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Cascade Control Loop Implementation in a Vapor Compression Refrigeration System Using LabVIEW®

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Abstract: This study presents a cascade control system implementation to regulate the outlet temperature in a evaporator of a vapor compression refrigeration systems which is integrated by an evaporator, a compressor, the expansion valve and the condenser. The equipment is partially instrumented with 4 temperature sensors and 4 pressure sensors, connected to the NI USB 6210 and NI USB 6008 data acquisition that allows manipulate the fans speed in the condenser and evaporator heat exchanger. The transfer functions of heat exchangers was approximated to a first order plus dead time in order to study the evaporator outlet temperature and the faster dynamic in the condenser outlet temperature for inner loop which allowed to design and tune the PID controllers through the Ziegler-Nichols method for the primary controller and the Austin tuning laws for the secondary controller. Finally, the performance controllers was evaluated using the integral of absolute value of error indicator, resulting the P-PI cascade controller under changes of set point whit comparative advantages rather than PI controller.

Key words: PID controller, cascade controller, vapor compressor refrigeration systems, transfer, condenser, temperature

INTRODUCTION

Energy is a very important factor in driving strong economic development and growth of any country and with the increasing demand on energy, the research on energy conservation and its efficient use is turning out to be one of the important topics. Reduction of energy consumption through efficient energy use or by reducing the consumption of energy services is a goal in all engineering fields (Harby *et al*., 2016). Global concerns about the environmental impact and finite availability of conventional energy sources have motivated efforts to develop technologies that harness clean and renewable energy sources (Mira-Hernandez *et al*., 2016). Air-conditioning systems which are often air-cooled, consume a considerable amount of the electricity generated due to the large differences in temperature between the condenser and evaporator in these systems (Qureshi and Zubair, 2013). These refrigeration systems are an important sector of energy demand and they represent a large percentage of total energy use. Simple vapor compression systems are often used for example in cold storage applications and cooling supermarket cases where evaporator temperatures vary from -40 to 7°C (Zubair, 1990).

Cascaded closed loop position controller is widely used in controlled electrical drives because of its simplicity (Robet and Gautier, 2014). Under the current efficiency trends, the energy usage of data centers in the US is estimated to become more than 100 billion kWh by 2011 which represents an annual energy cost of approximately $7.4 billion. With the introduction of a proposed carbon tax in the US, the annual costs could become as high as $8.8 billion by 2012 increasing annually (Jackson Braz Marcinichen *et al*., 2012). Actually is under investigation a big number of cooling process in the mechanical field as the magnetic and others fields too according the requirements and applications of temperatures to process (Sun and Hu, 2003; She *et al*., 2016; Ma *et al*., 2017; Zlatanovic and Rudonja, 2012). It has been realized many control implementations about this systems, Matthew, Estrada and Rasmussen,

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proposed a cascade control loop in the overheat in a multi-evaporator cooling system in which from a pressure setup they could take control of the overheat, therefore, the system could work in a more efficient way (Elliott *et al.*, 2011). A decentralized control structure was implemented in a vapor compression cooling system, evaluating some driver couples to obtain a better performance for a different operation points of the system (Elliott and Rasmussen, 2013; Hencey *et al.*, 2008; Zhao *et al.*, 2013).

The main objective of this study is to present the results of a cascade control loop implemented in a vapor compressor refrigeration system in order to regulate the superheat of the cycle and the energy consumption of the compressor under charge of set point and disturbance rejection.

MATERIALS AND METHODS

This study of the study presents concepts, definitions and a description of any instruments used to carry out the right development of this experimental investigation.

Vapor compressor refrigeration systems: The ideal steam compression refrigeration system is one of the most imple mented in refrigerators, air conditioning systems and heat pumps. The thermodynamic cycle is composed by four processes, from state to state a isentropic compression, later a constant pressure heat reject in the condenser from states to state, then to the state the expansion process and finally a constant pressure heat absorption in an evaporator is carried out to close the systems as shown on Fig. 1 (Coker, 2015). The real compression process have friction effects, they increase or diminish the entropy and the heat transfer, therefore, the entropy of the refrigerant can increase (process 1-2) or decrease (process 1-2') during a real compression process, depending on the predominance of the effects. The compression process (1-2') can also be more desirable than the isentropic compression process for the specific volume of the refrigerant and therefore, the energy requirements are more little in this case.

