

EXPERIMENTAL INVESTIGATION ON VARIABLE SPEED COMPRESSOR WITH AND ELECTRONIC EXPANSION VALVE IN A REFRIGERATION SYSTEM

Taynara Geysa Silva do Lago, taynaragsl@fem.unicamp.br

Claudia Rosa do Espirito Santo Nóbrega, claudiarosa@fem.unicamp.br

Kamal Abdel Radi Ismail, kamal@fem.unicamp.br

Luiz Felipe Mendes de Moura, felipe@fem.unicamp.br

UNICAMP-FEM, Departamento de Energia.

Rua Mendeleiev, 200. Cidade Universitária 13083970 - Campinas, SP - Brazil - Caixa-Postal: 6122

Abstract. *This work reports the results of an experimental study realized on a vapor compression refrigeration system with an electronic expansion valve and variable speed compressor with the objective of energy saving and improving system performance. The experimental rig is composed of two systems. The main system is composed of a forced air condenser unit, evaporator, hermetic compressor and expansion elements (thermostatic expansion valve and the electronic expansion valve), while the secondary system has a pump for circulating the secondary fluid (alcohol), and air conditioning heat exchanger. The experimental data was obtained from the manufacturer's data to identify the optimum points of operation. Based on these findings, the influence of the compressor speed and the opening of the expansion device on the performance of the refrigeration system were investigated. The results showed that for each compressor speed there is an opening of the electronic expansion valve (EEV) which gives maximum coefficient of performance, COP, and stable degree of superheat lower than that obtained with thermostatic expansion valve (TEVs). This allows better use of the evaporator surface area and enhancement of the total efficiency of the system.*

Keywords: *Variable Speed Compressor, Electronic Expansion Valve, Coefficient of Performance, Efficiency*

1. INTRODUCTION

The energy consumption and demand are increasing in recent years, as well as the ascendancy in the use of refrigeration and air conditioner. The increasing use of electric power has caused many economic and environmental damage, and necessary new investments in building optimized power generating units, with the interest to meet growing demand.

With regard to the various existing cooling systems at the present time, the vapor compression refrigeration system is still in use, especially in domestic refrigerators, home air conditioner and refrigeration plants, where it is essential to control the performance of such equipment and the development of thermodynamic models.

Addition to the compressors with variable speed, electronic expansion valve are extremely important in refrigeration systems. The adjustment of the degree of opening of the expansion element directly affects the refrigerant flow in the circuit that influences the degree of superheat, and provide a pressure difference between the condenser and evaporator.

The variation of the compressor speed is the most efficient way to control the system cooling capacity, this is because the cooling capacity is adapted to the load (Tassou and Quereshi, 1998). Thus, for a low load condition, the refrigeration apparatus can reduce the compressor speed, causing losses are reduced and less power is absorbed into the network.

Aprea and Mastrullo (2002) compared the energy performance of a refrigeration system, fitted with electronic expansion valve (EEV) and with thermostatic expansion valve (TEV) in permanent and transient conditions. They considered two situations: departure equalized and no equalized. The valves were mounted in parallel on the input of an evaporator with forced air convection belonging to a refrigeration system with a water cooled condenser and a semi-hermetic compressor. The tests were performed using refrigerants R22 and R407C. The electronic expansion valve controlling the degree of overheating in evaporator outlet Analysis of refrigeration system behavior using variable speed compressor at 10°C. The authors concluded that the EEV and TEV provided similar performance coefficients in steady state conditions, which did not occur in transient regime, where the EEV provided better performance. According to these authors, the main advantages of EEVs are a rapid response to changes in operating conditions, ease of control of superheat setting (setpoint) and the smallest fluctuations in controlling this variable. Also, emphasize that the EEVs are more suitable expansion device mounted to operate in systems with variable speed compressors, despite this observation, they did not study the effect of the rotation of the compressor.

