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Performance of thermostatic and electronic valves controlling the compressor capacity

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SUMMARY

The performance of the energy consumption of an electronic valve and a classical thermostatic valve has been compared when these expansion valves are adopted in a vapour compression plant subjected to a cold store. The main aim is to verify experimentally which type of expansion valve would be preferable from energy point of view when a classical thermostat or a fuzzy logic algorithm are used as the control system for the refrigeration capacity. The fuzzy logic-based control is able to modulate continuously the compressor speed through an inverter. The results show that with a fuzzy algorithm, the thermostatic expansion valve allows an energy saving of about 8% in comparison with the electronic valve. When on–off control is used, the electric energy consumption obtained both with the electronic valve and with the thermostatic valve is comparable. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: thermostatic valve; electronic valve; experimental plant; energy saving

1. INTRODUCTION

In the last years the energetic and economic optimization theme of a vapour compression plant has determined great interest. In this regard the expansion valve type adopted plays a leading role on the inverter-driven air conditioning and refrigeration plants (Hewitt *et al.*, 1995; Matsuoka and Nagatmo, 1988; Yasuda *et al.*, 1992), since the superheating optimum control provides a correct amount of refrigerant mass flow at the evaporator inlet, determining a precise capacity control. For many years capillary tubes or thermostatic expansion valves (TEV) have been adopted in air conditioning and refrigeration plants as expansion device to control the evaporator inlet refrigerant mass flow rate. However, in many situations the electronic valves (EEV), even if characterized by higher costs, are preferable (Schmidt, 1999) in comparison with the thermostatic valves above all when there are wide load variations, as for example in case of a

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water chiller, or to avoid the typical hunting problem. Moreover, the EEV can be used with each type of refrigerant fluid and for remote controls. In particular, related to the TEV and EEV performances when the compressor speed by means of an inverter is varied, the studies in literature are still limited. So with regard to this problem in this paper, an analysis of the energetic performances of a vapour compression experimental plant linked to a cold store using as expansion valve, both an electronic valve and a thermostatic valve, has been realized. The main aim is to verify experimentally what expansion valve type is preferable from the energy point of view when as refrigeration capacity control system are adopted either the classical thermostat or an algorithm, based on fuzzy logic, able to modulate continuously the compressor speed by means of an inverter.

2. EXPERIMENTAL PLANT

2.1. Experimental plant description

The experimental vapour compression refrigeration plant, subjected to a commercially available cold store and reported in Figure 1, is made up of a semi-hermetic reciprocating compressor, an air condenser followed by a liquid receiver, a manifold with three expansion valves to feed an air cooling evaporator inside the cold store. The fluid refrigerant adopted is the R417A. The compressor speed is regulated by means of a PWM inverter. It is formed by a rectifier, that related to the compressor motor, converts the three-phase main voltage (380 V, 50 Hz) to DC voltage and then reverses by an inverter the DC voltage to a three-phase AC supply-voltage; at the output of the inverter the voltage is adjustable in frequency and magnitude. The cooling load in the cold store is simulated by means of some electric heaters linked to a regulator and the electric power is measured by means of a wattmeter. In Table I, the transducers specifications used (Coriolis effect flowmeter, RTD 1000 4 wires thermoresistances, piezoelectric absolute pressure gauge, wattmeter) are reported.

2.2. Expansion valves

The valves group, appropriately designed and built for the refrigeration plant, consists of a manual valve, a thermostatic valve and an electronic valve mounted in parallel with the possibility to work independently closing the circuits with opportune check valves. Generally, the working of an electronic valve is obtained by means of the proportional integral control that allows to hold constant the refrigerant superheating when the cooling load varies (Rathje and Zangenberg, 1995; Schmidt, 1995; Haberschill *et al.*, 1996; Hewitt *et al.*, 1995). In particular, the electronic expansion valve adopted is a solenoid valve controlled by an electronic regulator. The electronic regulator working is based on two refrigerant temperatures and two air temperatures measured at the evaporator inlet and outlet by means of four thermoresistances Pt 1000. It is possible to set the superheating requested by means of the control unit and in this way the electronic regulator fixes the opening times of the solenoid valve. When the actual superheating is different from the value selected, the controller by means of an electric signal sent to the solenoid opens or closes the valve opportunely. The TEV tested is the model TEX2 with orifice n.03 of the Danfoss; also the EEV and its electronic regulator are of the Danfoss. The models are AKV10-3, AKC-114, AKV-21 for the valve, electronic regulator and the control unit, respectively. In particular, by means of the control unit it is possible to regulate different working parameters as for example the glide temperature.