PID and cascade controller: The PID driver is an alimentation control mechanism that calculate the deviation or mistake between a measured value and the value, we want to get to apply a corrective action that change the setup of the process. The PID control law is:

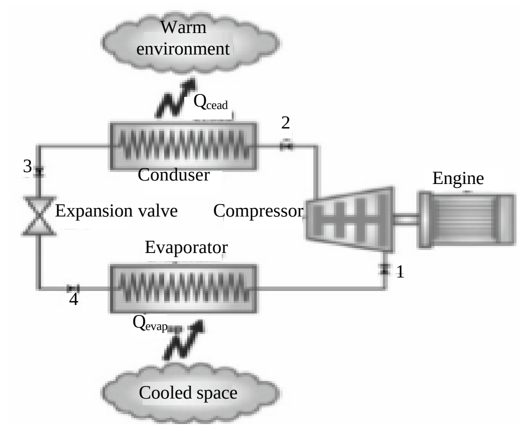

Fig. 1: Vapor compressor refrigeration system thermodynamic cycle

Table 1: Zeigler-Nichol's open loop method

Controller type	K_p	Ti	Td
P controller	U/LR	∞	0
PI controller	0.9 U/LR	3.2 L	0
PID controller	1.2 U/LR	2 L	0.5 L = Ti/4

$$u = u_{iv} + K_p\left((y_{sp}-y)\right) + \frac{1}{\tau_i}\int_0^t (y_{sp}-y)dt + \tau_d\left(\frac{d(y_{sp}-y)}{dt}\right) \quad (1)$$

Where:

K_p = The proportional gain, the integral time constant
τ_i = The derivative time constant
τ_d, u_{iv} = The stationary state of the input variable
y_{sp} = The set point of y

The proportional value determines the reaction of the actual mistake, the integral generate a proportional correction like the integral of the accumulative mistake, the tracing mistake is reduced to zero and the derivative determines the time reaction that the mistake is produced (Lynch *et al.*, 2015).

The Ziegler-Nichols rules was used to determinate the proportional gain values, K_p the integral time T_i and the derivative time T_d based in the transitory respond characteristics of any plant in open loop. In the first method, the answer of the plant under a unitary step is obtaining in an experimental way, allowing calculating the driver tuning from the equations shown in Table 1 where the equivalent dead-time is L, the rate or slope R and the step of amplitude is U (Ingimundarson and Hagglund, 2000).

The cascade controller is defined as the configuration where the output of a feedback controller is the set point for another feedback controller at least. More exactly, the cascade control involves feedback control systems or circuits that are ordered one inside of another as shown on Fig. 2 (Yin *et al*., 2016). The controllers was evaluated under an objective performance criteria using the integral function in the error to measure the effectiveness of control (Liu *et al*., 2015) which is calculated as:

$$IAE = \int_0^{\infty} e(t)dt \tag{2}$$

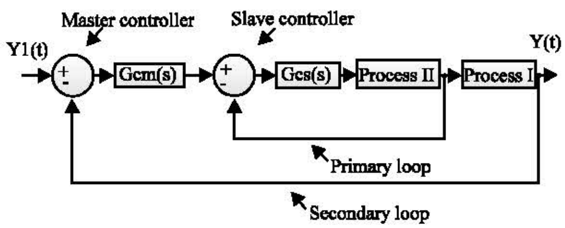

Fig. 2: Cascade control scheme

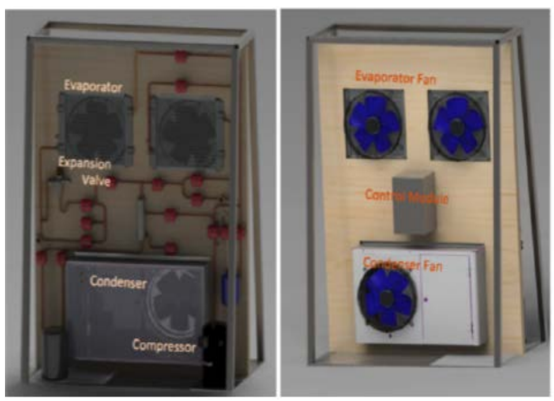

Fig. 3: Experimental equipment setup

Experimental equipment and interface programming: The equipment is a conventional vapor compression refrigeration system, consisting of a set of evaporators, compressor, condenser and thermostatic expansion valve as shown in Fig. 3.