Choi et al. (2003) studied experimentally the control of refrigeration capacity of an air condenser mounted with a scroll compressor of variable rotation and with two evaporators controlled by two EEV with step motor. It was concluded that maximum capacity of refrigeration in each rotation is achieved when the superheat degree at the outlet of evaporators becomes equal to 4°C.

Pottker (2006) investigated the influence of refrigerant charge, the rotation of compressor and the opening degree of electronic expansion valve in the refrigeration system performance, in order to identify operation conditions of maximum efficiency.

Aynur et al. (2009) pointed out that the volume air conditioning systems variable air (VAV) were introduced in 1960 and aimed at reducing the consumption of power during periods of operation at partial load.

Alegrias (2009) analyzed the effect of changes in rotation speed compressor on performance of a cooling system for steam compression using R-134a as refrigerant fluid in order to obtain the maximum COP. The behavior and response system made necessary the study of the effect of the dimensions of the capillary tube used in the expansion process. Furthermore, it compared the combined effects of the element with the variable speed compressor.

Kizilkan (2011) concluded that an advantage of the variable speed compressor refrigeration systems is the possibility of modifying the equipment refrigeration capacity, because of this the performance of the refrigerating system can be improved for operation at the optimum frequency of the compressor, changing the machine speed to certain condition thermal loading.

Li et al. (2015) developed a power model of a semi-theoretical compressor to air conditioning units type roof, equipped with variable speed compressor and variable speed fan, based on theoretical analysis and experimental studies. In conditions normal, the compressor power is correlated with the outdoor air temperature and velocity compressor with relative error of $\pm 8\%$. The model was developed for energy reduction compressors in direct expansion.

In the present study experiments were realized the interaction between speed variable compressor and electronic expansion valve in the refrigeration system in order to identify optimum point of operation for maximum efficiency. Experimental tests were then accomplished firstly with EEV operating of controlled form and varying the rotation of the compressor after independently by varying the rotation of the compressor and the opening of an EEV. These experimental data are important to develop control strategy in refrigerant systems

2. ANALISYS EXPERIMENTAL

Figure 1 shows a schematic layout of the test rig under study composed of a refrigeration system for vapor compression which uses R-134a refrigerant and a secondary fluid system with air conditioning using a ethanol solution as working fluid.

The mechanical vapor compression refrigeration system is divided into two parts. The low pressure system is composed of the refrigerant flow control, the evaporator and suction line. The high pressure system consists of the compressor of the exhaust line or hot gas line, the condenser and the liquid line, as shown in Figure 2.

The compressor used is hermetic alternative model of variable capacity of Embraco. The gas compression is made in a variable volume chamber by a piston, with the suction and discharge valves, arranged to pump coolant. A frequency inverter controlled by an external frequency signal does the variation of compressor speed. The frequency range is 53-150 Hz, and the speed range is 1600-4500 rpm.

The condenser fabricated by Elgin is a heat exchanger for forced air-cooling fitted with copper tubes and fins robust which ensures efficiency to reject heat. Its thermal capacity is 3/4 HP (559.3 W) and pipe 6 mm internal diameter coupled liquid line display in expansion valve.

The evaporator is a heat exchanger concentric tubes countercurrent flow. The internal tube of copper, with 1300 mm length and 6 mm diameter, which is circulating R-134a. The secondary fluid, ethyl alcohol solution, flows through the annular section (external tube) 17 mm internal diameter.

The thermostatic expansion valve is TN 2 Danfoss model with the orifice 00. The operation of the valve depends on the pressure and evaporator bulb of the thermostatic control pressure. The thermostatic bulb must be installed at the evaporator outlet in thermal contact with the suction pipe, to continuously monitor the temperature of the refrigerant exiting the evaporator.

The electronic expansion valve, E2V03 model used in experimental bench was donated by CAREL company. This is the only valve of market that responded the need the conditions of the proposed work, since the maximum cooling capacity of the system is around 700 Watts and the maximum capacity of the refrigeration valve is 1.3 kW. By means of temperature sensors and pressure at the evaporator outlet, the actual superheat is calculated by a controller which feeds the actuator of the electronic expansion valve. The driver of the electronic valve, EVD evolution, provides the stator a low-voltage signal to the valve to rotate the rotor clockwise or counterclockwise. The internal mechanism converts the rotary motion into axial displacement of the rod.