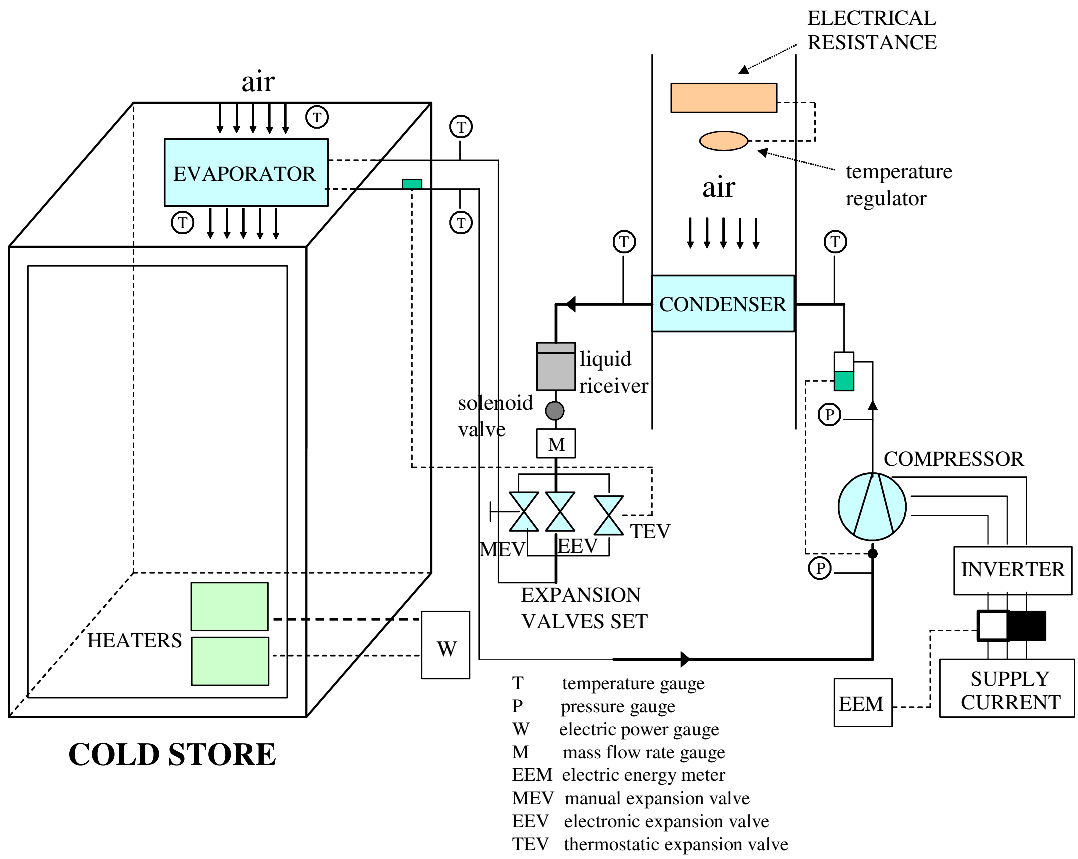

Figure 1. Refrigeration plant subjected to a commercially available cold store.

Table I. Transducers specifications.

