EXPERIMENTAL EVALUATION OF THERMOSTATIC AND ELECTRIC EXPANSION VALVES PERFORMANCIES USING R417a

Marcelo S. Rocha, marcelo.rocha@poli.usp.br

José Roberto Simões-Moreira, jrsimoes@usp.br

SISEA – Alternative Energy Systems Laboratory, Mechanical Engineering Department, Escola Politécnica - Universidade de São Paulo - Av. Prof. Mello Moraes, 2231, 05508-900, São Paulo, SP, Brazil - Phone/FAX: +55 11 30915684, www.pme.poli.usp.br/sisea

Abstract. *The objective of this work is to present the test results of a comparative experimental evaluation between a regular thermostatic expansion valve (TXV) and an electric expansion valve (EEV) performance on controling the refrigerant flow into the evaporator of a 5.0 kW refrigeration cycle. The refrigerant used in this work was R417a, a substitutive ternary blend for R22 in refrigeration and air conditioning applications. The mass flow rate was measured under a series of thermal charge conditions and the expansion valves capacity to maintain the degree of supeheating at certain degree of subcooling. The experimental data were analyzed and compared with theones from literature. The system performance was analysed for the two expansion valves an under many operational conditions.*

Keywords: *Electronic expansion valve, Thermostatic expansion valve, Mass flow rate, Performance.*

1. INTRODUCTION

One of the most important components of any refrigeration system is the expansion device that besides providing the necessary pressure drop it also has the additional function of controlling the refrigerant mass flux into evaporator, maintaining the superheat set point to adjust the refrigeration load. Obviously, the refrigerant mass flux control is an important process parameter and it needs a special attention.

Methods for producing the necessary pressure drop between the condenser and evaporation has increased over the years. Quite probably, the first technique was simple orifices, capillary tubes and hand valves set to a particular flow restriction and load condition. Its usefulness was limited by the fact that it had to be previously and manually set for each change in system load.

The capacity of capillary tubes, which generates a pressure drop by having a high internal flow friction, is limited to follow refrigeration load variation. In the same way, a fixed orifice as the pressure drop device displays poor capability to impose flow restrictions for variable refrigeration load. Advances in the area of mechanical valves led to the conception of automatic expansion valves. Automatic expansion valves maintain a pressure in the evaporator, and open in response to a drop in suction pressure. While automatic expansion valves are able to follow load oscillations better than fixed restrictors or capillary tubes, their operating characteristics are sometimes in opposition to those needed for an efficient controlling system.

An efficient expansion device for refrigerant control is the thermostatic expansion valve (TXV). The TXV works by sensing and controlling the superheat in the evaporator. Superheat is a direct measure of the work done, or heat absorbed, by the evaporator. Therefore, by controlling the superheat, a TXV regulates the proper amount of refrigerant into the evaporator under a large range of load conditions, and it still prevents back flooding from damaging the compressor. TXV`s have a sensing bulb filled with a substance, usually formed by a mixture of refrigerants, which expands when heated and actuates on a spring balanced device to open or to close the flow controlling orifice.

With an increasing automation of refrigeration systems, new technologies for specific system parts control have been developed as an effort for process operational optimisation and, mainly, for energy consumption reduction. Electronically controlled refrigeration systems have the advantage of having faster control responses and avoid thermally induced failure of devices and components.

1.1. Expansion valves performance

The refrigeration system performance is predicted by manufactures and this information assumes that the refrigerant enters the expansion valve in the liquid state. Invariably the refrigerant will leave the condenser in the liquid state but, as seen above, if there is a significant pressure drop in the liquid line from the condenser to the expansion valve, under certain limited circumstances, vapor will form in the refrigerant and so a two-phase mixture will enter the expansion valve. As a result, the mean specific volume of the refrigerant will be higher than that one of a liquid phase alone and, therefore, it is likely that the mass flow rate through the expansion valve and, consequently, the overall refrigerating capacity will be lower than that one if there were no vapor presence. The amount of refrigerant flow (mass flow) into the evaporator will determine the capacity of refrigeration and the expansion valve must be able to feed enough refrigerant to sustain any increase in capacity demand. The most significant loss of expansion valve capacity will occur if the valve is fed with a two-phase mixture. Besides that, along with the presence of vapour, other factors will affect the valve capacity. Both the liquid refrigerant temperature and pressure drop across expansion valve will affect its performance but as hardly as the upstream pressure as found by Bahajji et al. (2005).