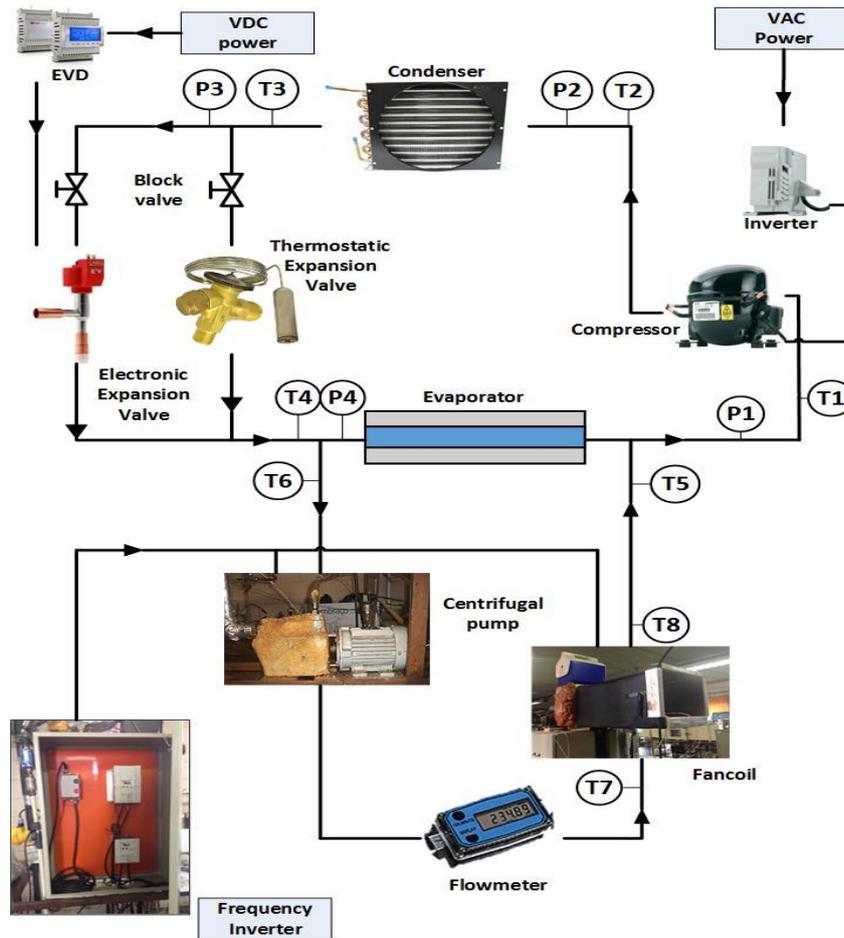


Figure 1- Experimental workbench configuration



Figure 2- Basic circuit of refrigeration of the experimental workbench

The secondary fluid system is composed of centrifugal pump and fan coil. The pump has variable speed control 0-3450 rpm and flow from 5 to 40 liters/min, and promotes the circulation of ethyl alcohol by evaporator, removing heat from same and thus supplying heat capacity for air conditioning. The secondary refrigerant circulates through the fan coil to remove the heat load to be cooled. The capacity of the heat exchanger of the air conditioning system is 600 W.

2.1 Measuring Instruments

Monitoring of the operating conditions of the refrigeration system is very important to control its operation. Specific sensors were used to register the temperature, pressure and flowrate and the data was fed to the acquisition system of Novus.

The temperature measurements were performed by two T-type thermocouples and eight Resistance Temperature Detectors (RTD). All the temperature sensors are calibrated and the temperature measurement showed uncertainty equal to $\pm 0.5^\circ\text{C}$. For pressure measurement were used three pressure transducers, two of Wika company and one of Carel Company. The instrument used in the experimental bench for measuring the flow rate of the secondary fluid is turbine flowmeter type of Omega Company, model of FTB790 series.