Transducer	Range	Accuracy
Coriolis effect mass flow rate meter	0–2 kg min^{-1}	$\pm$ 0.2%
RTD 1000 4 wires	$-$100–500°C	$\pm$ 0.15°C
Piezoelectric absolute pressure gauge	1–10 bar; 1–30 bar	$\pm$ 0.2%; $\pm$ 0.5% F.S
Wattmeter	0–3 kW	$\pm$ 0.2%
Electric energy meter	0–1000 MWh	$\pm$ 1.0%

3. EXPERIMENTAL PROCEDURE AND FUZZY ALGORITHM DESCRIPTION

3.1. Experimental analysis

The experimental tests have been realized adopting the vapour compression plant subjected to a cold store above described. These tests have been conducted choosing as temperatures of

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set-point 0 and 5°C for the air in the cold store. Each test has been conducted for 6 h and the cooling load has been simulated by means of the periodic opening of the cold store door and some electric heaters. In particular, the cold store door has been opened for 10 min twice per hour with an outdoor air temperature of about 19°C to simulate a typical use. In these conditions the cold store door has been opened for about 30% of the total execution time of the test. The experimental apparatus has been equipped with 32 bit A/D data acquisition cards linked to a personal computer allowing a high sampling rate and a monitoring of all the measures carried-out by means of the transducers; the data acquisition software has been realized in a Labview environment. In particular, the fluid thermodynamic properties experimentally measured have been: the evaporator inlet and outlet refrigerant temperatures, the evaporator inlet and outlet air temperatures, the condenser inlet and outlet refrigerant temperatures, the condenser inlet and outlet air temperatures, the evaporation and condensation pressures, the refrigerant mass flow rate and the electric energy consumption.

3.2. *Fuzzy algorithm description*

For each value of the set-point, the experimental tests have been realized using as expansion valve both a thermostatic valve and an electronic valve, adopting as compressor refrigeration capacity control system both the classical thermostat, that determines compressor on/off cycles, and the algorithm, based on fuzzy logic and built-in Labview environment. Related to the fuzzy controller, already determined by authors in a former paper (Aprea *et al.*, 2004) and reported in the appendix, it is capable of regulating with continuity the compressor electric motor supply current frequency. The fuzzy logic is based on the determination of the fuzzy-set that represents the possible values of the variables. The fuzzy theory with respect to the traditional logic theory, according to which an element can belong or not to a particular set, allows the partial membership of an element to a set. Each value of the variables is characterized by a membership value which changes with continuity from zero to one. Thus, it is possible to define a membership function for each variable that establishes the membership rate of a variable at a certain set. From an operative point of view, a controller fuzzy receives the values of the input variables, performs some operations and determines an output value. This process is characterized by three principal phases: fuzzification, inference mechanism and defuzzification. The fuzzification process allows to transform a value defined into a fuzzy value; the inference process determines the output fuzzy by means of the rules fixed according to the experimental reality; the defuzzification process permits to transform the fuzzy output into a defined value. The main difficulty of the fuzzy logic is connected with the necessity of a good specific experience in the design and the building of a fuzzy controller. So, as for the regulating parameters some experimental considerations have allowed us to set the control variables of the reciprocating compressor speed.

4. RESULTS AND DISCUSSION

It has been observed by means of an experimental analysis first of all that the fuzzy algorithm, adopted as refrigeration capacity control system, works better with the thermostatic valve. To understand this it is necessary to observe that the solenoid electronic valve receives an immediate impulse of major opening to carry back the superheating (Figure 2) to the value

