# STUDY OF A REFRIGERATION SYSTEM OPERATING WITH VARIABLE SPEED COMPRESSOR AND AN ELETRONIC EXPANSION VALVE

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**Abstract.** *This paper deals with the evaluation of an experimental refrigeration system with maximum cooling capacity of 15 kW, operating on an automated form, with variable speed compressor and electronic expansion valve. The first goal was to establish the optimal conditions for the operation of the experimental facility that could be an air conditioning operating during the summer. At the same time and collectively to the first objective, instrumentation and control strategies were adopted, allowing extending the focus of this research to another topic, energy savings in air conditioning systems. The experimental facility has been submitted at two different configurations of tests. The first depicted a conventional air conditioning system that, basically, consists of an alternative compressor working at the nominal frequency, two concentric tubes heat exchangers, a thermostatic expansion valve and the refrigerant R22. In the second case, the compressor speed was changed by an inverter frequency and an electronic expansion valve (EEV) replaced the thermostatic expansion valve (TXV), the other parameters were maintained without modifications. Two experimental designs were created (one for each system configuration) to verify the importance of a couple of parameters in the overall behavior of the refrigeration system in steady state flow. The methodology used during the analysis was the RSM (response surface methodology). The first experimental plan was based on the coefficient of performance (COP) analysis and it returned the optimum operation conditions of the conventional system, and prove the importance of refrigerant charge among other parameters on the COP. The results of the second battery of tests showed that the COP was extremely sensitive to variations of the frequency of compressor operation and the degree of superheating, demonstrating the flexibility of the system for applications of variable cooling capacities. Finally, the comparison between the two configurations of the system was performed in the transient regime. The results showed that when the system operates at frequencies below 60 Hz and it is implemented a PID controller in the mechanism of expansion, it has enabled the improvement in COP of the automated system compared to the COP of the conventional system, which used an on-off controller. In the moments that the compressor was turned on, the COP of the conventional system was established in 3.1. While, the COP of the automated system ranged from 4.8 to 5.4, following the modulation of the electronic expansion valve throughout the test period. It resulted in an average monthly consumption of electricity 35% less than the consumption of the conventional system.*

***Keywords**: air conditioning system, variable speed compressor, eletronic expansion valve, COP.*

## 1. INTRODUCTION

Since the creation of the vapor compression cycle in 1834, researches in the industry of refrigeration and air-conditioning were directly linked to the development of techniques that allowed improving the efficiency of equipments used in this sector. In recent decades much has been discussed about the environmental degradation caused by the emissions of greenhouse gases in the atmosphere. Since then, the Montreal (1987) and the Kyoto (1997) protocols are seeking to reduce the emission of these gases. The carbon dioxide, mainly those emitted after the burning of fossil fuels to generate electricity and promote the work necessary for the operation of compressors, contributes indirectly to global warming.

The refrigeration and air-conditioning use control techniques to ensure a particular thermal condition. This conditioning refers both to the thermal comfort for people as well as the maintenance of special conditions required for processes or products. Some authors estimate that electricity consumption in developed countries for applications in Heating, Ventilation, Air Conditioning and Refrigeration (HVACR) in the residential, commercial and industrial is responsible for 30% to 35% of the total electric energy consumed.

The decreasing of the COP of different configurations of air conditioning due to the losses generated by the on-off modulation have been addressed by Nguyen *et al*. (1982) who concluded that the intermittent operation of the system causes several problems, such as the high amount of energy consumed to drive the compressor and maintain an optimum temperature of evaporation.

Considerable energy savings can be achieved by combining the frequency inverter and the electric motor of the compressor. Antunes *et al*. (2007) experimentally evaluated the COP of a chiller. They analyzed the system efficiency ahead of the technique of the variation of mass flow of refrigerant in the refrigeration circuit, which consisted of manipulating the TXV for the entire frequency range of the compressor work, in order to maintain the temperature of evaporation constant at -5.0 ºC. The results indicated that the optimal frequency range was between 40 Hz and 50 Hz, it resulted in higher values of COP.

According to Maia (2000) typical mechanisms of expansion, such as TXV, are not quite capable of harmonizing the variable speed operation with the appropriate flow of refrigerant in the evaporator.

This paper aims to contribute with the knowledge about the necessity of replace old techniques of control in refrigeration by new technologies capable of promoting reductions in energy consumption and consequently less damage to the environment.

For this, two experimental plans were developed. The first refers to a conventional refrigeration system (on-off control) and the second refers to an automated system. The comparison between them will demonstrate that significant power savings can be achieved when better control techniques are used in the mechanism of expansion and when the compressor operates bellow of the nominal frequency.For this, two experimental plans were developed. The first refers to a conventional refrigeration system (on-off control) and the second refers to an automated system. The comparison between them will demonstrate that significant power savings can be achieved when better control techniques are used in the mechanism of expansion and when the compressor operates bellow its nominal frequency.

## 2. METHODOLOGY

Initially, the refrigeration system has been subjected to experimental designs to examine the importance of some of parameters in the global behavior of the refrigeration system in steady state. The experimental facility has been submitted at two different configurations of tests. The first depicted a conventional air conditioning system and the second depicted an automated system. In addition, a comparative analysis of the operation of the conventional system and the automated system was made, both in the transient regime with the aim of visualizing the behavior of various system parameters (temperatures, mass flow of refrigerant, refrigeration capacity, power consumption and COP) against the two types of control adopted (On-Off and PID).

### 2.1. Experimental Facility

The experimental facility was built with the intention of observing the properties of the working fluids at various points in the system, showing its actual behavior.

