SYSTEM FOR STUDIES OF CONTROL STRATEGIES APPLIED IN THE REFRIGERATED CHAMBERS

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ABSTRACT: The process of cold storage chambers contributes largely to the quality and longevity of stored products. In recent years, it has been intensified the study of control strategies in order to decrease the temperature change inside the storage chamber and to reduce the electric power consumption. This study has developed a system for data acquisition and process control, in LabVIEW language, to be applied in the cooling system of a refrigerating chamber of $30m^3$. The use of instrumentation and the application developed fostered the development of scientific experiments, which aimed to study the dynamic behavior of the refrigeration system, compare the performance of control strategies and the heat engine, even due to the controlled temperature, or to the electricity consumption. This system tested the strategies for on-off control, PID and fuzzy. Regarding power consumption, the fuzzy controller showed the best result, saving 10% when compared with other tested strategies.

KEYWORDS: energy-saving, PID controller, fuzzy controller, cold storage.

SISTEMA PARA ESTUDOS DE ESTRATÉGIAS DE CONTROLE APLICADAS EM CÂMARAS FRIAS

RESUMO: O processo de armazenamento refrigerado em câmaras contribui, em grande parte, para a qualidade e a longevidade dos produtos. Nos últimos anos, têm-se intensificado os estudos de estratégias de controle com a finalidade de diminuir a variação da temperatura dentro da câmara de armazenamento e de reduzir o consumo de energia elétrica. Neste trabalho, foi desenvolvido um sistema para aquisição de dados e controle do processo, em linguagem LabVIEW, para ser aplicado no sistema de refrigeração de uma câmara frigorífica de $30m^3$. A utilização da instrumentação e do aplicativo desenvolvido possibilitou a realização de experimentos científicos, com o objetivo de estudar o comportamento dinâmico do sistema de refrigeração, comparar o desempenho das estratégias de controle da máquina térmica, tanto em função da temperatura controlada, quanto ao consumo de energia elétrica. Neste sistema, foram testadas as estratégias de controle liga-desliga, PID e *fuzzy*. Em relação ao consumo de energia elétrica, o controlador *fuzzy* obteve o melhor resultado, economizando 10% em relação às outras estratégias testadas.

PALAVRAS-CHAVE: economia de energia, controlador PID, controlador *fuzzy*, armazenamento refrigerado.

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INTRODUTION

The cold storage is important for a better conservation of agricultural products. According to CHITARRA & CHITARRA (2006), at every 10 °C below, in the storage chamber, the metabolic reactions halve.

The control strategy of on-off type, normally used in refrigeration systems, cause premature deterioration of the compressor, high consumption of electricity, and permanent unwanted oscillations in temperature inside the storage chamber (BUZELIN, 2003).

Thus, temperature control by varying the compressor speed has emerged as a viable alternative for the reduction in energy consumption, preservation of equipment, and proper maintenance of the temperature inside the storage chamber. Several scientific studies point to the benefits of this type of control, such as that performed by HUA et al. (2009), which highlights the increase in system performance and reduced of electricity consumption.

The development of a mathematical model with multiple inputs and multiple outputs (MIMO) to represent a cooling system was proposed by MENEGHETTI (2009). This model was submitted to the mathematical simulations, with implementation of control strategies of the on-off type, PID and fuzzy. At the study, it was verified the feasibility of reducing the consumption of electricity in a conventional cooling system, submitting it to a system of variable speed, and, as a result, giving the system a small variation of air temperature in the cooling chamber.

The fuzzy set theory can be applied in several areas. OLIVEIRA et al. (2005) used this theory to estimate the thermal comfort in sheds for intensive animal production, analyzing how the composition of the temperature independent variables and relative air humidity influence the dependent variable, called "thermal comfort".

In industrial processes, the use of fuzzy control has increased greatly in recent decades, especially in those difficult mathematical modeling processes, due to its ability to function in a system based solely on expert knowledge, and also to interrelate all the variables process (SILVA et al., 2006).

HUANG et al. (2010) conducted a comprehensive review of the literature on soft computing methods, among which the application of fuzzy logic in precision agriculture. The authors consider the fuzzy logic as a tool for decision support in the areas of crop management, precision irrigation, soil analysis and application of chemicals.

This work aimed to study the dynamic behavior of the temperature and the electric power consumed by the compressor of the refrigerated chamber, during the storage phase of agricultural products, using control strategies on-off, PID and fuzzy. In this condition of use, the system will be subject only to minor problems; no major changes are needed in the original components, nor the use of servo-controlled expansion valve, requiring only the performance in the frequency of the motor-compressor set.