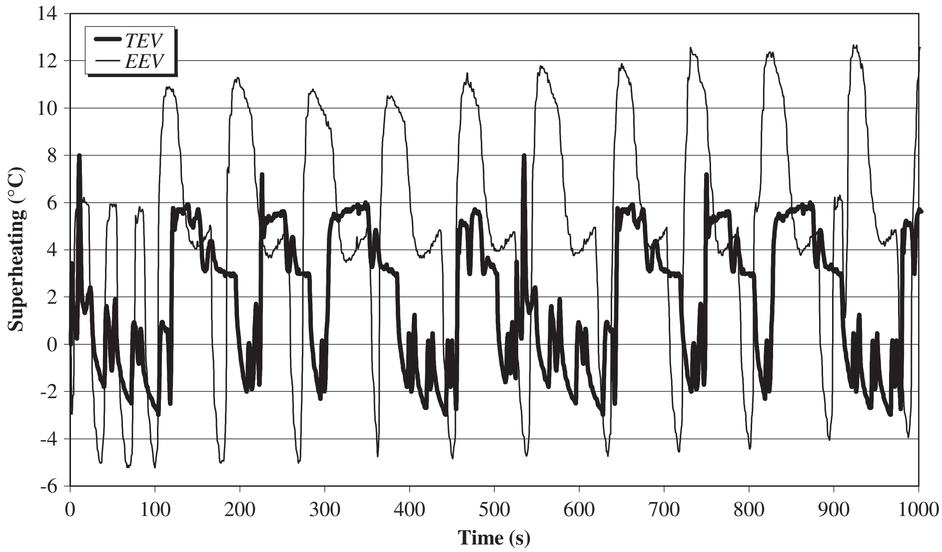

Figure 2. Superheating with EEV and TEV with set-point 0°C and fuzzy control.

selected, when there are variations of the cooling load and therefore of the compressor electric motor supply current frequency. This does not happen with the thermostatic valve that on the contrary presents a major inertia to regulate the refrigerant mass flow rate at the evaporator inlet. In these conditions the refrigerant mass flow rate will be major with the electronic valve in comparison with the thermostatic valve; it has been noted that the refrigerant mass flow rate related to the working with the electronic expansion valve is on average higher by about 8% than the refrigerant mass flow rate with the thermostatic valve operating. Following this situation it is possible to observe in Figure 3 that the compressor electric motor supply current frequency is higher when an electronic expansion valve is adopted. So the thermostatic expansion valve presents an energy saving of about 8% in comparison with the electronic valve (Figure 4). Moreover, it is possible to observe that the thermostatic valve and the electronic valve performances are practically comparable when the thermostat is adopted as controller (Aprea and Mastrullo, 2002). It is possible to explain this comparing, in the same operating conditions, the evaporation and condensation pressures (Figures 5 and 6) and then the compression ratio obtained with the refrigeration plant working both with the electronic valve and with the thermostatic valve. In particular, comparing the two valves performances it can be noted both that the compression ratio results to be comparable and the major fluctuations of the pressures are related to the electronic valve. In particular, as it is easily deducible in Figure 4, it has been observed experimentally that, using as control system of the compressor capacity the classical thermostat, the electronic valve presents in the same operating conditions an energy saving of about 3% respect to the thermostatic valve.

Moreover, it has been observed by means of experimental analysis (Figure 4) that, both with the electronic valve and with the thermostatic valve and whichever is the temperature of the set-point considered (0 and 5°C), it is possible to obtain with the fuzzy control algorithm an electric energy saving on average equal to 14% in comparison with the classical control with thermostat.