Choi and Kim (2004) carried out similar investigations were the influence of the expansion valve on the performance of a heat pump using R407c under several refrigerant charges. The authors tested capillary tube and EEV (electronic expansion valve) performance on heat pump capacity under different refrigerant charging range from –20% to +20% of full charge and evaporation temperature of 25 ^{o}C. For capillary tube using R22 and R407C, it was observed a higher sensitivity to the refrigerant charge condition, and system COP reduction under refrigerant overload condition due to the higher superheating. For EEV it was observed higher system COP and capacity due to the low dependence on the refrigerant charging condition using R407C, compared to the capillary tube, concluding that electronic control leads to higher system performance and stability.

A large evaluation of TXV and EEV comparing their performances with the use of R22 and R407C was made by Aprea and Mastrullo (2002). Permanent and transitory regimes were analysed and no considerable COP difference between EEV and TXV were observed, with the use of R22 or R407C. The EEV presented fast response to the operational condition changes and more adaptability to new set superheating. The authors verified the incapacity of the TXV to the refrigerating control when variable velocity compressors were used. They observed that during dynamic operation, if the evaporation dynamic pressure decreased after compressor stop or start, a two-phase mixture could be pumped to the compressor making severe damage. For transitory operational conditions like cycle start the EEV flow control is quite linear and faster than TXV that presents non-linear control. Furthermore, the compressor power consumption is small for EEV control than TXV.

The transient effect of the suction pressure was also analysed by McMullan e Hewitt (1995), and they concluded that superheating has a strong influence on the valve control capacity. Park et al. (2001) realized a large study of an air-conditioned system using an EEV by implementing a numerical model. The authors changed the compressor velocity and determined the best valve lift for an optimised COP. Finally, the authors did not find any work that considered the influence of vapor presence at an expansion valve inlet, which is the paper main goal.

1.2 Expansion valve control basics

Typical control algorithms or sets of instructions used to control any electronic expansion valve are commented below. Just as with traditional mechanical control system, EEVs are primarily liquid superheat controlled devices. When using EEVs, the manner in which the superheat will be sensed must be determined first.

There are two basic schemes for sensing liquid superheat. Actual superheat is a pressure-temperature relationship, specific to each refrigerant. When electronically derived, pressure-temperature superheat requires the use of a pressure transducer, a temperature sensor, and a pressure-temperature table or equation. Another, simpler, but less accurate measure of liquid superheat, is the two temperature method. In the two-temperature method the temperature is sensed at the inlet and at the outlet of the evaporator.

The difference in temperatures is assumed the superheat. Refrigerants or blends with temperature glides may affect two-temperature superheat control. A distinct advantage of two-temperature superheat is the low cost; pressure transducers are far more expensive than thermistors. Additionally, it works with any refrigerant without reprogramming. The temperature difference between the two sensors will indicate superheat no matter what the pressure-temperature relationship of the refrigerant. The main disadvantage of the two-temperature method is the uncertainty upon the inlet sensor location. For the two-temperature superheat method to be accurate, the inlet sensor must be located in a position that has saturated refrigerant present at all times. Failure to find, or use, the proper location can lead to poor control or compressor damage. Generally as temperature rises, the voltage sent out through the signal wire also rises. The controller uses this voltage to calculate the temperature of the refrigerant with the use of a pressure-temperature table encoded in the controller itself.

Pressure-temperature tables are familiar to the air conditioning and refrigeration industry and are available in many forms. To be useful to an electronic device, they are encoded in a "look up table". When a *P-T* (pressure-temperature superheat) controller is used, the lookup table for the specific refrigerant used in the system must be programmed into the controller. Another way pressure-temperature relationships of one or more refrigerants are stored in the memory of a controller is by use of the "equation-of-state". The equation of state is a mathematical description of refrigerant properties. Since EEV controllers are small computers, they have the ability to process equations efficiently and quickly. Once the pressure of the refrigerant is sensed and the lookup table is used to calculate the saturated temperature, only the real suction temperature must be sensed to determine the operating superheat. Temperature sensors detect suction temperatures.

The solution to both methods needs a Digital Linear Actuator (DLA), which is used to convert rotation to a push/pull output force. A simple gear train increases the force and may account in mechanical advantage.

Li et al. (2004), developed an automobile refrigerant system control method by using an EEV presetting the flow rate response for any operational conditions. It was proposed a new control method based on a fuzzy self-tuning algorithm, showing that it can feed adequate refrigerant flow into evaporator under abrupt changing of the compressor speed, which is a specific and hard operational condition.