The equipments of the experimental facility are basically an alternative compressor, two concentric tubes heat exchangers, two expansion valves, a filter drier, a Coriolis mass flow meter and all appropriate instrumentation. The installation of two mechanisms of expansion, in by pass, was performed with the intention to use each valve separately for each experimental plan. Figure 1 depicts, schematically, the experimental facility of this study.

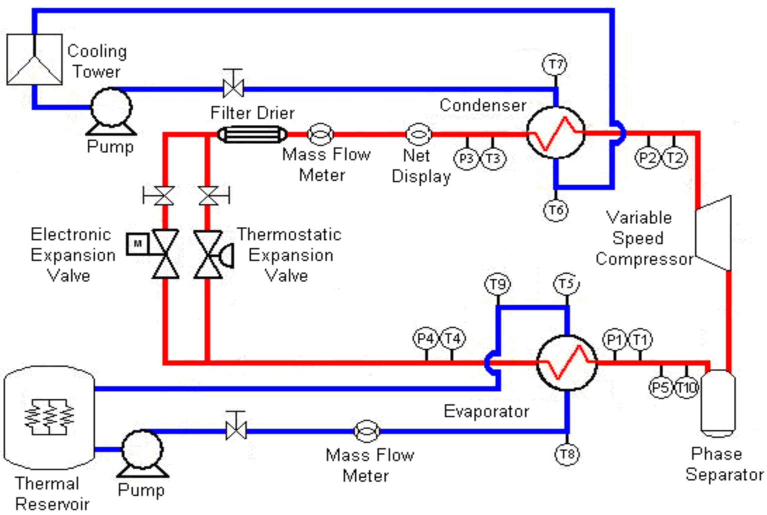



Figure 1. Schematic representation of the experimental facility

Sensors were used to measure the temperature (PT-100) and pressure (piezo-resistive), the data acquisition was conducted using an electronic board with analog output signal. A Coriolis flow meter was used to measure the flow of R22 in the main circuit. The analog signals of temperature, pressure and flow were converted to digital through the PLC. Data were monitored and managed through an interface created with the software LABVIEW. The secondary fluid, which is the water that circulates through the condenser, flows through a cooling tower. Moreover, the heat transfer in the evaporator is accomplished using a thermal storage tank that simulates a thermal load through an electrical resistance, with the function of maintaining stable the desire water temperature in the inlet of the evaporator. The electrical resistance has a power of 21.0 kW and is controlled by a proportional controller, programmed in the PLC. A frequency inverter was also installed, mainly, to control the speed of the compressor according to the system required.

### 2.2. Design of Experiments

The methodology used during the analysis was the RSM (response surface methodology). According to Calado and Montgomery (2003), that use the response surfaces when the variables are influenced by many independent variables and the objective is to optimize these responses. The generation of a surface response of a given variable appears in a central composite design, which represents the array of experiments carefully organized according to the factorial, axial and central points to the factor level.

The first experimental plan was based on the COP analysis. The intention was to return the optimum operation conditions of the conventional system. The second experimental plan, developed to the automated system, aimed to explore the entire frequency range of the compressor.

The identification and selection of factors for experimental designs were based on the prior knowledge of the functioning of the experimental facility and other results achieved by similar studies. The interest variables taken during the first experimental design were: the mass flow of water in the evaporator, [kg/s]; the water temperature at the evaporator inlet, [°C]; and the refrigerant charge, [kg].

The first two factors were chosen in order to establish the ideal conditions of secondary fluid. The third factor was the refrigerant charge. The amount of R22 to fill the main fluid line should be carefully chosen in order that the system operates safely and efficiently.

The second design of experiments for the automated system involved the following factors: the operating frequency of compressor, [Hz]; the degree of superheat, [°C].

The first factor was chosen in order to be held the same task using less energy, i.e. an amount of heat to be exchanged in the evaporator was generated (similar to the refrigeration capacity achieved by the conventional system) and the system operated at speeds below the speed of the compressor on the nominal frequency, 1750.0 rpm at 60.00Hz.

The second factor to be manipulated was the superheating degree of the system. The mass flow of refrigerant was controlled by opening or closing the expansion device. This control is related to the value of the superheating degree adopted in the electronic expansion valve driver.

The input parameters of the secondary fluid (water mass flow and water temperature) in the evaporator and the refrigerant mass were adopted according to those that resulted in the highest COP for the conventional system (results of the first experimental design).

## 3. RESULTS

### 3.1. Analysis of Conventional System

The first experimental design aimed to explore the limits and provide the optimum conditions of operation of the experimental facility. By using the software STATISTICA, it has developed a central composite design with three factors: the mass flow of water circulating through the evaporator, the temperature of water entering the evaporator and the charge of R22. Nineteen tests were planned, eight of them being factorial, six being axial and five being central. The factors were adopted according to Table 1.

Table 1 – Values at lower, central and upper levels of mass flow of water in the evaporator, the water temperature at the evaporator inlet, as well as the mass of R22 for the first experimental design.

| Experimental design factors | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $\dot{m}_W$ [kg/s] | | | $T_{W,INLET,EV}$ [°C] | | | $m_{R22}$ [kg] | | |
| **Levels of factors** | | | | | | | | |
| Lower | Central | Upper | Lower | Central | Upper | Lower | Central | Upper |
| 0.25 | 0.30 | 0.35 | 25.0 | 27.0 | 29.0 | 1.6 | 1.8 | 2.0 |

The most important answer of the experimental design, shown in Figure 2, is the COP of the conventional system.