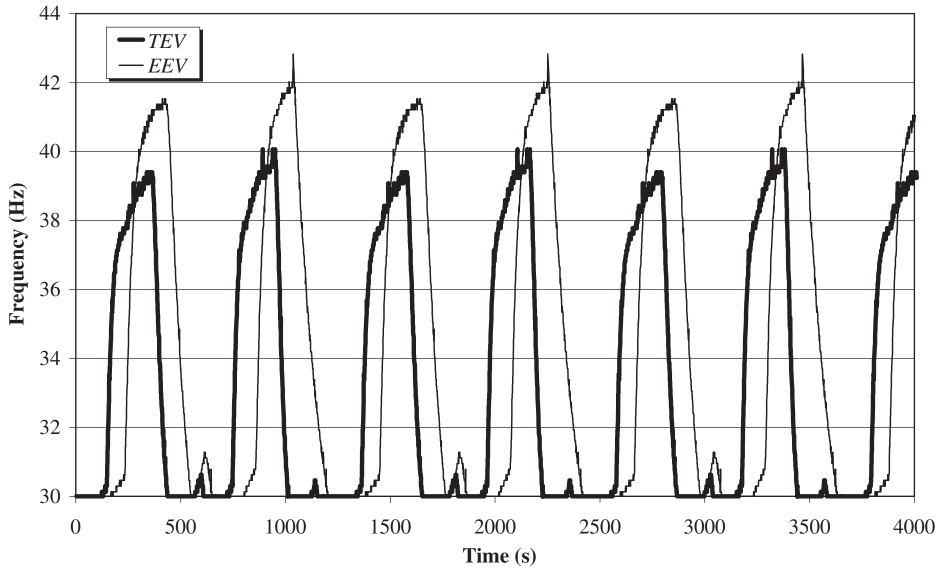

Figure 3. Frequency trend related to fuzzy control with set-point 5°C for an EEV and TEV.

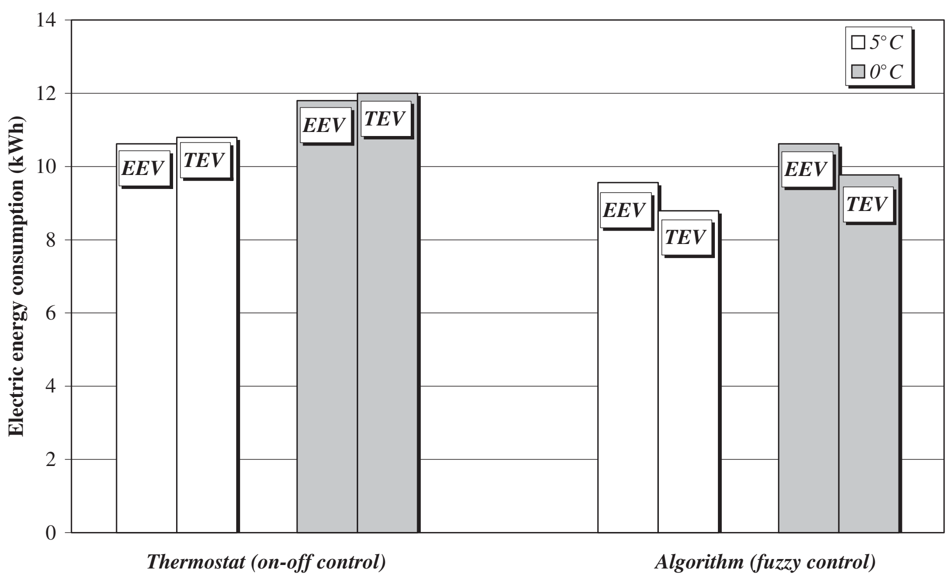

Figure 4. Comparison in terms of energy consumptions between EEV and TEV with on–off and fuzzy controls.

Besides, it is possible to note that the absolute energy consumption decreases by about 10% related to a set-point temperature of 5°C in comparison with the set-point temperature of 0°C (Figure 4). It is important to observe that the fuzzy control system allows, regulating the compressor speed, to reach the temperature of the air needed in the cold store and to maintain