In the same kind of investigation, Wu et al. (2005) present controllability tests for control strategy with fuzzy control algorithm achieving the desired control accuracy for the room air temperatures, without considerable oscillation, using EEV´s. Therefore, it was concluded that such a control method, including the control strategy and algorithm, is feasible and valuable for multi-evaporator air conditioners (MEAC) product development work in practice.

2. FLASHING MECHANISM THROUGH EXPANSION DEVICES

Flashing in expansion devices is a particular and important phenomenon that has been largely investigated for decades. For subsonic flow condition, the flashing through expansion devices and, at extreme conditions, it can give origin to shock waves as it has extensively been investigated by Simões-Moreira & Bulladrd (2003), and Vieira & Simões-Moreira (2007). The process described before has been the object of critical two-phase flow in small (refrigeration and air conditioning systems), but it can apply to anywhere where flashing is present.

Special attention has been done to the flashing process in air-conditioning and refrigeration systems, mainly when it represents a decreasing on expansion device capacity to feed refrigerant into the evaporator and to maintain the specified superheat. The flashing process at the inlet of the expansion device, i.e., vapor presence into the refrigeration liquid line is a more frequent occurrence than one would like or expect. All refrigeration cycle design theory guides on subcooling liquid refrigerant as a way to prevent the flashing problem. The use of liquid subcooling in the evaporator exit is probably the most well-known and generally accepted method of suppressing that phenomenon. The technical literature presents some of the main causes of flashing occurrence as exposed below:

- Excessive frictional pressure drop in the liquid line;
- Installation of flow restriction devices in the liquid line causing localized pressure drop;
- Excessive line lift;
- Off design refrigerant charge;
- Thermal gains from ambient.

The first two flashing causes are directly related to the liquid line head pressure. Generally, the condensing temperature (head pressures) for air conditioning applications is about 310 K and it can be as low as 300 K for a refrigeration system (Stoecker & Jones, 1985). When considering the energy cost of running the compressors without addressing the generation of flashing before the liquid entering the expansion device, these condensing temperatures have been found to be the most optimum condensing ones. Due to the flow from the condenser to the expansion device inlet line, some pressure drop is expected as consequence of frictional losses and additional pressure drop may occur if any flow restriction device, such as regular valve, is installed in between. In addition, flashing can occur where a dryer is installed which may cause a flow restriction.

Condensers and the evaporators of large refrigeration systems are located far apart from each other and, in some cases, at different gravitational levels. Such is the case when the condenser and the other machinery are located at the ground level and the evaporator is a one or more floor above. Some pressure head reduction will occur by simple gravitational head reduction that may induce the formation of flashing. Another cause can be excessively long pipe runs; the pressure drop causes flashing to occur. It may occur in long liquid lines where it may be exposed to a temperature above the corresponding saturation one. Finally, flashing can also be an indication of refrigerant leakage, particularly if bubbles are known not to be present previously. Furthermore, other factors can induce flashing occurrence, such as refrigeration system malfunction, in which the low refrigerant charge is the cause of vapor bubbles presence into the liquid line and it can reduce the system performance.

The expansion valve has its capacity hardly reduced when starved of refrigerant, when not being fed by liquid. With the saturated condensing pressure drop there is a reduction in available TXV pressure drop, an increase in available liquid density and a reduction in liquid enthalpy. O´Brian (2005) presented the use of a liquid pump after the condenser and the liquid receiver as way to avoid the flash gas into liquid line. His study showed that assuming that there was not only liquid available into liquid line, it could be estimated that the EEV capacity loss could be about 20% and the TXV capacity loss could be about 28%. Both TXV and EEV capacities were subject to available liquid quality and sufficient liquid pressure available at inlet.

Although all the problems posed before there is no control system in the literature concerning to the possibility of to detect and indicate a possible refrigerant vapor presence at liquid line or to permit a valve control by the action of an electronic controller. In a recent work, Hrjak et al. (2001) present four methods of detecting droplets in the stream of superheated vapor at the evaporator exit of a refrigeration system. The authors show a construction technique of a thin-film resistance sensor (MEMS) to detect and measure the liquid droplets.

2.1 Considerations about mass flow rate models

Expansion device studies have been the main target of many works for evaluating a parametric influence on mass flow control, but in-depth analyses concerning the influence of flashing at the expansion valve inlet as a way to optimize refrigerant flow control are scarce, mainly for new refrigerant blends develop for use in heat pump, air-conditioning and refrigeration.