The correct operation of any refrigeration system operating on the vapor compression cycle should follow several thermodynamic parameters, thus preventing damage of its components. The limits of operation for the thermodynamic aspects are: evaporation temperature (0 °C to 5.0 °C) and condensation (30 °C to 35 °C), the superheating degree (6 °C to 12 °C) and the subcooling degree (3 °C to 10 °C).

The test number 8 represents the optimum operation point of the system. Besides presenting a maximum refrigeration capacity (9.0 kW) and the value of the coefficient of performance reached 2.9.

It is interesting to observe that the COP is extremely sensitive to changes in the mass of refrigerant. This behavior is evidenced in the last two surfaces in Figure 2, observing the axis on the mass of the refrigerant, it is noted that theminimum value of this factor, 1.4 kg, corresponds to the COP value of 1.1. As the charge increases to 2.0 kg, the

COP reaches a maximum value of 2.9. Above the charge of 2.0 kg, the evaporation capacity decreases and the subcooling degree rises, causing, consequently, the fall of the COP.

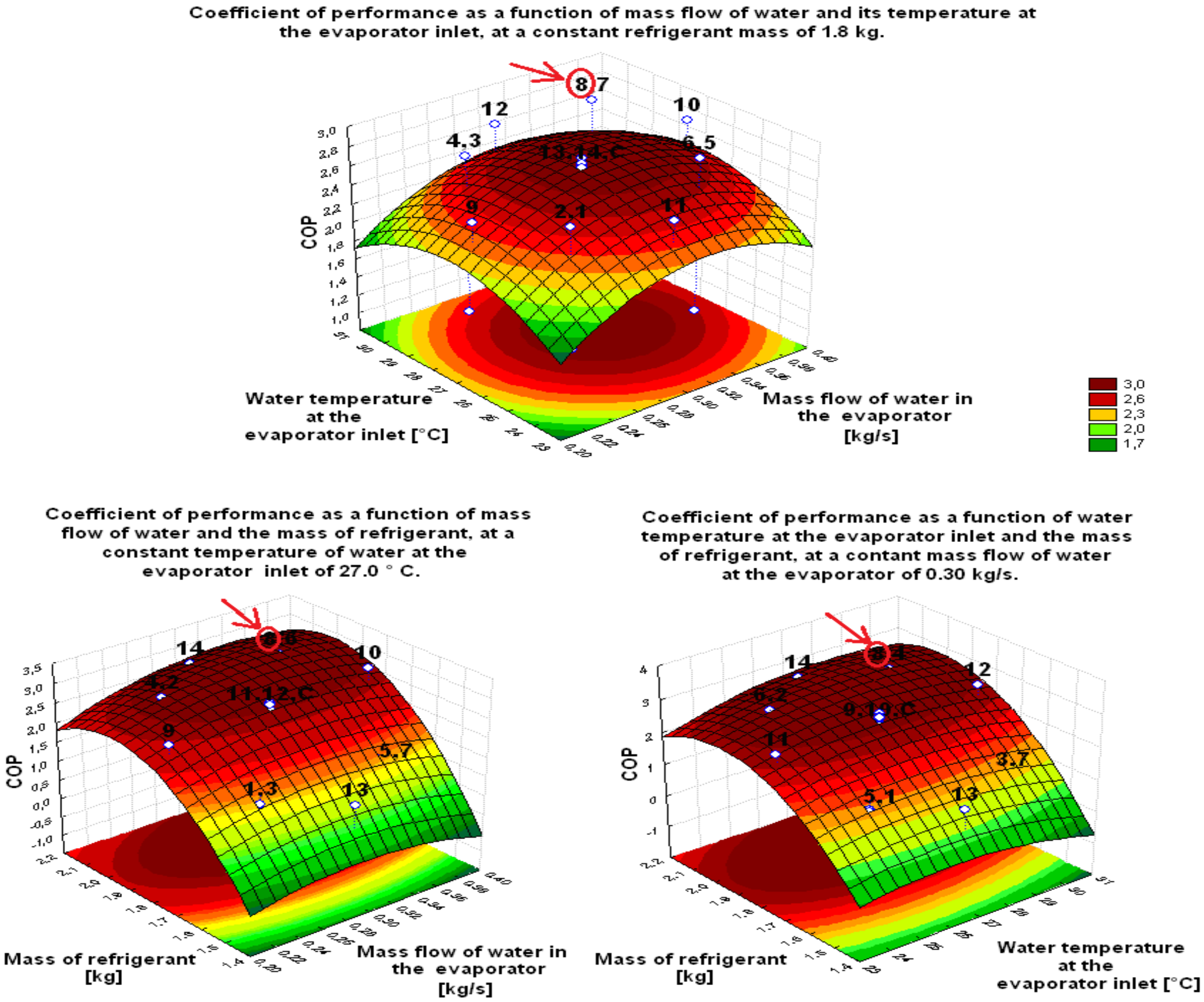



Figure 2 – Response surfaces for the COP of the conventional system.

## 3.2. Analysis of Automated Refrigeration System

The second design of experiments aimed to explore the entire frequency range of compressor operation and optimize the variation of the mass flow of refrigerant in different operating conditions. It has developed a central composite design to two factors: the frequency of compressor operation and the degree of superheat of the refrigerant after the evaporator. Thirteen tests were planned, being four of them factorial, four axial and five central. The levels of both factors were adopted according to Tab. 2.