MATERIALS AND METHODS

In this work we used a conventional refrigerated chamber of 30m^3, usually used for cold storage of fruits and vegetables. Its components, such as compressor, pipes, condenser, evaporator, and expansion valve, were kept in their original settings, unlike the proposed by EKREN et al. (2010), who tested different control actions in a cooling system (chiller), acting both in the variable speed of the motor compressor, as well as in the thermostatic expansion valve by means of a stepper motor.

The equipment used in the implementation of the system is described in Table 1.

TABLE 1. Equipments used in the system implementation

Equipment	Brand	Model	Capacity
Hermetic compressor	Copeland	CS14K6E-TF5-522	4,256 kcal h^{-1}
Evaporator	Macquay	FBA -190	4,400 kcal h^{-1}
Condenser	Macquay	M4Q045-EF01-4	4,256 kcal h^{-1}
Frequency inverter	WEG	CFW080160T2024PSZ	6.1 kVA
Quantities transducer electrics	Kron	MultK-05	44 electrical quantities
Sensor of temperature	Sensyn	PT100	-200 °C a 850 °C
Temperature sensor	Sensyn	TT100	-40 °C a +85 °C
Solid state relay	Markare	MKRL-100-4-4	16 Amperes
Pressure transmitter	Wika	R1	0 a 60 bar
Acquisition board	National Instruments	NI6224	32 analog inputs e 4 analog outputs
Electrical resistances		Cônicas	2.8 kW

In the diagram of the implanted instrumentation (Figure 1), the installed devices are identified, and used for data acquisition and process control, as well as control signals for communication between the computer and the process, and the performance monitoring devices.

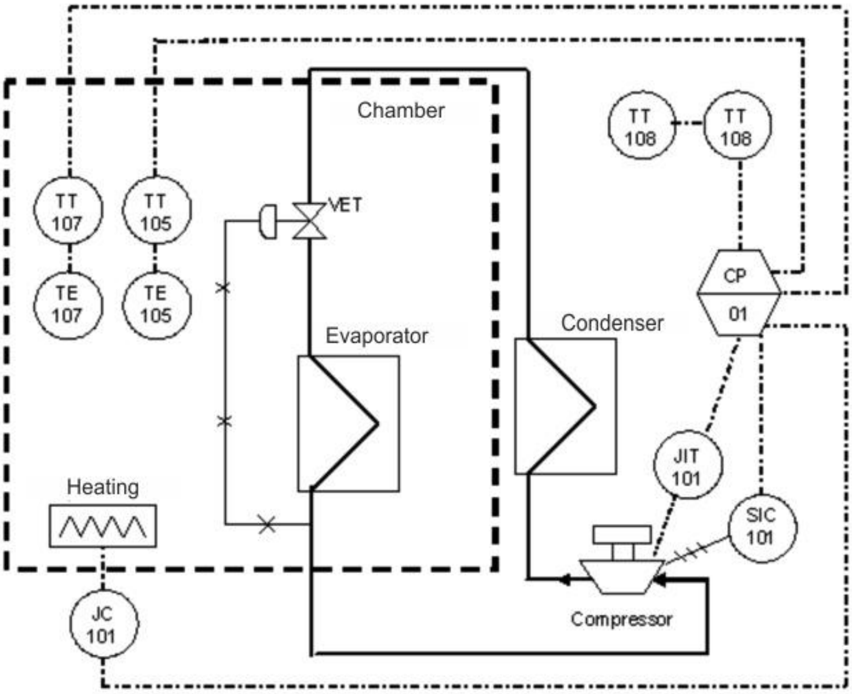


FIGURE 1. Diagram of instrumentation used in the study.

The instruments installed in the cooling system are described in Table 2, according to their identifications, functions and locations.

The temperature measurement used sensor elements of the type Pt-100, three-wire, coupled to temperature transmitters with output signal current (4-20 mA).

The air temperature at the evaporator inlet was used as the measured variable for control systems, for it is the reference used by the original control system. The fuzzy control also used the air temperature at the center of the chamber as a measured variable.

The reference value of 2 °C, adopted for the tests, was obtained operating the open-loop system, with the frequency of the compressor at 30 Hz, and a heat load of 800 kcal h^{-1}. In this situation, the temperature inside the chamber has stabilized at 2 °C in steady-state.