To facilitate obtaining the values of the total efficiency of the compressor a power meter. The consumed power meter used is Power Analyser of Instrutherm, model MPR-40. The instrument is connected to the compressor and consumed power measurement is performed (W) in real time.

There are also two frequency inverters. A frequency inverter for the motor pump in the secondary refrigerant, which, in turn, has an analog input 0 to 10, V (DC) and controls the engine rotation speed at range 0 rpm to 3600 rpm. The second frequency inverter controls the motor speed of "fan coil".

The operation of the compressor and variation of its rotation depends on a square wave signal with frequency from 53.4 to 150 Hz, sent to the frequency converter (VCC inverter). Thus, for compressor performance evaluation a waveform generator was used to send the signal to the inverter that feeds the compressor.

The drive used on the workbench for valve control is the EVD Evolution with PID control, model EVD0000E50. For data acquisition, we used FieldLogger of NOVUS to monitor all temperature and pressure transducers in the system.

The experimental uncertainties of the calculated variables were determined in accordance with the best statistical procedures with 95% confidence interval. Table 1 presents the propagation of uncertainty of the calculated variables.

Table 1. Uncertainty propagation of variables

Variables	Uncertainty
Temperature Evaporation and Condensation	$\pm 0,505^\circ\text{C}$
Superheat and Subcooling	$\pm 0,51^\circ\text{C}$
Pressure	± 0.0042 a $\pm 0,0202$ bar
Flowrate R-134a	1.40×10^{-4} a 3.4×10^{-4} kg/s
COP	± 0.05 a 0.08
Thermal Load	± 11.76 a 27.46 W
Efficiency	± 1.02 a 1.88%
Compression Power	± 0.88 a 2.94 W

2.2 Experimental Procedure

In general, two sets of tests were performed: 1) Tests with variation of compressor speed and the electronic expansion valve controlled; 2) Tests with variation of compressor speed and with the opening of the EEV manually. Initially, the compressor speed analysis was done with 13 points compressor speed by varying the frequency 10 to 10 Hz of the compressor maximum speed, 150 Hz (4500 rpm) up to 70 Hz (2100 rpm). 70 Hz (2100 rpm) at 55 Hz (1650 rpm), changes were performed at 5 Hz. Finally, 55 Hz (1650 rpm) to 53.4 Hz (1602 rpm) with variation of 1.6 Hz. These changes were made to coincide with the working points according to the manufacturer's manual. To perform the second set of tests, the valve controller is positioned for manual control of the valve opening with fixed openings close to experimental values obtained with the controller drive of the previous tests, with compressor speed to 1602, 2100, 2700, 3300, 3900, 4500 rpm, varying thermal loads to these rotations.

The heat transfer rates at the evaporator and condenser were obtained both for refrigerant and for the secondary fluid. In the refrigerant side heat transfer rates were calculated by multiplying the mass flow by the refrigerant enthalpy difference between the inlet and the outlet of each heat exchanger. On the secondary fluid heat transfer rates were calculated by multiplying the flow rate of secondary fluid, the density, the specific heat and the temperature difference between the inlet and outlet of heat exchanger.

The actual coefficient of performance (COP) was calculated by dividing the refrigeration capacity by the compressor electric power. The total efficiency of the compressor is the variable used to determine compressor performance. The ratio of the ideal work of compression and the real work of compression is defined as the total compression efficiency.

It is important to observe that the enthalpy of the refrigerant is obtained indirectly by measuring of the temperature and pressure. Thus, it was possible to determine the enthalpies with the insertion of temperature and pressure data obtained by FieldLogger in the CATT3 program (Computer Aided Thermodynamic Table 3).

3. RESULTS AND DISCUSSION

3.1 Experimental analysis with EVV and VVC

Initial analysis was realized by the use of the electronic expansion valve and the compressor speed as the pre-established variables. Thus, there was a change in the compressor speed in the range between 1602 rpm and 4500 rpm at an initial mass flow rate of ethanol of 0.072 kg / s.