Table 2 - Values at lower, central and upper levels of frequency of operation of the compressor and the degree of superheat of the refrigerant after the evaporator to the second experimental design.

| **Experimental design factors** | | | | | |
|---|---|---|---|---|---|
| $F$ [Hz] | | | $T_{SH}$ [°C] | | |
| **Levels of factors** | | | | | |
| Lower | Central | Upper | Lower | Central | Upper |
| 40.00 | 50.00 | 60.00 | 5.0 | 10.0 | 15.0 |

The response surface and the counters levels, as visualized in Fig. 3, illustrate the behavior of the COP according to the variation of the two factors of the second design.

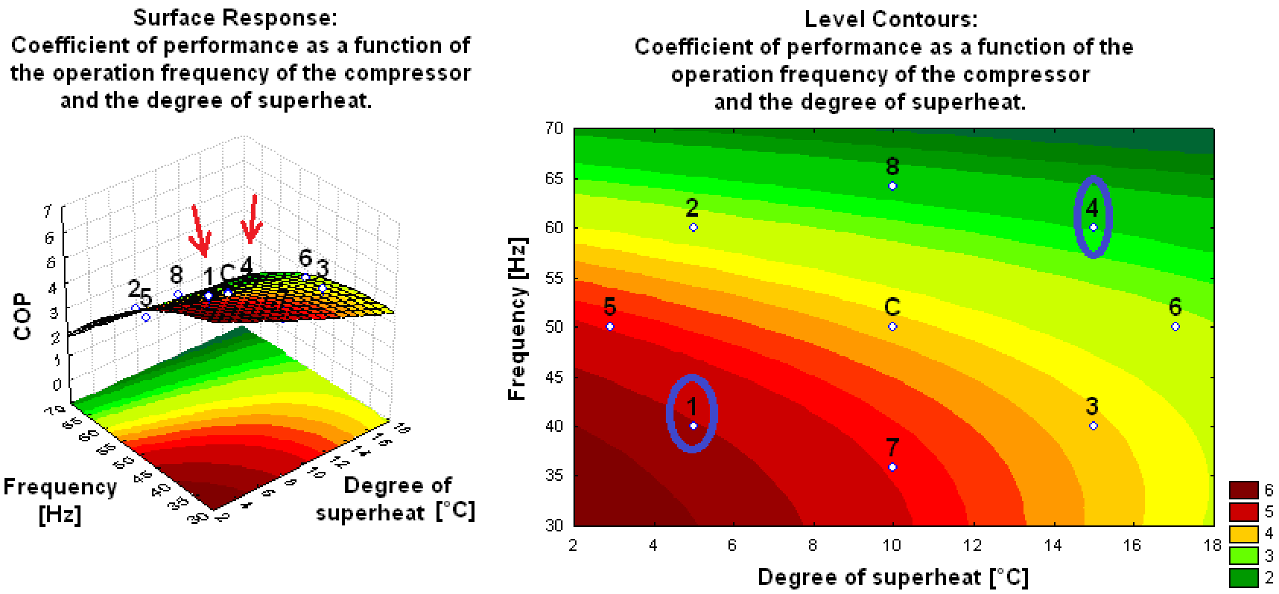



Figure 3 – Response surface and level counters for the COP of the automated system.

The maximum value of COP corresponds to test number 1 and the minimum COP value for the test number 4. It was also observed that values of frequencies below the nominal frequency (60 Hz) combined with minimum values of the superheating degree led the COP of the automated system to maximum values. From the conditions of water supply in the evaporator and charge of R22 fixed, different capacities and COPs were achieved, demonstrating the flexibility during the system operation.

The test number 2 was performed in 60 Hz, 5.0 °C of superheating and 2.0 kg of R22, the same condition of the test number 8 for the conventional system. The increase of the COP to 3.5 is related to the use of the electronic expansion device that controlled the degree of superheating with more accuracy.

Equation 1 represents the empirical model for the COP of a commercial air-conditioning system with a $R^2$ of 0.89.

$$COP = 9.12 - 0.10T_{SH} - 0.08F \quad [1]$$

### 3.3. Analysis of the Transient Regime

The analysis of the refrigeration system in steady state flow was controlled by the superheating degree in both the conventional system and automated system. However, the system working in the transient regime is similar to the daily operation of the equipment. With the intention of characterizing the behavior of an air conditioning system operating during the summer, it was conducted over to control a second parameter, the temperature water at the evaporator outlet.

The system controller was designed to maintain the outlet water temperature of the evaporator fixed at 22 °C. The inlet water temperature at the evaporator was always maintained at 29 °C and the water mass flow rate in the evaporator fixed at 0.35 kg/s for all testing situations.

The conventional system operated at 60 Hz and the refrigerant charge of 2.0 kg, the values of these two parameters and condition of the water in the evaporator, mentioned before, were chosen based on test number 8 of the first experimental design, which means the optimum conditions for conventional operation.

For the comparison, it was imposed that the automated refrigeration system should achieve at least the same refrigeration capacity of the conventional system, 9.0 kW. For this, the operating conditions of the automated test followed the test number 1 of the second experimental design, in other words, the condition of maximum cooling capacity and COP. Therefore, the superheating degree remained at approximately 5.0 °C, with the charge of two kilograms of R22 and the operating frequency of the compressor fixed at 40 Hz.

It is observed in Fig. 4 that the action of each controller starts when the water temperature at the evaporator outlet reaches 22 °C. The reaction is distinct from the conventional system and the automated system. While the conventional system disables the compressor, the automated system begins the process of modulation, never allowing the controlled variable exceeds 23 °C and never turning off the compressor. The on-off control act itself at the time that the water temperature at the evaporator outlet reaches 25 °C, at the moment that the compressor starts. The discharge temperature of the refrigerant during the conventional operation stabilized at 115 °C, while the automated system operated at the temperature of 102°C.