The systems is integrated by two fin and tube evaporators, a thermostatic expansion valve used to regulate the injection of liquid refrigerant to the evaporators, a 1 Hp compressor, R 22 and a 12000 BTU condenser heat exchanger. In order to manipulate the equipment, a graphical user interface in Labview was designed allowing to check at real time the variables and controller performance over the process as shown in Fig. 4.

Figure 5 shows in the thermodynamic cycle of the experimental equipment has a series of variables that must be monitored both for the control loops and for the calculation of their performance behavior, these variables are the temperature and pressure at 5 different points, evaporator 1 outlet (ST1)-(SP1), evaporator 2 outlet (ST2)-(SP2), compressor inlet (ST3)-(SP3) and finally the compressor outlet (ST4)-(SP4) and heat exchanger outlet (ST5) -(SP5).

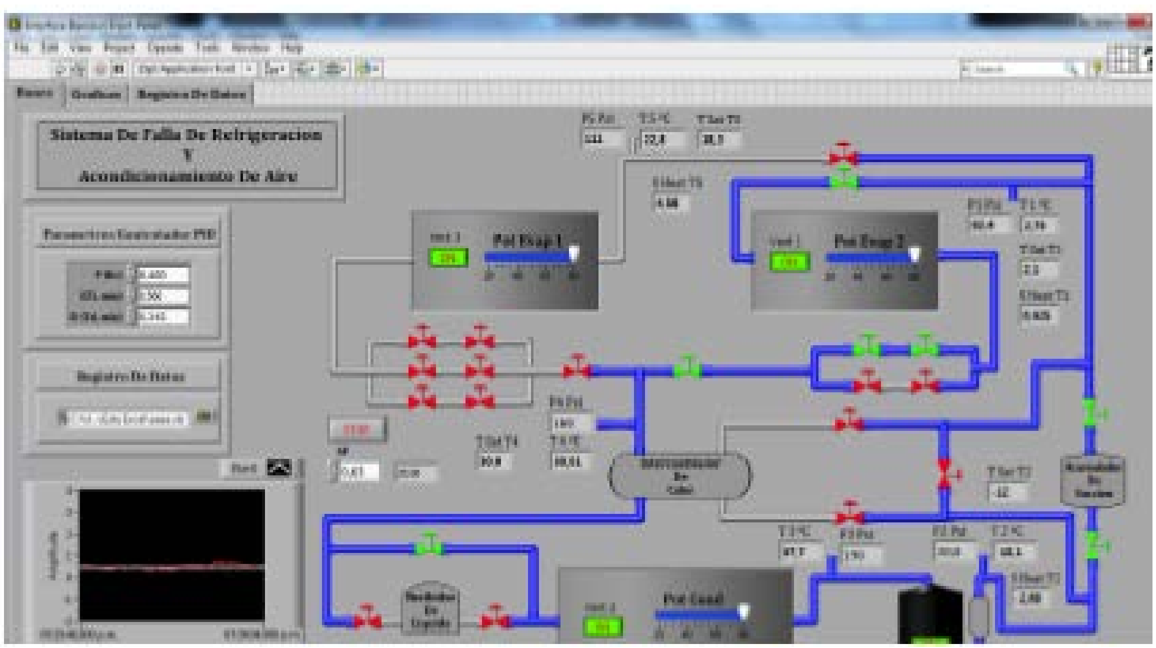

Fig. 4: Graphical user interface