Figure 3 presents the changes in COP and flow rate, Figure 4 shows the condensing pressure and evaporation, while Figure 5 presents the power consumption and thermal load of the system. The results shown in these figures depend on compressor operating speed. To obtain these data, the experiment was started by activating the system with the maximum speed of the compressor 4500 rpm (150 Hz) and the electronic expansion valve automatically controlled to an 8 K superheat. It was also adjusted the frequency inverters pump and fan coil to heat load required for such rotation letting the system reach steady state for evaluating the COP and other related parameters. Soon after the compressor speed is reduced by modifying the frequency of 10 10 Hz to rotation 2100 rpm (70 Hz), then variation of 5 in 5 Hz to rotation 1650 rpm (55 Hz) and a final variation 1.6 Hz to the minimum speed. Always taking care to obtain continuous and thus evaluate the system in each working speed to the minimum value stipulated 1602 rpm (53.4 Hz).

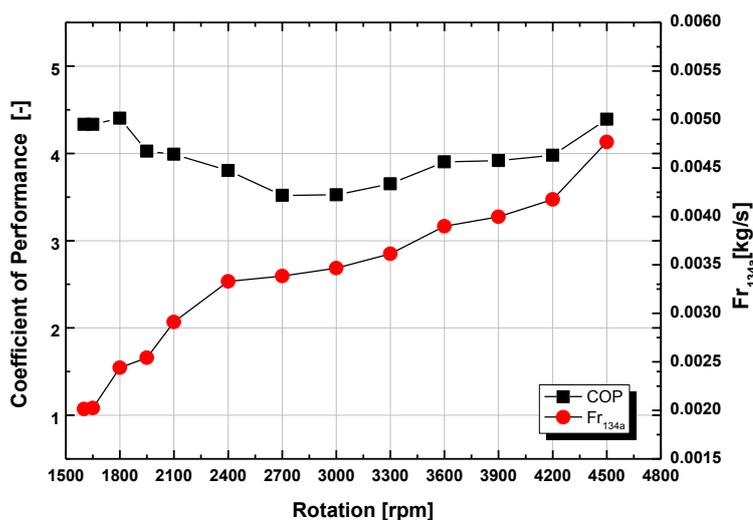


Figure 3 - COP and the flow rate (fr134a) in function of compressor operating speed.

It is worth mentioning that, the use of the electronic expansion valve causes reduction of condensation pressure in all operating conditions of the compressor, compared to the use of a thermostatic expansion valve. Moreover, EEV has fast reactions to the capacity changes, facilitating the rapid stabilization of the system. Thus, for rotations 1602 rpm (53.4 Hz) and 2100 rpm (70 Hz) we obtained higher COP values because of the low condensation temperatures, lower compression rate and lower values of compressor power consumption. The increase of the compressor speed from 2400 rpm (80 Hz) to 3900 rpm (130Hz), increase the condensation pressure, increase the mass flow of the refrigerant and load thermal and the power consumption showed much higher values, and lower COP. From 4,200 rpm (140 Hz) to 4500 rpm (150 Hz), the COP showed higher values because of the maximum thermal loads and coolant flow, and reasonable power consumption, since the latter did not vary much from that of the speed of 4200 rpm (100 Hz) at 4500 rpm (150 Hz).