The most elementary valve model considers a thermodynamic equilibrium and the refrigerant mass flow rate through an orifice with a differential pressure is obtained from Bernoulli's equation, i.e.,

$$\dot{m}_C = C_d A \sqrt{2\rho\left(P_u - P_d\right)} \text{, and} \tag{1}$$

$$C_d = \frac{\dot{m}_A}{\dot{m}_C} , \tag{2}$$

where, $\dot{m}_C$ is the ideal refrigerant mass flow (isentropic) through expansion valve, $\dot{m}_A$ is the actual refrigerant mass flow through expansion valve, C_d is the discharge coefficient, ρ is the liquid density, P_u is the valve upstream pressure, and P_d is the valve downstream pressure.

Almost invariably, expansion devices in refrigeration systems take the form of some type of automatically adjustable orifice. In a flooded evaporator, the adjustment will be by the means of a float switch to maintain the liquid refrigerant level and, in the more common thermostatic expansion valve (TXV), the adjustment is made in response to a temperature sensor at the evaporator exit to maintain a constant refrigerant superheat.

Important results were obtained by Vinnicombe and Ibrahim (1991) concerning to the verification of flashing occurrence into liquid line. The tests results at duty load greater than design one for the expansion valve show that they confirm the manufactures contention that the valves can operate at duties larger than the design ones. Furthermore, at full and partial load duty for each of the valves show that over all the conditions imposed, apart from at high condensing temperature and low load where valve instability was observed, the system performed most satisfactory and no practical difficulties were experienced. In fact, at the low condensing temperatures the compressor ran far more smoothly and quietly. At low condensing temperatures where the desired refrigerating capacity cannot be maintained even when the expansion valve is fully open, it can be seen that both the TXV`s behaved broadly as expected and their capacities were significantly larger than the declared capacities. It is noticeable that the extra capacity of the valve in excess of the declared capacity is very significant and it allows the system to maintain the set load condensing temperatures much lower than that predicted from the declared data. Nevertheless, further technical improvements cannot be included during the design stage because solutions are different for each operational condition and particular refrigeration system.

Bahajji et al. (2005) developed an experimental study about flashing process through expansion valve using the refrigerants R22, R290, and R410A. They evaluated the upstream and downstream expansion valve pressures, subcooling, and valve flow area on the refrigerant mass flow. Upstream pressure revealed to hardly influence the refrigerant mass flow for all refrigerants tested. Next, it was observed that the downstream pressure has little influence over refrigerant mass flow that indicates that the flashing phenomenon was well anticipated by the flow models analysed. The next experiment indicated that the subcooling had a major influence over the refrigerant mass flow, i.e., the higher the subcooling the higher the mass flow. Finally, the flow area had a large influence over the mass flow, but the influence was clearly different for each one of the tested refrigerants due to different thermodynamic properties. In addition, flow area models were compared with the geometrical (actual) valve area assuming that the little amount of vapor present at the inlet (about 2% in volume) was negligible so that the Bernoulli's equation was also used. The central discussion on the mass flow model through nozzles is how to determinate the throttle pressure (P_i), proposing three hypothesis for the throttle area depending on differential pressure models. The conventional nucleation theory based model was adopted to obtain a more precise flow area model which establishes a differential pressure between the thermodynamic saturation pressure and the minimum pressure in a depressurisation process, giving best predicted flow area compared to the geometrical one.

According to Shanwei et al. (2005), at low differential pressure the refrigerant flow is, in practice, determined by the fully open orifice size of the valve and the eq. (1) and (2) can determine the mass flow rate. When the pressure difference is large, the flow is determined by the capacity of the compressor and the size of the orifice in the expansion valve will be reduced automatically to maintain the set superheat. Investigations similar to those carried out by the aforementioned works show that the refrigerant flow and therefore the refrigerating capacity is proportional to the differential pressure over the expansion valve implying that low condensing temperatures imply in a low mass flow rate and that is the reason put forward why the condensing temperature must be maintained high. However, Bahajii et al (2005) showed that the use of a relatively large orifice could reduce the problem, although the limit is the range of TXV operations, which may become unstable. The instability (hunting) results in a cyclic overfeeding and underfeeding of the evaporator and the most serious consequence can be a refrigerant in the liquid state entering into the compressor leading to a possible mechanical failure.

For subcooled flow, the most used model to predict the mass flow through nozzles are the homogeneous equilibrium model (HEM), which assumes that the two phases are flowing with the same velocity in thermal equilibrium and it considers that the mixture is a pseudo fluid having a thermodynamic properties averaged by the vapor quality.