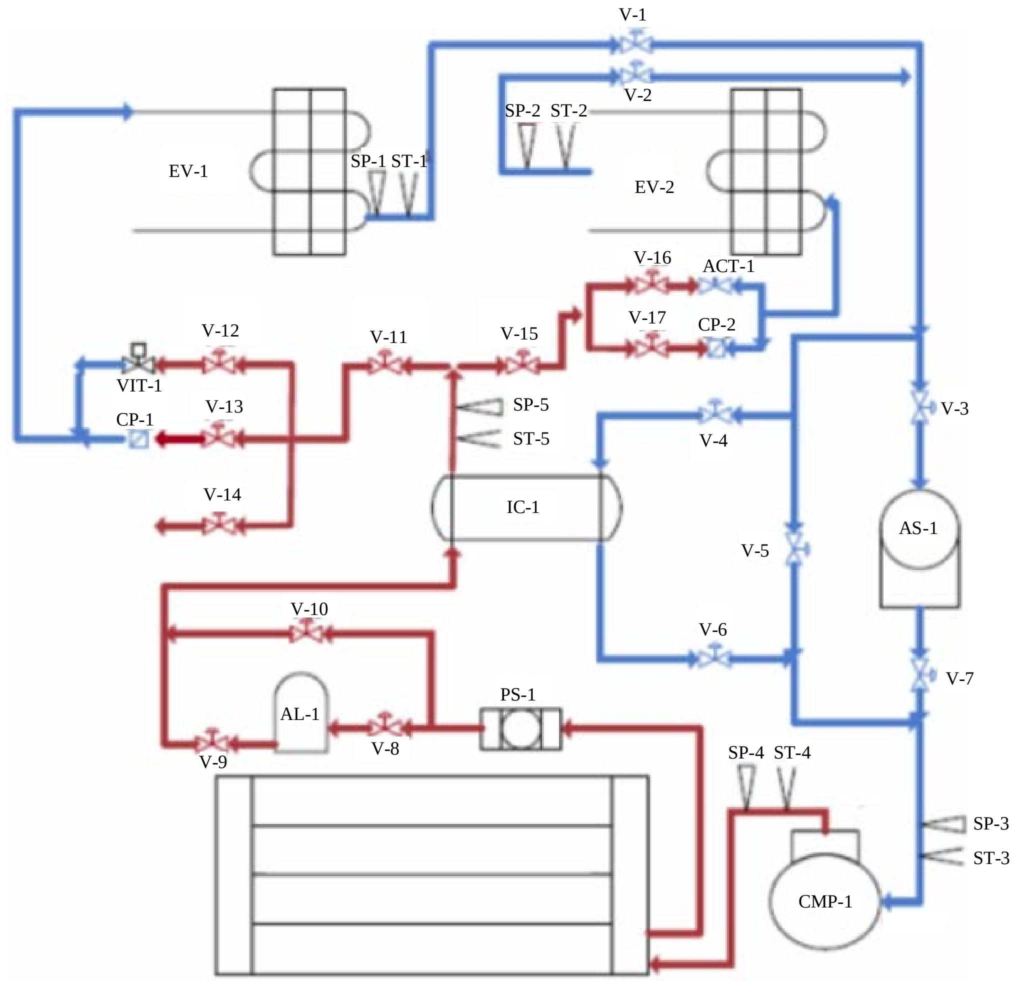

Fig. 5: Instrumentation system diagram

RESULTS AND DISCUSSION

In order to identify the transfer function of the process, a step input was applied to the condenser fan, from 80% power units to 30% units and later measurement the condenser and evaporator output temperatures through the sensors TT3 and TT2, evaporator output condenser output temperatures, respectively as shown on Fig. 6. The parameters of the transfer functions obtained for the 2 processes are show in Table 2.

From the previously identified plants, the controllers PI of the primary loops and secondary loops were calculated as Table 3 shows.

Once it was obtain the controller parameters, it was configured in the controller interface programming. From many experimental responds it is clearly observed that a constant superheat is associated with an equal variation of both temperatures which causes that the difference between temperatures is the same. The increase of this

