$\eta_v = \frac{\dot{m}_{ev}}{\rho_i V n} \qquad \text{Eq. (2)}$$

Where ρ_i is inlet density in $kg\ m^{-3}$, V is the swept volume in $m^3\ rev^{-1}$, and n is compressor speed in $rev\ s^{-1}$.

And compressor isentropic efficiency is calculated as:

$$\eta_c = \frac{\dot{m}_{ev}(h_{is,i}-h_i)+\dot{m}_{inj}(h_{is,inj}-h_{inj})}{\dot{E}} \qquad \text{Eq. (3)}$$

Where h_i and h_{inj} are the inlet and injection enthalpies in $J\ kg^{-1}$, $\mathrm{h}_{is,i}$ and $\mathrm{h}_{is,inj}$ are the enthalpies with the inlet entropy and injection entropy respectively calculated at outlet compressor pressure and $\dot{E}$ is the compressor electrical power input in W. Injection mass flow rate is calculated with the total mass flow rate measured after liquid receiver and evaporator mass flow rate measured after high side pressure economizer.

4. RESULTS

Figure 4 shows the volumetric efficiency obtained for the injection compressor where the labelling 0/40 means the operating point measured at 0°C evaporation temperature and 40°C condensation temperature. Clearly, there are two different zones defined above and below the nominal frequency of 50 Hz.

At frequencies above 50 Hz, volumetric efficiencies increases at higher speeds. Main reason of this observed trend is due to lower relative influence of leakage at higher speeds. Curves trends are similar at the different points measured and total pressure ratio between condenser and evaporator is the reason of different volumetric efficiencies between points, i.e. 0/40 curve has the lowest pressure ratio ($p_r = 3$) and -10/60 curve has the highest pressure ratio ($p_r = 6.7$).

At frequencies below 50 Hz, there is a sudden jump in the volumetric efficiency and isentropic efficiency at 40 Hz. This phenomenon is observed for all conditions except 10/50. This point out of the trend has been analyzed in deep (data analysis calculation, sensors signal, etc.) and replication of the experiment is made. No mistake or errors have been found and measurement replication is giving the same result. Authors cannot propose a clear explanation of the phenomenon, there is some speculations about oil seal or supercharging injection effects that have to be confirmed in future research.

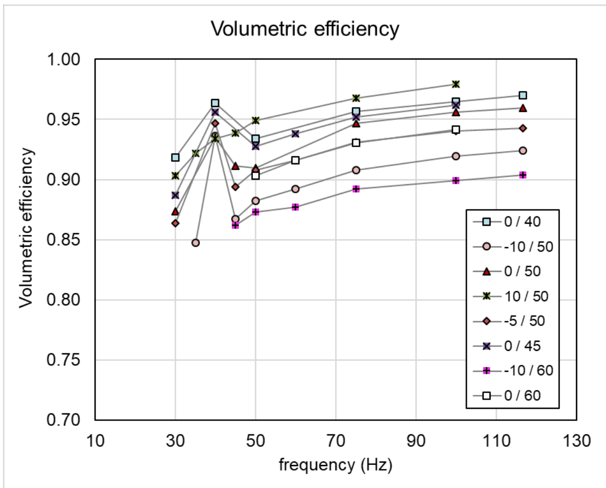

Figure 4: Injection compressor volumetric efficiency

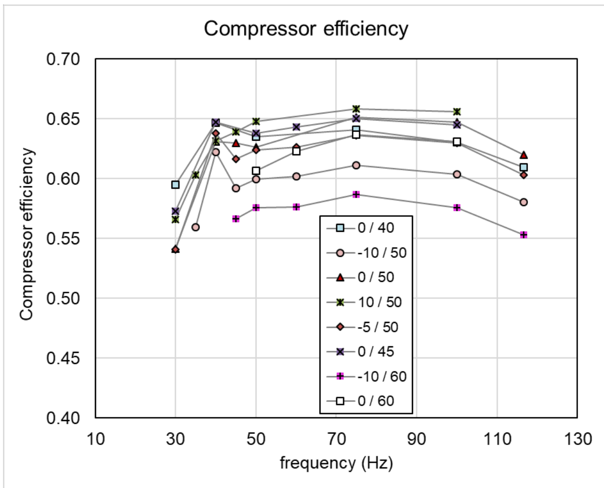

Figure 5: Injection compressor isentropic efficiency

Next figures (Figure 6 and Figure 7) shows comparison of the compressor working with and without injection. Peak values at 40 Hz are not detected in the no-injection mode, giving a clue that the phenomenon is related with the injection process.