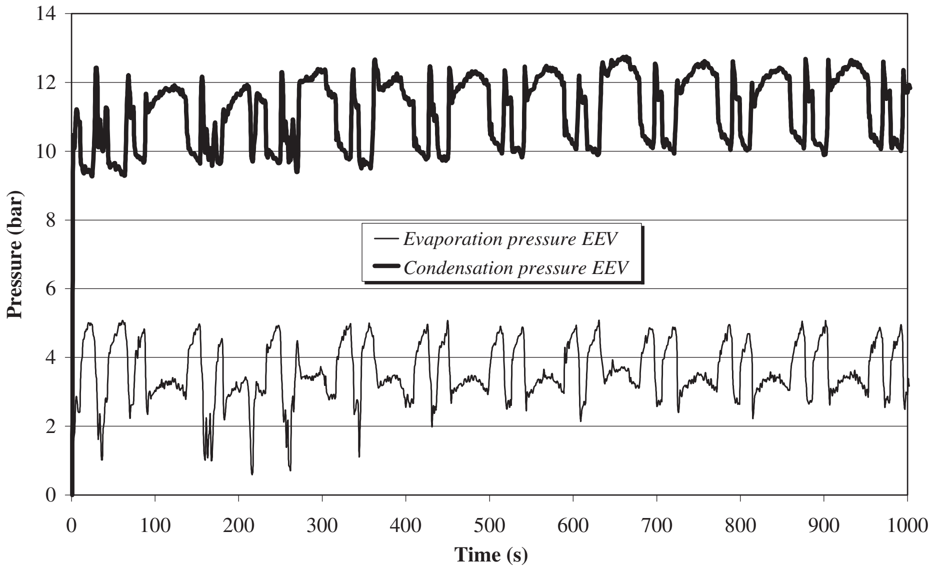

Figure 5. Evaporation and condensation pressures for an electronic valve with set-point 0°C and on–off control.

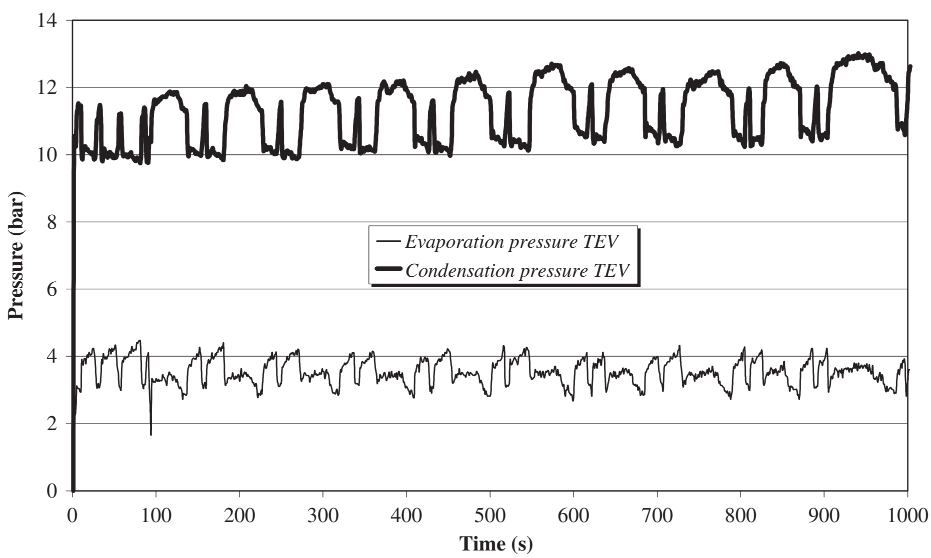

Figure 6. Evaporation and condensation pressures for a thermostatic valve with set-point 0°C and on–off control.

its oscillation in the range ± 1°C; this last value is acceptable as it corresponds to the differential band of a thermostat. Finally, it is necessary to observe that though the electronic valve assures a major sensibility and versatility to regulate the refrigerant flow at the evaporator inlet in comparison with the thermostatic expansion valve, this valve is characterized by major costs. So referring to the results experimentally obtained, it is possible to deduce that for the refrigeration plant above described, it would be better to adopt a thermostatic valve on varying the compressor electric motor supply current frequency.