The operating conditions presented very close to the limits for air conditioning during the summer season as can be observed in Fig 5. The superheating degree remained in the range of 7.5 °C to 9.0 °C for the conventional system. This same parameter varied from 2.0 °C to 5.0 °C in the automated operation. The subcooling degree during conventional operation stabilized at 12.5 °C, while this same parameter did not exceed 10 °C for the system operating in the automated mode.

Behavior of temperatures in the heat exchangers

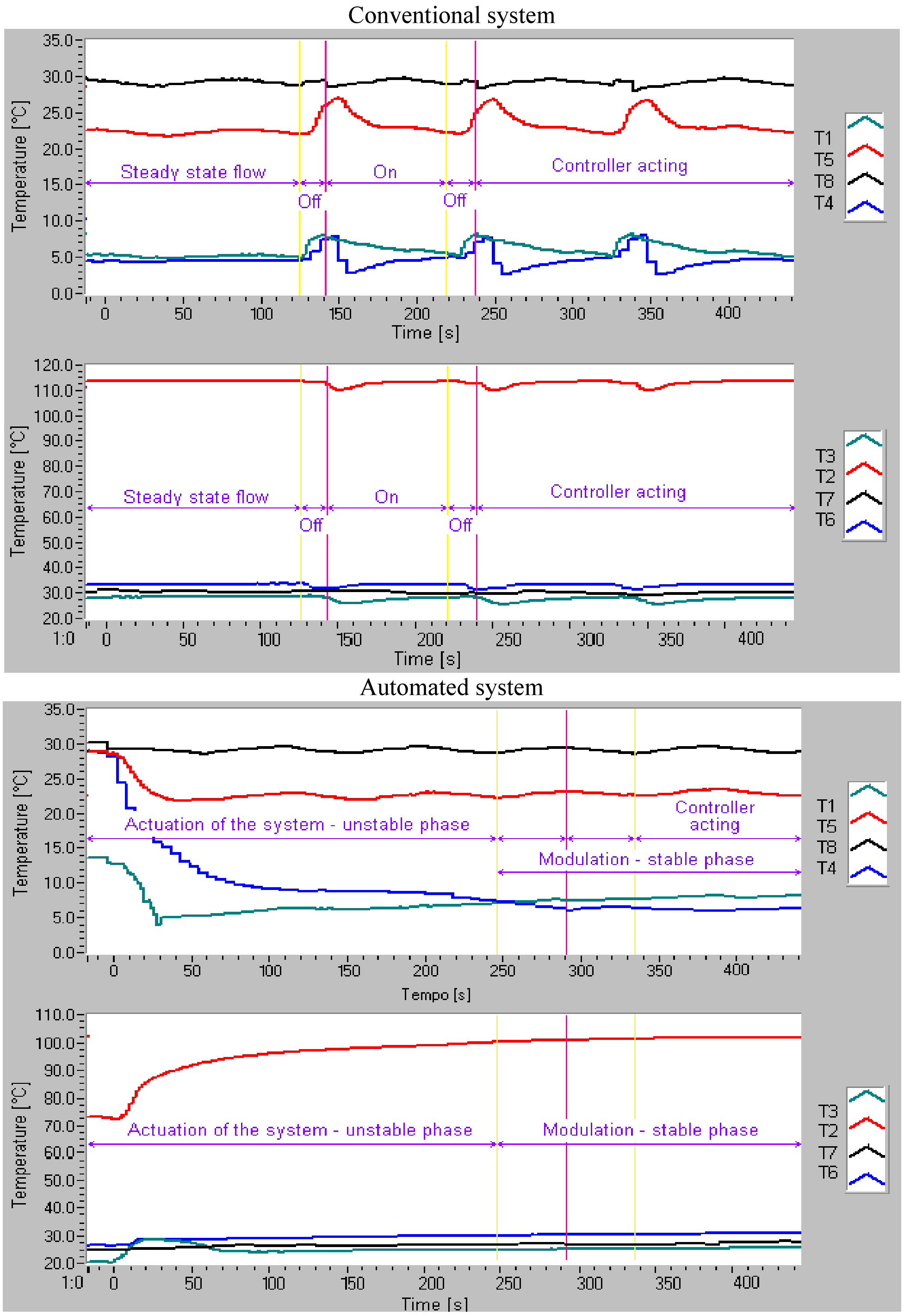
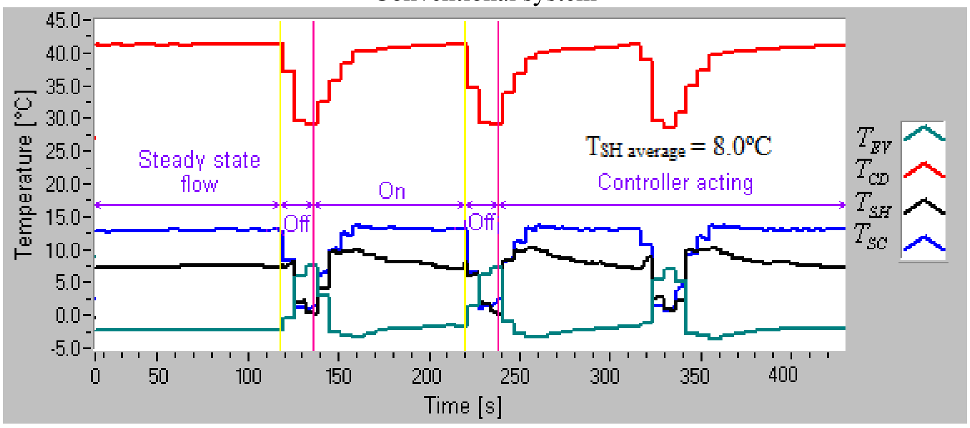



Figure 4 – Behavior of the temperatures of the primary and the secondary fluids during the heat transfer in the evaporator and condenser for each refrigeration system.