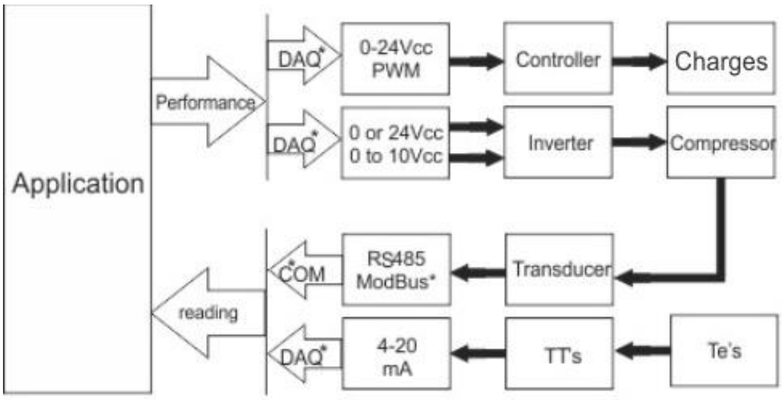
TABLE 2. Description of instruments used for data acquisition and control.

Identifications	Function	Location
CP 01	Computer Case	Control Room
SIC 101	Frequency inverter	Auxiliary panel
JIT 101	Transducer of electrical	Auxiliary panel
JY 101	Power relays	Auxiliary panel
TT 105, 107 e 108	Temperature Transmitters	Auxiliary panel
TE 105	Pt100 temperature sensor	Evaporator inlet
TE 107	Pt100 temperature sensor	Center of the chamber
TE 108	Pt100 temperature sensor	Environment outside the chamber

To the rotation control of the compressor motor, a frequency converter was used, controlled by an analog signal from 0 to 10 Vdc. The activation of the compressor motor was controlled by a digital signal 24 Vdc. Thus, it was possible to turn on or off, and also vary the frequency drive of the compressor motor between 30Hz and 60Hz. This frequency range was established according to the specifications of the compressor, in order to avoid problems of lubrication and cooling it of.

To simulate a thermal load compatible with the products possibly stored in cold chamber, three electric heaters were used, with a total installed power of 2.8 kW, driven by solid state relays, controlled by PWM signal (width modulation pulse).

Figure 2 shows the block diagram with the direction of flow and data types for signal acquisition and control, members of the implemented system.



*DAQ (Data AcQuisition): PCI device of input and output signals for data acquisition and performance.
*COM (Component object Model):Technology that allows the communication between software and hardware
*ModBus: data communication protocol used in industrial automation systems.

FIGURE 2. Flow diagram for data acquisition, monitoring and control.

The signs of the actuators and sensors were processed by a microcomputer, running an application developed in LabVIEW, version 8.5, which performs data acquisition, monitoring and process control.

The experiments were performed with the refrigerated chamber operating at steady state, for 100 min, with the data acquisition rate set at one sample per second, and thermal load in 1,530 kcal h^{-1}. This value of heat load represents 36% of the total cooling capacity of the refrigeration system, and simulates the condition of cold storage, i.e., situation in which case the system ought to supply small temperature variations inside the chamber, mainly caused by the respiration heat of the product, and also the loss through the walls, floor and ceiling.

The calculation of the energy consumed by the compressor was carried out using the values measured and transmitted by the electrical quantity transducer, using serial interface RS485 (Modbus RTU protocol). The main electrical quantities measured were: voltage and current in three phases, power factor, apparent power and active power. The electrical energy consumed in the period under analysis was calculated by integrating the active electrical power in time.

The on-off controller was implemented with a hysteresis of 1 °C around the reference value. This value was determined to enable reproduction of the same conditions of the previously existing controller in the storage chamber.

The PID controller implemented follows the structure of the classical-parallel type, which the proportional gain also affects integral and derivative actions. The ability to anticipate the disturbance is a characteristic of a fuzzy controller, a fact found by OLIVEIRA et al. (2005), in his work about Matlab ambient simulation to estimate the sensation of thermal comfort for laying hens in production.

The fuzzy controller implemented in this study used the LabVIEW *toolkit fuzzy* application, which operates at the reference value (set point) of the PID controller, modifying it according to the difference between the values of temperatures in the center of the chamber and the evaporator inlet, and also because of the tendency of variation of the error in steady state. For the *fuzzification*, the MAMDANI method was used, and for the *defuzzification*, the method of center of area (COA), as observed in simulations in the study of NASCIMENTO et al. (2011), which determined the fuzzy index of thermal comfort for broilers.

It was used the performance index I_{MSE} (MSE - Mean Square Error) to monitor, evaluate and compare different control strategies, calculated according to Equation 1.

$$I_{MSE} = \frac{1}{n} \sum_{n-1}^{n} (e_{(t)})^2 \tag{1}$$

where,

e(t) - error in the reference value, and

n - number of samples.

RESULTS AND DISCUSSION

The control strategies PID and fuzzy used as controlled variable the air temperature inside the storage chamber, and as manipulated variable the electric frequency of the compressor, aiming to improve the system performance in relation to temperature variation within the camera and the power consumption of the system. According to HUA et al. (2009), the performance in speed variation of the compressor proved to be an effective technique when you want a stable temperature value inside the chamber, and lower electricity consumption by the system.