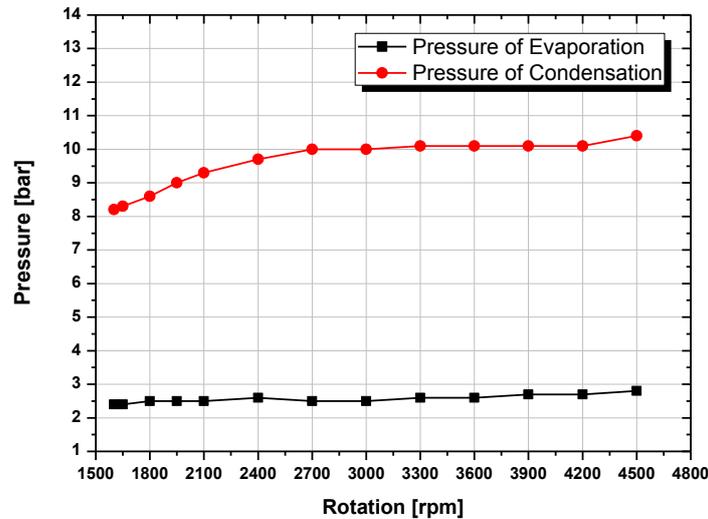


Figure 4 - Pressure Evaporation and Condensation in function of compressor operating speed.

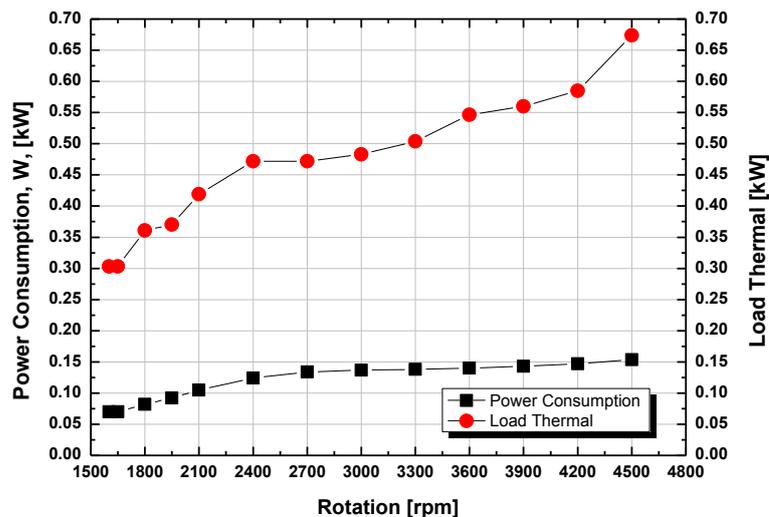


Figure 5 - Thermal Load and Power Consumption in function of compressor operating speed.

3.2 Analysis of the opening of the EEV for different rotations

The objective here is to evaluate the effect of the opening of the electronic expansion valve for the different rotations of the compressor. To perform the test, the valve controller is positioned for manual operation with fixed openings close to experimental values obtained with the controller drive of the previous tests, for compressor speed (1602, 2100, 2700, 3300, 3900, 4500 rpm) and varying thermal loads.

Figures 6 and 7 present, respectively, the evaporation and the condensation pressures due to the opening of EEV for each rotation of the compressor. Figure 8 shows the influence of the opening EVV on the COP.

It may be noted that for each rotation of EEV there is an opening that increases the COP. Thus, the coefficient of performance can be maximized for each rotation by adjustment of the opening of the expansion valve. It is worth noting that the higher the speed, the greater the valve opening.

Also the same figures show that independent of rotation, increasing the opening of EEV increases the evaporation and the condensation pressures, and that as speed increases, the optimum evaporation pressure decreases and the condensation pressure increases which means increase in the compression ratio. This increase in compression ratio reduces the maximum COP with increasing rotation, as illustrated in Figure 8.

The increased mass flow of refrigerant in circulation raises the evaporation pressure and thus increases the refrigeration capacity. The change of the thermal load, as shown in Figure 10, is proportional to the refrigerant flow, as can be seen in Figure 9. The higher thermal load requires higher mass flow rate, which is accomplished by higher rotational speed of the compressor. The variation of the opening of EEV, rotation of the compressor, and the subcooling evaporation temperature directly affects the flow of refrigerant in the refrigeration cycle. When the opening of EEV increases, the refrigerant flow that is sent to the evaporator also increases.