Behavior of the limiting parameters for proper operation

Conventional system




Automated system

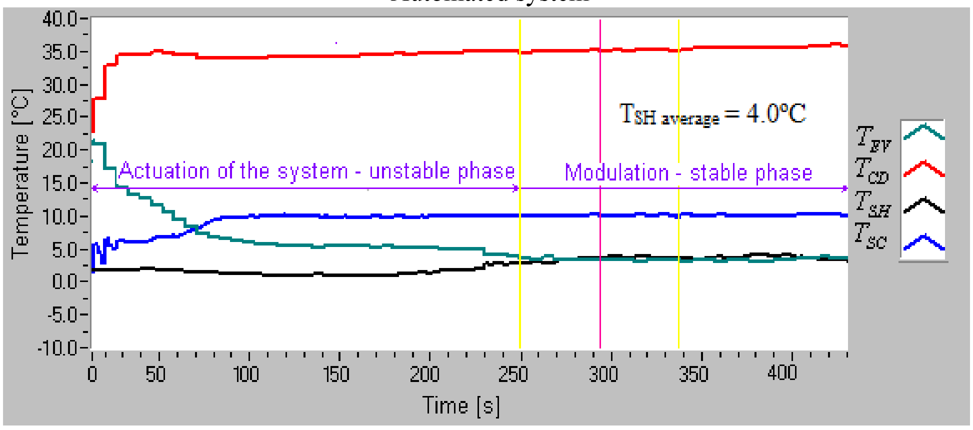
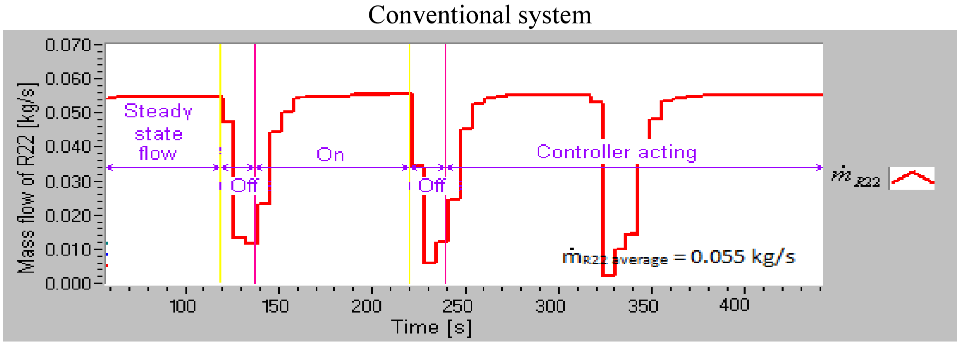



Figure 5 – Behavior of the evaporation and condensation temperatures and the superheat and sub cooling degrees for the refrigeration systems.

Behavior of the mass flow of refrigerant

Conventional system




Automated system

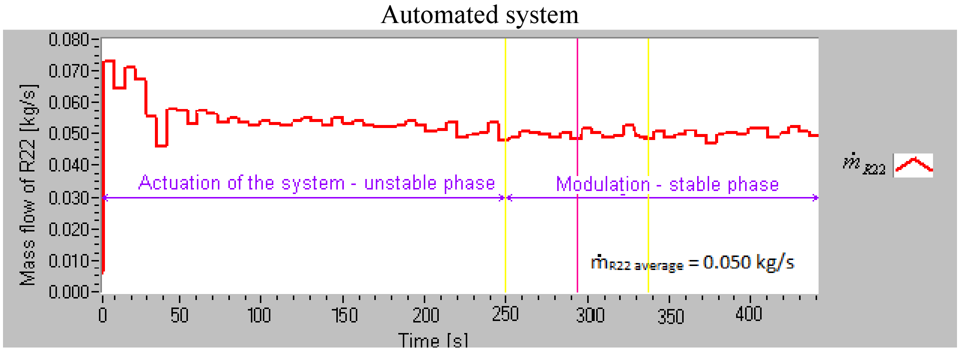



Figure 6 – Behavior of the mass flow of refrigerant for the refrigeration systems.

The differences in the operation conditions are related to the pressures ratio of the system. While the conventional system operated at a pressure ratio of 3.4 to ensure approximately 9.5 kW of refrigeration capacity, the automated system performed the same cooling capacity in the evaporator with the compressor working at a ratio between the discharge and suction pressures of only 2.4.

The thermostatic expansion valve, TXV, of the conventional system had the role of maintaining the superheating degree in the desired range, while the electronic expansion valve, EEV, besides maintaining the appropriate superheating degree, a uniform refrigeration capacity was ensured when the system operates in automated mode. The modulation of TXV was minimal to ensure the desired superheating degree. Note that the special function (modulating thermostat) of EEV generated a typical behavior of PID control, where the mass flow rate of the R22 varied from 0.048 to 0.054 kg/s, allowing the continuous operation of the compressor. The specific action of each expansion device can be seen in detail in the Fig. 6.

Figure 7 illustrates the behavior of the cooling capacity in the evaporator and the power required in both cases. The behavior of the power consumption was constant, since all tests were performed at constant operation frequencies of the compressor. As can be observed, the conventional system presented a power consumption of 3.1 kW, obtaining a cooling capacity of approximately 9.5 kW.