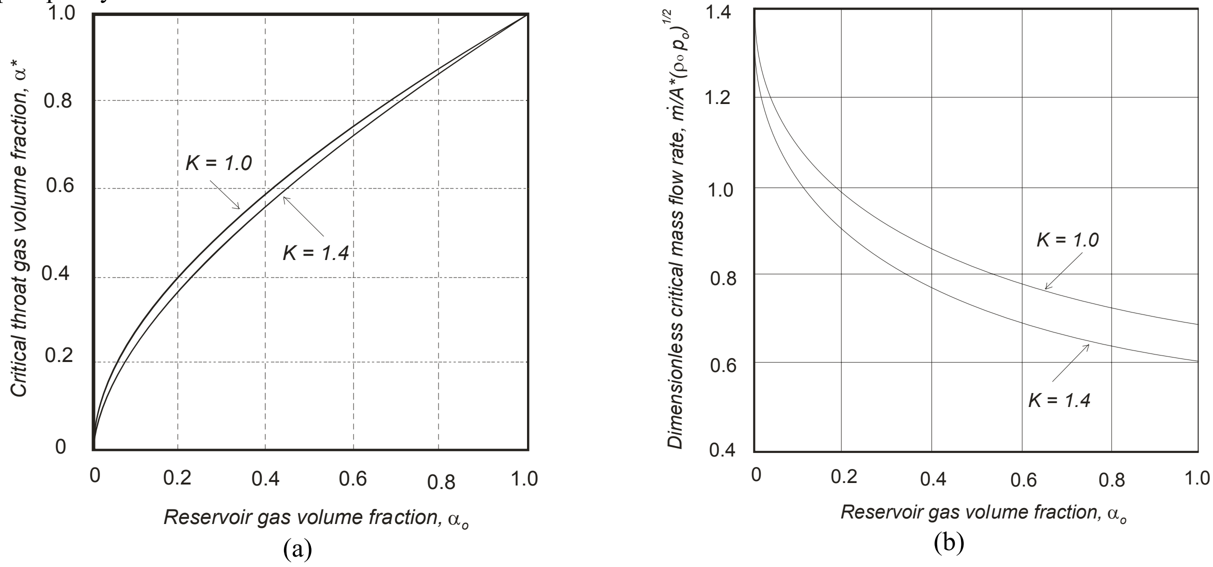

Figure 1. Gas-liquid mixture flow through a nozzle: (a) critical throat gas volume fraction, α*, against reservoir gas volume fraction, α_o, and (b) dimensionless choked mass flow rate, $\dot{m}/A^*(p_o\rho_o)^{1/2}$, against the reservoir vapor volume fraction, α_o, (Brenem, 1995).

Abdul-Razzak et al. (1995a, 1995b, and 1995c) investigated and compared the different models developed to the mixture density prediction for a tow-phase flow through a venturi tube and other measurement devices: homogeneous equilibrium model, separated flow density model, equivalent density model, and velocity slip ratio model. The comparison showed that each model has a specific applicability range, and the homogeneous equilibrium model revealed to have the largest applicability range. Bahajii et al. (2005), is one of the few recent works available in specific literature that investigated using the refrigerants R22, R290, and R410A.

Many authors have proposed critical flow models and working correlations, such as those of Crespo et al. (2001), Boccardi et al. (2005), Shanwei et al. (2005), among many others, usually valid for all expansion devices including nozzles, capillary tubes, short capillary tubes, and other flow expanders. In an important work, Brenem (1995) presented a homogeneous flow model for two component mixture flow through a nozzle, given the reservoir conditions p_o and α_o as well as the polytropic index k, and the liquid density (assumed constant). From these variables it was possible to know both the critical gas volume fraction and dimensionless mass fraction as can be observed in Fig. 1.

Although a large number of literature examples are available, four important reviews, among others, present an overview of the flashing phenomenon studies evolution in the last decades: Isbin (1980), Shin and Jones (1993), Bilnkov et al. (1993), and Wallis (1980).

3. EXPERIMENTS AND TEST FACILITY

The test facility has been setup in the Alternative Energy Systems Laboratory (SISEA) and it is sketched in Fig 2. A typical refrigeration cycle was acquired for the tests along with the data acquisition. The designed refrigeration capacity was 5.0 kW and it has an evaporator operating in the temperature range from 260 K to 320 K. The refrigerant R417A was chosen because it is an alternative azeotropic refrigerant for R22. The evaporator is a tube inserted in a recalculating water bath provided with electrical heaters to supply the cooling load. The heaters are thermostatically controlled to maintain a constant return temperature to the evaporator at full and partial load conditions. The condenser is an air-cooled heat exchanger and the compressor a regular hermetic one. The test facility was mounted according to the recommendations of ASHRAE Handbook, Equipments (2002). Table 1 shows the transducers specifications.