5. CONCLUSIONS

In this paper, an analysis of the energetic performances of a vapour compression experimental plant subjected to a cold store adopting as expansion valve, both a thermostatic valve, and an electronic valve, has been realized. In particular, this comparison has been carried using as compressor refrigeration capacity control system, both the classical thermostat, that determines compressor on/off cycles, and an algorithm, based on fuzzy logic and built-in Labview environment, able to regulate with continuity the compressor speed. It has been observed by means of experimental tests that, both with the electronic valve and with the thermostatic valve, whichever is the temperature of the set-point considered (0 and 5°C), it is possible to obtain adopting the fuzzy control algorithm an electric energy saving on average equal to 14% in comparison with the classical control with thermostat. Moreover, it has been observed that the absolute energy consumption decreases by about 10% referring to a set-point temperature of 5°C, with respect to the set-point 0°C. Related to the comparison in terms of energy consumption between the electronic valve and the thermostatic valve it has been noted that when the fuzzy algorithm is adopted as refrigeration capacity control system, the thermostatic expansion valve allows an energy saving of about 8% in comparison with the solenoid electronic valve in the same operating conditions. On the contrary, when it used the on–off control, the electric energy consumptions, using both the electronic valve and the thermostatic valve, are comparable; in particular, the electronic valve presents an energy saving of about 3% respect to the thermostatic valve. Finally, referring to the results experimentally obtained, it is possible to deduce that, varying the compressor electric motor supply current frequency, it would be better from the energy point of view, for the refrigeration plant above described, to adopt a thermostatic valve; on the contrary, the performances in terms of energy saving of the two valves result are comparable when the thermostat is adopted, even though the electronic expansion valve is characterized by major costs.

NOMENCLATURE

AC = alternating current
DC = direct current
EEV = electronic expansion valve
HFC = hydrofluorocarbon
ODP = ozone depletion potential
TEV = thermostatic expansion valve

APPENDIX A

In Figure A1, a block diagram of fuzzy control process of the cold store air temperature is reported. In particular, the figure shows a two-input one-output fuzzy controller. The input

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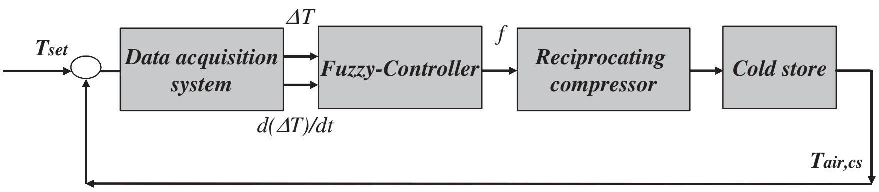

Figure A1. Fuzzy control algorithm block diagram.

Table AI. Fuzzy algorithm rules.

		ΔT				
f		vl	l	ms	h	vh
d(Δ*T*)/d*t*	l	vl	l	ms	h	h
	ms	l	l	ms	h	vh
	h	ms	ms	h	h	vh

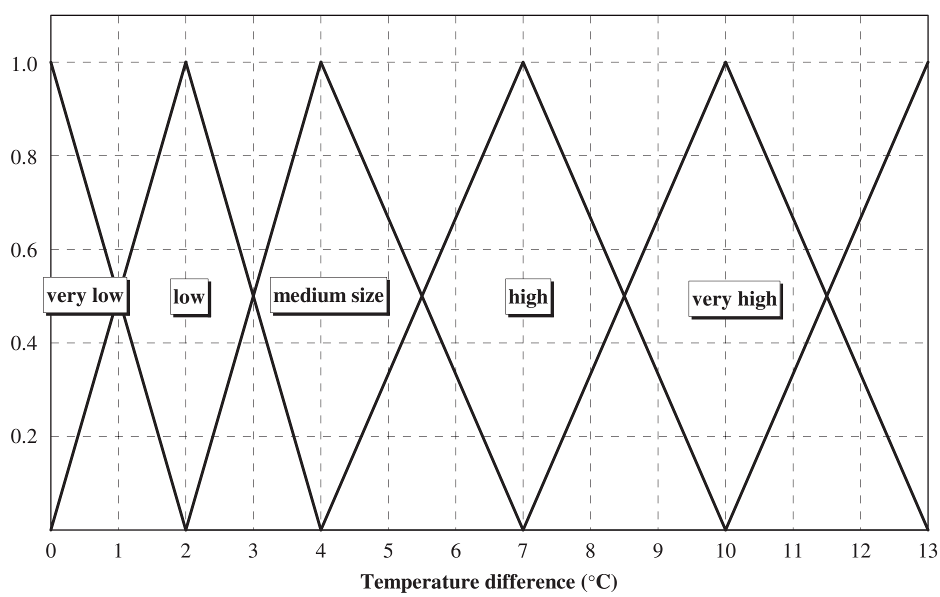

Figure A2. Membership function of the temperature difference between the set-point temperature and the real temperature of the air in the cold store.