The increase in temperature and evaporation pressure with the an increase in the opening of VEE, and increase of refrigerant in the evaporator, results in a decrease in the value of the mass flow rate of the refrigerant in the condenser and reduction of the degree of subcooling. The condensation temperature is an important parameter that changes with evaporation temperature. When the evaporation temperature increases, the condensation temperature increases due to the compressor speed and the thermal load, as shown in Figure 11.

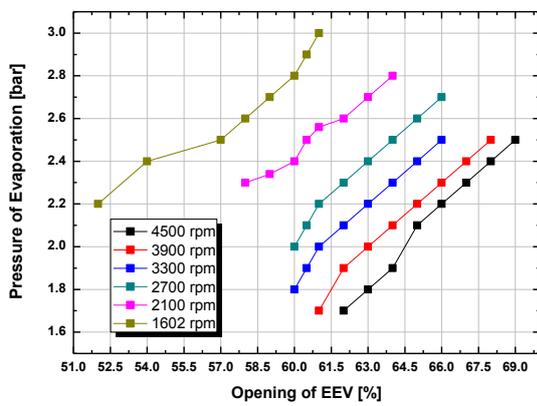


Figure 6 - Evaporation pressure in function of the opening of EEV

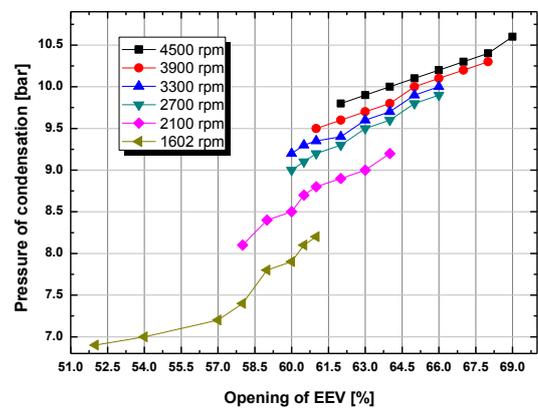


Figure 7 - Condensing pressure in function of the opening of EEV

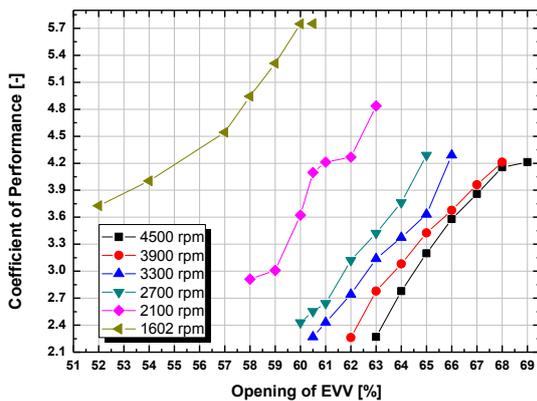


Figure 8 - COP in function of the opening of EEV

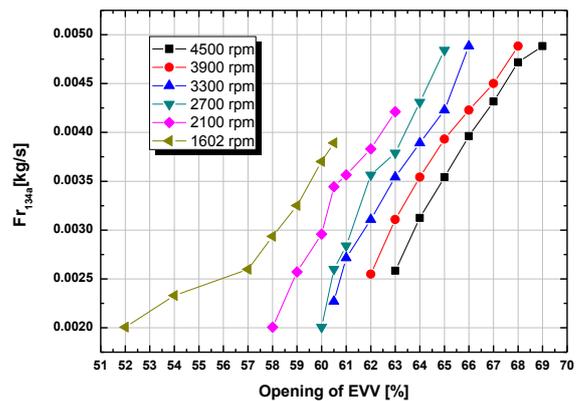


Figure 9 – Flow rate of refrigerant in function of the opening of EEV

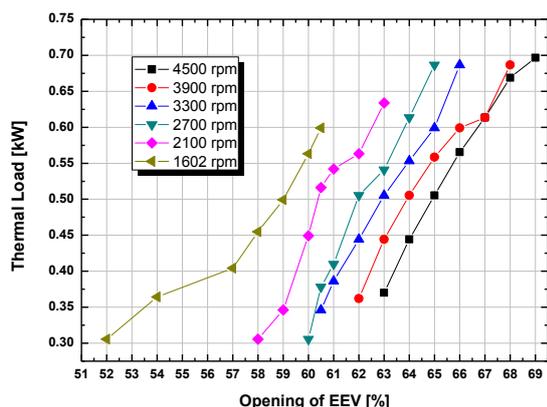


Figure 10 - Thermal Load in function of the opening of EVV

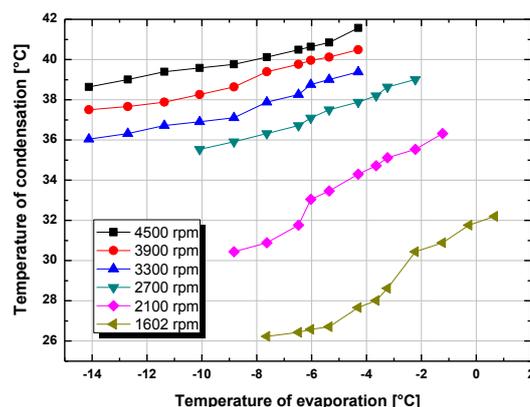


Figure 11 - Variation condensation temperature with evaporation temperature

4. CONCLUSION

Variable Speed Compressor adjusts the speed according to the thermal load without harming the efficiency parameters.

Systems with electronic expansion valves and variable speed compressor are more efficient because they operate at a maximum point COP and provide a cooling capacity equivalent or close to the thermal load demand.

The results point out opportunities for implementing multivariable control systems, which take advantage of adequate interaction of compressor speed and the opening of the EEV and hence maximize the efficiency of refrigeration systems.

5. ACKNOWLEDGEMENTS

The first author wishes to thank the CAPES for the study scholarship, CAREL by donation of electronic expansion valve, NOVUS AUTOMATION by donation of data acquisition system, and the second author wish to thank the FAPEMA for the study scholarship while the third author wishes to thank the CNPQ for the PQ grant.