Behavior of refrigeration capacity and power consumption

Conventional system

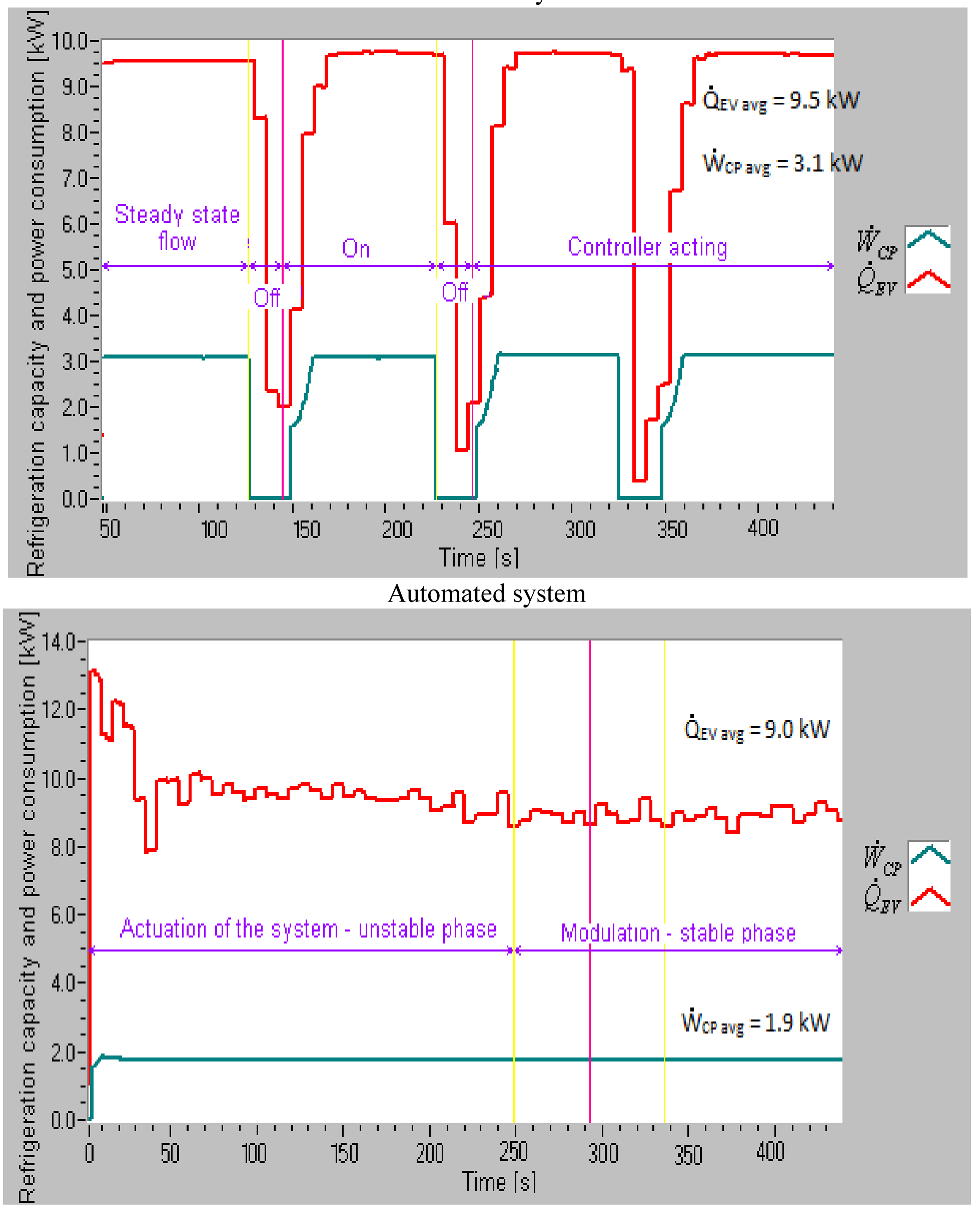


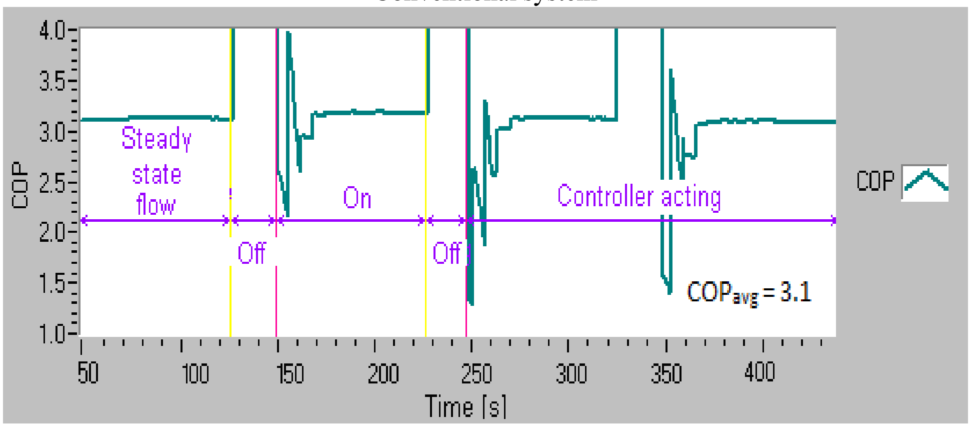

Figure 7 – Behavior of refrigeration capacity and power consumption for the refrigeration systems.