variables are the temperature difference between the set-point temperature and the real temperature of the cold store air (ΔT), and the derivative of this temperature difference in time ($d(\Delta T)/dt$); the fuzzy output variable is the frequency of the supply current of the compressor electric motor (*f*). In particular, Table AI shows the rules fixed to set the algorithm and the five fuzzy subsets used to characterize the input and output linguistic variables marked with the following labels: very low (vl), low (l), medium size (ms), high (h) and very high (vh). Moreover, after some experimental considerations to understand the control characteristics of the reciprocating compressor, the membership functions have been defined for the temperature difference between the set-point temperature and the real temperature of the cold store air (Figure A2), the derivative of this temperature difference in the time and the frequency of the compressor electric motor supply current. The triangular membership function, with one centre and two limits, has been adopted. It has been considered as a variable input also the derivative to take into account mainly the fast variations when the cooling load varies suddenly. The values of the compressor motor supply frequency considered in the output fuzzy subset membership function, are located in the range 30–50 Hz. The inference mechanism employed has been the product inferencing method (Larsen, 1980; Ross, 1995; Zadeh, 1965). This mechanism allows a better interpolative reasoning among the input and output variables because the effect of these variables on each other is obtained more effectively. The adopted defuzzification method is based on the determination of the mass centre of a compound set; so the fuzzy output is turned into a well defined analogic signal (Leekwijck and Kerre, 1999; Rotshtein and Shtovba, 2002).

REFERENCES

Aprea C, Mastrullo R. 2002. Experimental evaluation of electronic and thermostatic expansion valves performances using R22 an R407C. *Applied Thermal Engineering* **22**(2):205–218.

Aprea C, Mastrullo R, Renno C. 2004. Fuzzy control of the compressor speed in a refrigeration plant. *International Journal of Refrigeration* **27**(6):639–648.

Haberschill P, Lallelmand M, Puttagarts A, Tamainot-Telto Z. 1996. Comportament dynamique de détendeurs thermostatiques de machines frigorifiques. *International Journal of Refrigeration* **19**(2):124–131.

Hewitt NJ, McMullan JT, Murphy NE, Ng CT. 1995. Comparison of expansion valve performance. *International Journal of Energy Research* **19**:347–359.

Larsen PM. 1980. Industrial applications of fuzzy logic control. *International Journal of Man-Machine Studies* **12**(1): 3–10.

Leekwijck WV, Kerre EE. 1999. Defuzzification: criteria and classification. *Fuzzy Sets and Systems* **108**(2):159–178.

Matsuoka F, Nagatmo H. 1988. Dynamic response and electrical control for the air conditioner. *JAR Transactions* **5**(1):43–54.

Rathje P, Zangenberg J. 1995. Determination of capacity for expansion valve for different refrigerants. *19th International Congress of Refrigeration*.

Ross TJ. 1995. *Fuzzy Logic with Engineering Applications*. McGraw Hill-Hill: New York.

Rotshtein AP, Shtovba SD. 2002. Influence of defuzzification methods on the rate of tuning a fuzzy model. *Cybernetics and Systems Analysis* **38**(5):783–789.

Schmidt F. 1995. Expansion valve and zeotrope refrigerant. *19th International Congress of Refrigeration*.

Schmidt F. 1999. Optimal control of electronic expansion valves in modern low charge evaporator systems requires fast reacting expansion valves and new controller design. *20th International Congress of Refrigeration*.

Yasuda H, Ishibane K, Nakayama S. 1992. Evaporator superheat control by an electrically driven expansion valve. *JAR Transactions* **9**(2):147–156.

Zadeh LA. 1965. Fuzzy sets. *Information and Control* **8**:338–353.

DOI: 10.1002/er