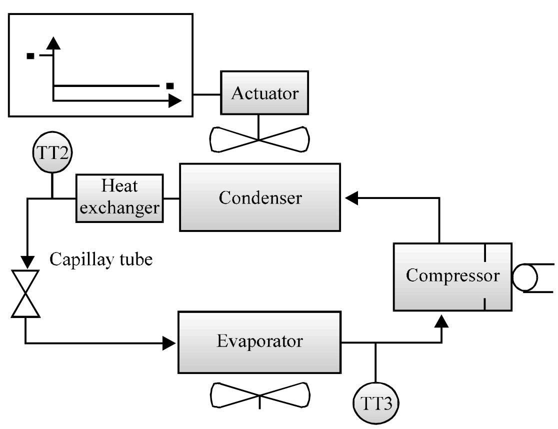

Fig. 6: Cascade controller implementation over the process

Table 2: Parameters identified for the transfer function

G(s)	k	τ	to
Evaporator TT3	-0.1158	66 s	14 s
Condenser TT2	-0.2384	58.5 s	10.5 s

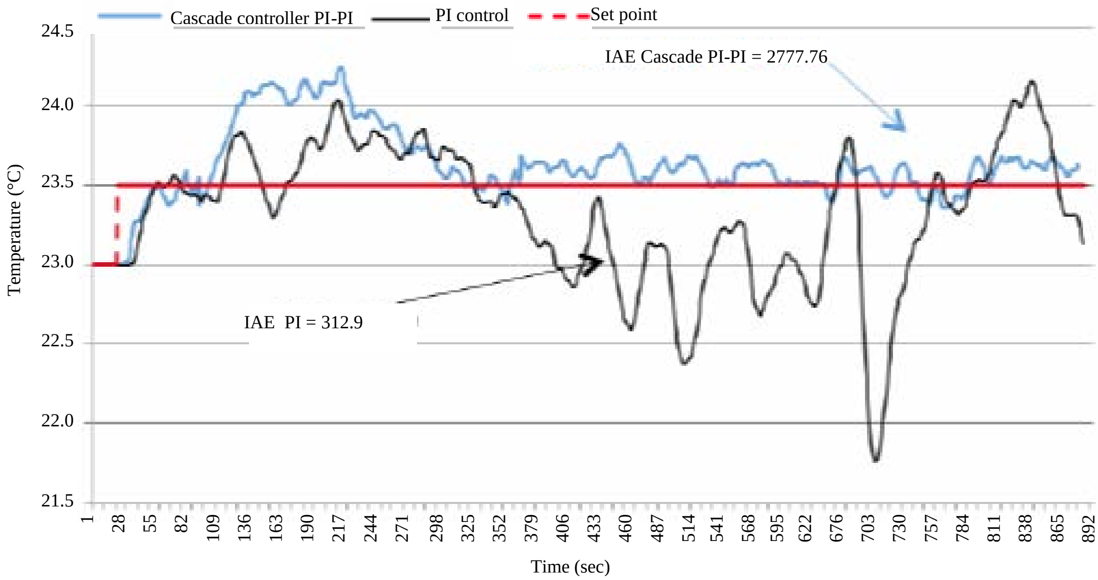

Fig. 7: Cascade controller dynamic answer against a conventional PI controller

Table 3: Cascade controller parameters

G(s)	K_p	T_i	T_d
G 1(s)	8.00	66 s	0 s
G 2(s)	-36.63	46.62 s	0 s

Table 4: Performance indicators respond under setpoint and perturbation change

Setpoint change	IAE	Perturbation change	IAE
P	186.40	P	80.3
PI	312.90	PI	243
PID	372.20	PID	94.7
PI-P	153.20	PI-P	73.4
PI-PI	277.76	PI-PI	196

superheat is due to the fact that there is a greater difference between the Temperature (T1) and the saturation temperature, however, variations of the superheat not >1°C are observed for which we consider that the controller shows a good behavior of the controllers used to guarantee the desired variable. By doing a comparative analysis between the IAE and ITAE of the three controllers shown in Table 4 it is clearly observed that the proportional controller shows the lowest performance best behavior during the setpoint change and in the presence of disturbances but the cascade PI-P improved the responds 21.6% with respect to the P controller and the PI-PI presented a better performance in 11.23% respect to the single PI controller under setpoint change. In term of perturbance rejection the best single controller implemented was the P controller which was improved working with the PI master controller in cascade law in 9.4%.

Finally, Fig. 7 shows the system dynamic respond against a set point change for a conventional controller PI in front of the cascade controller implemented, it was observed that the cascade controller dynamic is too much fast, allowing to adjust the temperature operation point in the evaporator in a more efficiently way, promoting the energy efficiency on the vapor compressor refrigeration systems.

CONCLUSION

It was found that the cascade control loop implementation allows increasing the energetic efficiency of the cooling system when an output evaporator temperature operation point is selected it should sbecause the condenser and evaporator fans need a lowest energy to function and it means a very nice energy saving. The laboratory scale test bench of the steam compression cooling system was virtually instrumented using LabVIEW®, it was used an acquisition data system of the national instruments company with Honeywell and Kobold sensors, calibrated by the least squares method. After the tests with instrumented bench was possible to check experimentally that the perturbations in the internal temperature control loop at the condenser output were fixed by the secondary controlle before it could to affect the primary variable which is the evaporator output temperature what it entails lowest operations times of the compressor and therefore, a less energy consume on this.

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