In the automated system the behavior of the cooling capacity in the evaporator followed the modulation of the EEV. The refrigeration capacity varied from 8.5 to 9.5 kW, following the variation of the refrigerant mass flow rate. During this test the power consumption of the compressor was 1.9 kW. Finally, the behaviors of the COP for each system are exposed in the Fig. 8.

As might be expected, the reduction in the demand for power consumption when operating the system at frequencies below 60 Hz and the implementation of a PID controller resulted in high values of COP for the automated system, compared with the COP of the system with the on-off controller. I was also observed that during the conventional operation, the COP curve returned infinite values in the moments that the compressor had been turned off. This result was consistent, since the refrigeration capacity was, instantly, divided by zero (value of the power consumption of the compressor). As mentioned before, with the compressor working, the COP of this system was 3.1.

COP behavior

Conventional system




Automated system

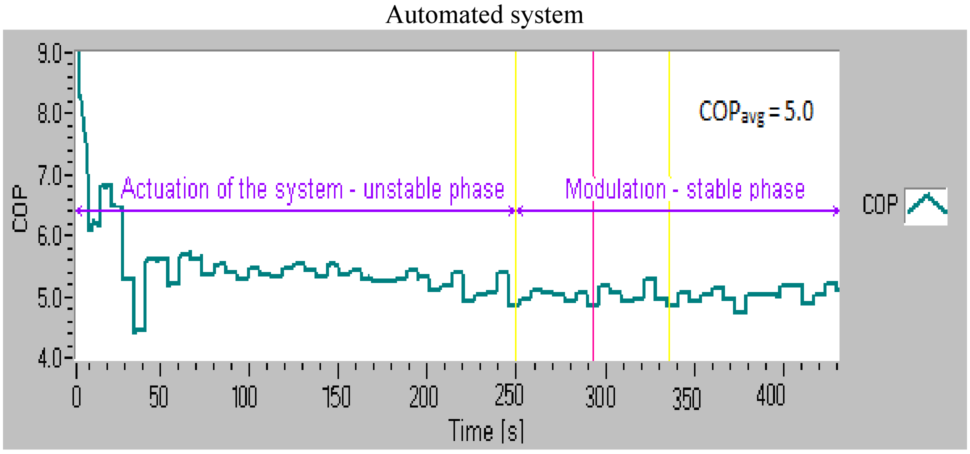



Figure 8 – The COP behavior for the refrigerant systems.

The automated system COP ranged from 4.8 to 5.4, following the modulation of the EEV throughout the test period. From these results it was possible to calculate the power demand and monthly energy consumption for the two systems, represented in Tab. 3.

Table 3 – Costs for the two refrigeration systems

| **Configuration of the refrigeration system** | **Power demand [kW]** | **Monthly energy consumption [kWh/month]** |
|---|---|---|
| Conventional | 2.94 | 517.44 |
| Automated | 1.90 | 334.40 |

The monthly energy consumption of the conventional system was 35% higher than the consumption of the automated system for this application of air conditioning during the summer, specifically for the condition where the simulation of the heat load was equivalent to 9.5 kW.

## 4. CONCLUSIONS

This paper presented a proposal to evaluate experimentally a refrigeration system with a maximum capacity of 15 kW, operating with variable speed compressor and electronic expansion valve. The experimental facility has been submitted at two different tests configurations. The first depicted a conventional air conditioning system and the second depicted an automated system.

Tests in steady state were represented in three-dimensional quadratic surfaces, which showed that the COP of the conventional system was extremely sensitive to changes in the charge of refrigerant. The other conclusion concerns the flexibility in operating the system. From the conditions of entry of water and charge of R22 fixed, it was observed that values of frequencies below the nominal frequency combined with minimum values of the superheating degree, led the COP of the automated system to the maximum value.

Finally it was desired to create a situation similar to the daily operation of an air conditioning during the summer. Therefore, both systems were analyzed in transient regime. As main results can be highlighted:

- The discharge temperature of the refrigerant during the conventional operation stabilized at 115 °C, while the automated system operated more safely and not higher than 102 °C;
- The thermostatic expansion valve, TEV, in the conventional operation maintained the superheating in the desired range, while the electronic expansion valve, EEV, besides to maintain the adequate superheating degree, the refrigeration capacity was maintained uniform in the operation of the automated system. The EEV presented a typical behavior of PID control, where the R22 mass flow rate varied from 0.048 kg/s to 0.054 kg/s, allowing a continuous operation of the compressor;
- The differences in the operating conditions are related to the pressures of work systems. While the conventional system operated at a pressure ratio of 3.4 and approximately 9.5 kW of refrigeration capacity, the automated system performed the same cooling capacity in the evaporator with the compressor working at a pressure ratio of 2.4;
- The conventional system provided 9.5 kW of refrigeration capacity, consuming 3.1 kW of power consumption and the coefficient of Performance of 3.1;
- The automated system followed the same conditions of those obtained for the conventional system, such as cooling capacity from 8.5 kW to 9.5 kW and the power consumption was 1.9 kW, resulting a coefficient of performance varying in the range from 4.8 to 5.4;
- With the automation of the conventional system was possible to reduce in 35% the average monthly energy consumption.

## 5. ACKNOWLEDGEMENTS

We would like to thank the companies BITZER Compressors, through the Eng. Alessandro da Silva, and CAREL Sud America Instrum Electronics, by the Eng. Roberto Possebon, for the compressor and electronic expansion valve, respectively, in this research. Finally, the foundations CAPES, CNPq and FAPEMIG for financial support.

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