Volumetric efficiency values are similar for both cases (injection and no-injection) as the injection process has no big influences in the evaporator mass flow rate as expected.

In the other side, isentropic efficiency values drop with injection compressor at condition 10/50 in all the frequency range and at condition 0/40 only at higher frequencies than nominal. In the 0/50 case, injection compressor performs with better efficiency. This performance is related with pocket pressure matching with intermediate injection pressure. There are phenomena of over-compression or under-compression when injection hole opens.

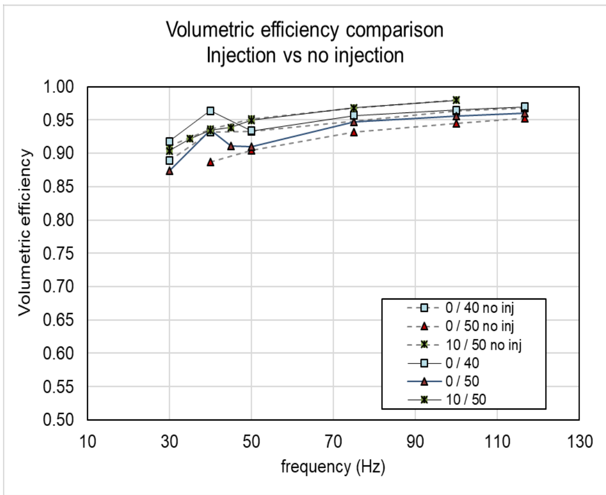

Figure 6: Volumetric efficiency comparison

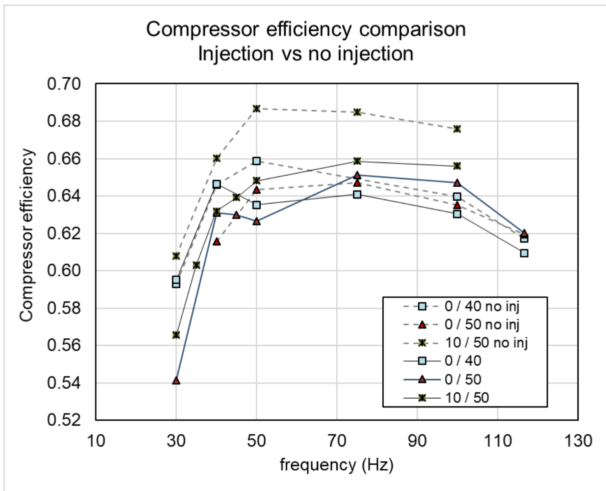

Figure 7: Isentropic efficiency comparison

Injection mass flow rate performance is shown in Figure 8 and Figure 9.

Intermediate pressure ratio shown in Figure 8 presents low influence with compressor frequency. A positive relationship is detected between total pressure ratio and intermediate pressure ratio. Higher values of total pressure ratio leads to higher values of intermediate pressure ratio.

Injection ratio, defined as the ratio of injection mass flow rate over evaporator mass flow rate, shows also a slight dependence with compressor frequency, being the evaporation and condensation temperatures the main dependence factor. Examining both figures, a direct dependence between intermediate pressure and injection ratio is found as stated by Tello-Oquendo (2017) for constant speed injection compressors.