A pressure controlled valve introduces an additional pressure drop in the liquid line from the condenser to the expansion valve. Additionally, an electrical resistance wrapped around the liquid line furnishes energy to partially evaporate the liquid, so that one can introduce vapor in the line at a known rate and quality.

A visualization section was placed immediately before the expansion valve to give a visual indication of the presence of vapor, and the impedance sensor was placed between the sight glass and the expansion valve to permit the void fraction measurement at the valve inlet.

Table 1. Transducers specifications.

Variable	Transducer	Range	Accuracy
Refrigerant flow rate	Volumetric	2 - 20 m^3/h	± 0.1 m^3/h
Temperature	RTD-Pt100 4 wires	260 – 320 K	± 0.1 K
Pressure	Piezoelectric effect	0 – 3.4 MPa	± 0.02 MPa
Void fraction	Electrical impedance	2 – 7 V	± 0.07 V

The first set of tests to be undertaken will be to monitor system performance when the condensing temperature is progressively reduced and, at the same time, ensuring that no flashing is present at the expansion valve inlet. The obtained results will be compared to the tests in which flashing occurs.

Repeating some of the tests described above, and introducing different pressure drops in the liquid line with the aid of the pressure control valve, it is aimed to investigate the effect of flashing on EEV performance. It is expected that the liquid line pressure drop should have two effects: first, when there is a considerable subcooling after the condenser, no flashing will be generated even after the pressure drop and so there will be a reduction in flow rate only as a result of reduced pressure drop across the expansion valve.

The second effect, when flashing occurs, the flow rate reduction and other important parameters will be measured for conclusions.

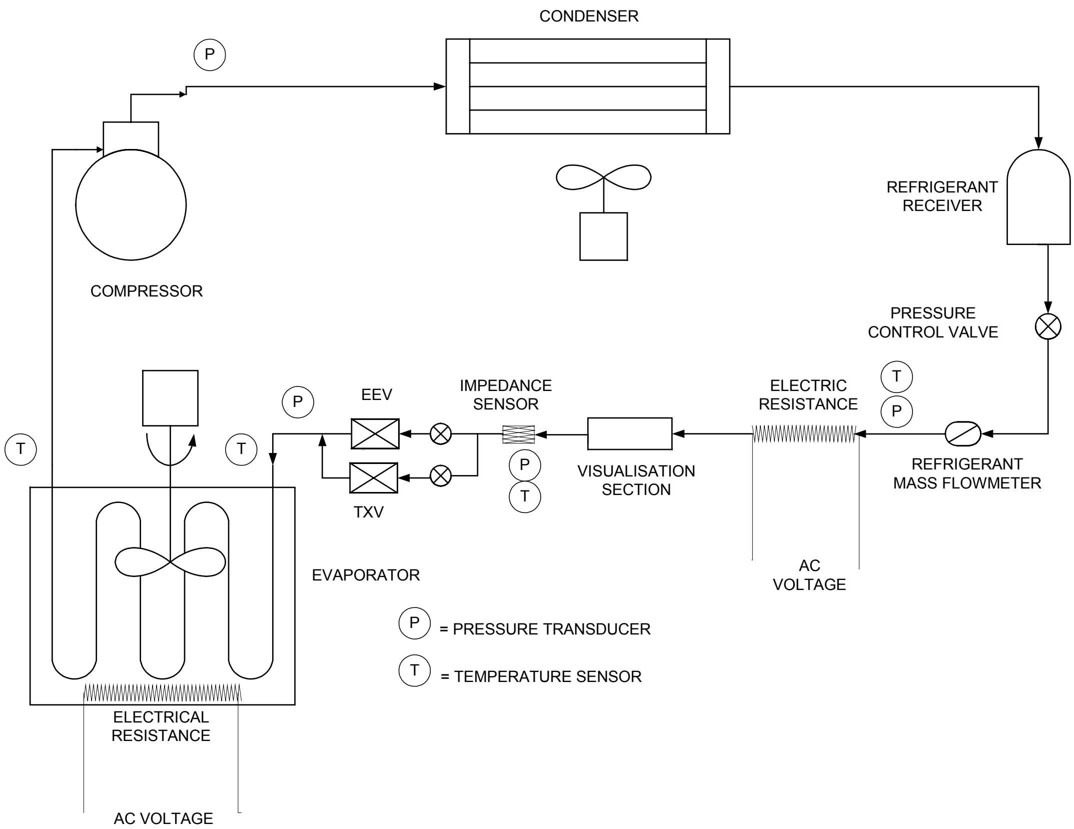

Figure 2. Schematics of the experimental test facility.