6. REFERENCES

- Aprea, M. and Mastrullo, R., 2002. "Experimental evaluation of electronic and thermostatic expansion valves performances using r22 and r407c". *Applied Thermal Engineering*, Vol. 22, pp. 206–218.
- Aynur, T. N., Hwang, Y. and Radermacher, R., 2009. "Simulation comparison of VAV and VRF air conditioning systems in an existing building for the cooling season". *Energy and Buildings*, v.41, pp. 1143- 1150.
- Alegrias, J. G. P., 2009. Performance Analysis of the capillary tube in small refrigeration system with variation of compressor speed. Dissertations. Uberlândia: UFU, BRASIL.
- Choin, J., Kim, Y., 2003. "Capacity modulation of an inverter-driven multi-air conditioner using electronic expansion valves". *Energy*, Vol. 28, pp. 141-155.
- Kizilkan, O., 2011. "Thermodynamic analysis of variable speed refrigeration system using artificial neural networks". *Expert Systems with Applications*, Vol. 38, pp. 11686–11692.
- Lago, Taynara G., S., 2016. Experimental Study and Control of a Refrigeration System with Variable Speed Compressor and Electronic Expansion Valve. Dissertations. Campinas: UNICAMP, BRASIL.
- Li, Y.; Liu, M. and Lau, J., 2015. "Development of a variable speed compressor power model for singlestage packaged dx roof top units". *Applied Thermal Engineering*, v. 78, 110–117.
- Pottker, G., 2006. Analysis of the combined effect of variable action compressors and expanders on the cooling system performance. Dissertation. Santa Catarina: UFSC, BRASIL.
- Tassou, S. A. and Quereshi, T. Q., 1998. "Comparative Performance Evaluation of Positive Displacement Compressors in Variable-Speed Refrigeration Applications". *International Journal of Refrigeration*, Vol. 21, No. 1, pp. 29-41.

7. RESPONSIBILITY NOTICE

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