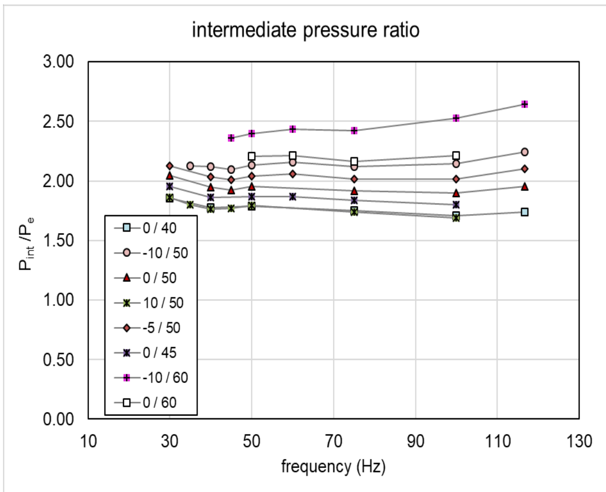

Figure 8: Intermediate pressure as function of compressor conditions

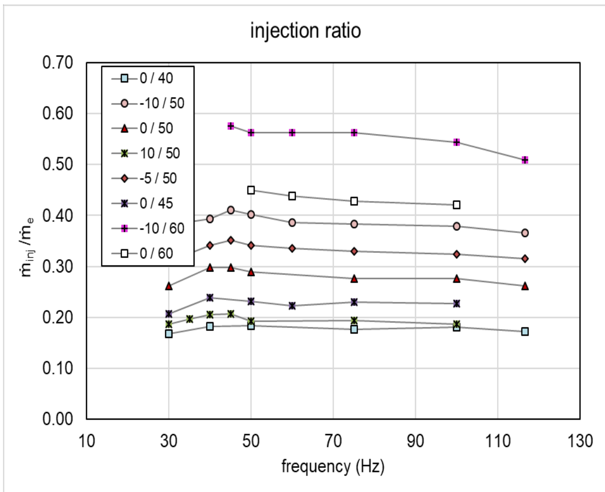

Figure 9: Injection ratio dependence on compressor conditions

Eq. (1) is fitted for each frequency and results are shown in Figure 10. Equations fits perfectly data for each frequency obtaining R-squared values between 0.98 and 1. Figure 11 shows dependence of intercept (A factor in equation (1)) and slope (B factor in Eq. (1)). Both factors shows the same behavior: two straight lines with the common point centered in the nominal frequency of 50Hz.

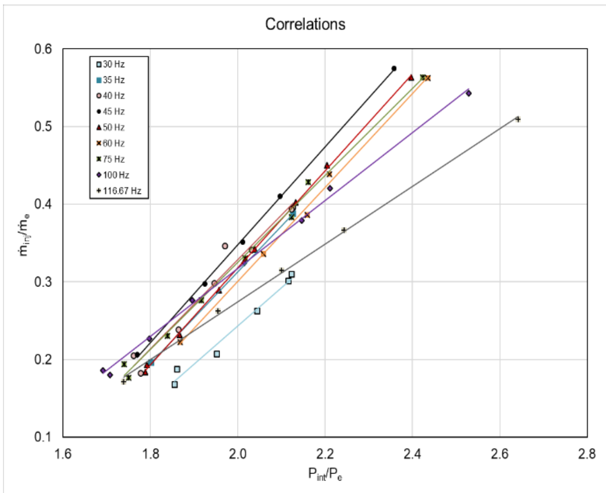

Figure 10: Injection mass flow rate correlation at different frequencies.

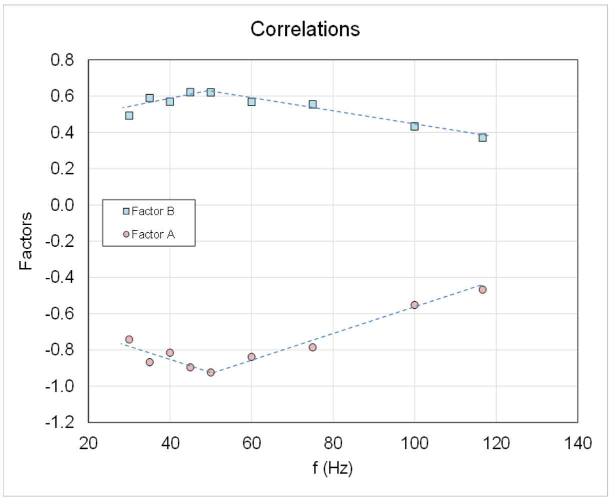

Figure 11: Slope and intercept dependence on frequencies

After examining these results presented, the following correlation is proposed in order to estimate the injection mass flow rate of the compressor:

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

Where coefficients are given in the following table:

Table 1. Coefficients fitted for Equation (4)

	$f < 50\ Hz$	$f \geq 50\ Hz$
A_0	$-5.162 \cdot 10^{-1}$	-1.332
A_1	$-8.462 \cdot 10^{-3}$	$7.468 \cdot 10^{-3}$
B_0	$3.391 \cdot 10^{1}$	$8.361 \cdot 10^{-1}$
B_1	$6.078 \cdot 10^{-3}$	$-3.942 \cdot 10^{-3}$

5. CONCLUSIONS

This paper presents an analysis of variable speed scroll compressors with vapor-injection (VS-SCVI). The following conclusions can be drawn from the study:

- Intermediate injection pressure and injection ratio is weak dependent on the compressor frequency.
- Two different compressor performance is detected depending on the frequency range: below or above nominal frequency of 50 Hz.
- An increase of volumetric and isentropic compressor efficiency is detected in around the frequency of 40Hz. This phenomenon can be related with the injection process flow dynamics.
- 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 the frequency.

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