The present type of sensor operates based on the difference of electrical properties of the two refrigerant phases. According to the operation frequency imposed on the signal applied between the electrodes along with the knowledge of the electrical properties of the refrigerant phases, the average dominating impedance of the two phase mixture filling in the cross section may be either resistive, or capacitive, or both. The sensor analysed in this study[1] will operate in the capacitive range. The elementary electrical model of the sensor and the measuring system is a parallel *RC* circuit, as discussed by Rocha and Simões-Moreira (2004). The mentioned work shows in a simple way that, it is possible to associate the overall two-phase mixture impedance, with the phases corresponding electrical properties, as follows.

[1] The sensor described in this paper is under guard of international patent process.

$$\left(\frac{k}{k_L}\right)_t \approx \left(\frac{V - V_V}{V_L - V_V}\right)_t , \tag{3}$$

where, the subscript "V" indicates the situation of pure vapor filling the test section, and "L" the situation of pure liquid filled between the electrodes. The subscript "t" denotes instantaneous value of the dimensionless conductivity, k/k_L. So, a time-average of the dimensionless conductivity can be expressed as:

$$\frac{k}{k_L} = \frac{1}{T}\int_T \left(\frac{k}{k_L}\right)_t dt , \tag{4}$$

where T is the total sample period of measurement.

The fluid conductivities are strongly dependent on temperature. In this way, it is necessary to use a dimensionless conductivity rather than the absolute value to avoid temperature influence over variable measurements. Therefore, for a sensor operating in the resistive range, the frequency of the applied signal is given by the condition imposed by used refrigerant electrical properties. A special electronic circuit will be designed for signal demodulation, and filtering as the same way as presented by Rocha and Simões-Moreira (2003, 2004, 2005a, and 2005b).

4. CONCLUSIONS

In this work, an overview of the expansion valves influence and behaviour over the refrigeration and air-conditioned systems were carried out as way to well present the actual problem. The main troubleshooting involving the use of thermostatic and electronically controlled expansion valves is the occurrence of flashing in the liquid line at the valve inlet. This paper examines this problem from an experimental point of view and a way of measuring the amount of vapor in order to provide an electronic signal for controlling purposes. To achieve that, the impedance sensor technique was proposed as an alternative tool to furnish a refrigeration control parameter.

5. ACKNOWLEDGEMENTS

The first author appreciates FAPESP for the personal support (process # 2005/01456-1) and second author thanks CNPq. This project has been supported by FAPESP (process # 2006/00216-0) for which both authors are thankful.

6. REFERENCES

Abdul-Razzak A., Shoukri M., Chang J-S., 1995a, Measurement of two-phase refrigerant liquid-vapor mass flow rate – Part I: Venturi and void fraction meters, *ASHRAE Transactions*, 101: 511-522.

Abdul-Razzak A., Shoukri M., Chang J-S., 1995b, Measurement of two-phase refrigerant liquid-vapor mass flow rate – Part II: Turbine and void fraction meters, *ASHRAE Transactions*, 101: 523-531.

Abdul-Razzak A., Shoukri M., Chang J-S., 1995c, Measurement of two-phase refrigerant liquid-vapor mass flow rate – Part III: Combine turbine and Venturi meters and comparison with other methods, *ASHRAE Transactions*, 101: 532-538.

Aprea C., Mastrullo R., 2002, Experimental evaluation of electronic and thermostatic expansion valves performances using R22 and R407c, *Applied Thermal Engineering*, 22: 205-218.

ASHRAE Handbook, Equipments, 2002.

Bahajii M.A., Corberán J.M., Urchueguía J., González J., Santiago J., 2005, Study about the flashing process through a metering expansion valve, *Experimental Thermal and Fluid Science*, 29: 757-763.

Blinkov V.N., Jones O.C., Nigmatulin B.I., 1993, Nucleation and flashing in nozzles – 2, *International Journal of Multiphase Flow*, 19: 965-986.

Boccardi G., Bubbico R., Celata G.P., Mazzarotta B., 2005, Two-phase flow through pressure safety valves. Experimental investigation and model prediction, *Chemical Engineering Science*, 60: 5284-5293.

Brennen C.E., 1995, Cavitation and bubble dynamics, *Oxford University Press, available in <http://caltechbook.library.caltech.edu/1/04/bubble.htm>*.

Choi J., Kim Y., 2004, Influence of the expansion device on the performance of a heat pump using R407c under a range of charging conditions, *International Journal of Refrigeration*, 27: 378-984.

Crespo A., García J., Jiménez-Fernández J., 2001, Stability criteria of the steady flow of a liquid containing bubbles along a nozzle, *ASHRAE Transactions*, 123: 836-840.

Grimmelius H.T., Woud J.K., Been G., 1995, On-line failure diagnosis for compression refrigeration plants, *International Journal of Refrigeration*, 18: 31-41.

Hrjak P.S., Shannon M.A., Leicht T.M., Miller N.R., 2001, Detection of liquid mass fraction at the evaporator exit of refrigeration systems, *International Journal of Thermal Science*, 40: 773-786.

Ibrahim G.A., 2001, Effect of sudden changes in evaporator external parameters on a refrigeration system with an evaporator controlled by a thermostatic expansion valve, *International Journal of Refrigeration*, 24: 566-576.

Isbin H.S., 1980, Some observations on the status of the two-phase critical flow models, *International Journal of Multiphase Flow*, 6: 131-137.

Li X., Chen J., Chen Z., Liu W., Hu W., Liu X., 2004, A new method for controlling refrigerant flow in automobile air conditioning, *Applied Thermal Engineering*, 24: 1073-1085.

McMullan J.T., Hewitt, N.J., 1995, Comparison of expansion valve performance, *International Journal of Energy Research*, 19: 347-359.

Mulay V., Kulkarni A., Agonafer D., 2005, Effect of the location and the properties of the thermostatic expansion valve sensor bulb on the stability of a refrigeration system, *Journal of Heat Transfer*, 127: 85-100.

O´Brian M., 2005, Liquid pressure amplification, *Refrigeration Engineer.Com, available in <http://www.refrigeration-engineer.com>*.

Outtagarts A., Haberschill P., Lallemand M., 1997, The Transient response of an evaporator fed through an electronic expansion valve, *International Journal of Energy Research*, 21: 793-807.

Park K.A., Choi Y.M., Choi H.M., Cha T.S., Yoon B.H., 2001, The evaluation of critical pressure ratios of sonic nozzles at low Reynolds numbers, *Flow Measurement and Instrumentation*, 12: 37-41.

Rocha M.S., Simões-Moreira J.R., 2003, Electric sensor for measurement of the mass ratio of ethanol and regular gasoline mixtures, *Proc. of XII Congresso e Exposição Interacional de Tecnologia e Mobiliade - SAE BRASIL 2003*, São Paulo, 10 p.

Rocha M.S., Simões-Moreira J.R., 2004, A rotating electric field multiple-electrode impedance sensor for void fraction measurement, *Proc. of 3rd International Symposium in Two-Phase Flow Modelling and Experimentation*, Pisa, 10 p.

Rocha M.S., Simões-Moreira J.R., 2005a, A simple impedance method for determining ethanol and regular gasoline mixtures mass contents, *Fuel*, 84: 447-452.

Rocha M.S., 2005b, Projeto, construção e teste de um sensor de impedância de múltiplos eletrodos aplicado à medião da fração de vazio em escoamentos bifásicos do tipo gás-líquido, *PhD thesis presented to the Mechanical Engineering Department, Universidade de São Paulo*, São Paulo, 131 p.

Shanwei W., Cuan Z., Jiangping C., Zhiujiu C., 2005, Experimental research on refrigerant mass flow coefficient of electronic expansion valve, *Applied Thermal Engineering*, 25: 2351-2366.

Shin T.S., Jones O.C., 1993, Nucleation and Flashing Nozzles – 1, *International Journal of Multiphase Flow*, 19: 943-964.

Simões-Moreira J.R., Bullard C., 2003, Pressure drop and flashing mechanisms in expansion devices, *International Journal of Refrigeration*, 26: 840-848.

Stoecker W.F., Jones J.W., 1985, Refrigeração e ar-condicionado, 2a Ed., McGraw-Hill, São Paulo, 481 p.

Vieira M.M., Simões-Moreira J.R., 2007, Low pressure flashing mechanisms in iso-octane liquid jets, *Journal of Fluid Mechanics*, 572: 121-144.

Vinnicombe G.A., Ibrahim G.A., 1991, The performance of refrigeration expansion devices, Report for Electricity Association Technology LTD, U 1420.

Wallis G.B., 1980, Critical two-phase flow, *International Journal of Multiphase Flow*, 6: 97-112.

Wu C., Xingxi Z., Shiming D., 2005, Development of control method and dynamic model for multi-evaporator air-conditioners (MEAC), *Energy Conversion and Management*, 46: 451-465.