On-off control strategy

The control strategy of the type on-off was implemented because it is the way that conventional cooling systems operate. This strategy, for being the original camera, was set as the reference for comparisons with the other two control strategies.

Figure 3 shows the drive cycle of the compressor motor and the behavior of air temperature at the evaporator inlet (T_air_Evap) when the control strategy on-off is implemented. It also shows the reference value set at 2 °C and controlled temperature variation. In this operating condition, the compressor is turned on or off in its maximum frequency of 60 Hz, operating in the on mode 66% of the time, resulting in a variation of temperature in the storage chamber of 1.0 °C to 3.3 °C. The drive cycle of the compressor motor caused a permanent oscillation in temperature inside the chamber and higher electricity consumption, which is consistent with the findings of BUZZELIN (2003).

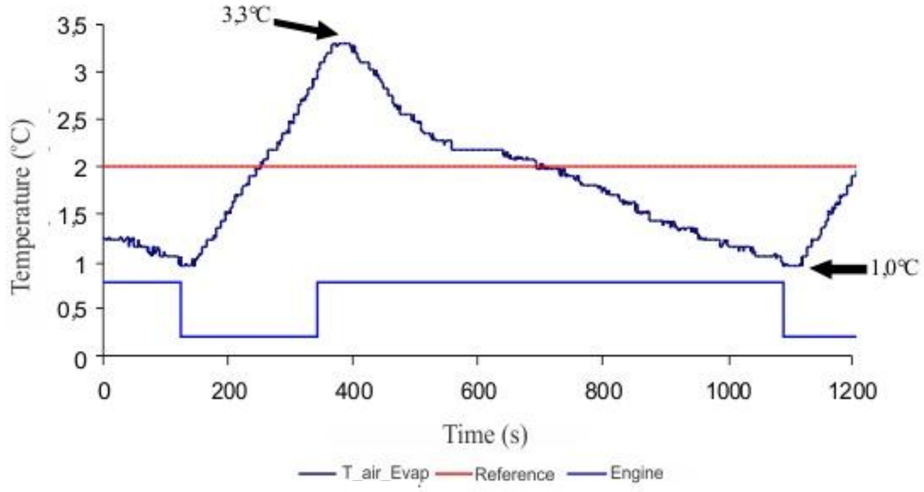


FIGURA 3. Action of the system with control on-off.

PID control strategy

The parameters of the PID controller (proportional, integral and derivative) were calculated based on the tuning methodology of Ziegler and Nichols, resulting in 121 to the proportional gain, 44s for integration time, and 11s for the derivative time.

Figure 4 shows the behavior of air temperature at the center of the chamber, at the evaporator inlet, and the reference value of temperature. Figure 5 shows the variation of the electrical frequency supplied to the compressor motor, when the control strategy PID is executed. Observing Figure 4, it appears that the variation of air temperature at the evaporator inlet (T_air_Evap) does not exceed 0.1 ºC around the reference value. Inside the chamber (T_Center), the temperature variation was of a maximum of 0.6 °C. The variable of activity, frequency of the drive of the compressor motor (Figure 5) ranged from 36.3Hz to 54.6Hz (60.5% to 91.0% of rated).

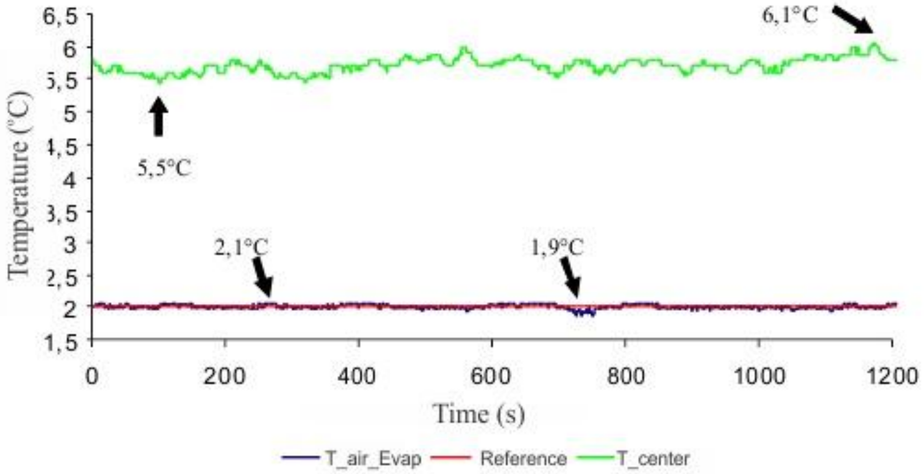


FIGURE 4. Action of the system with control PID - temperatures.

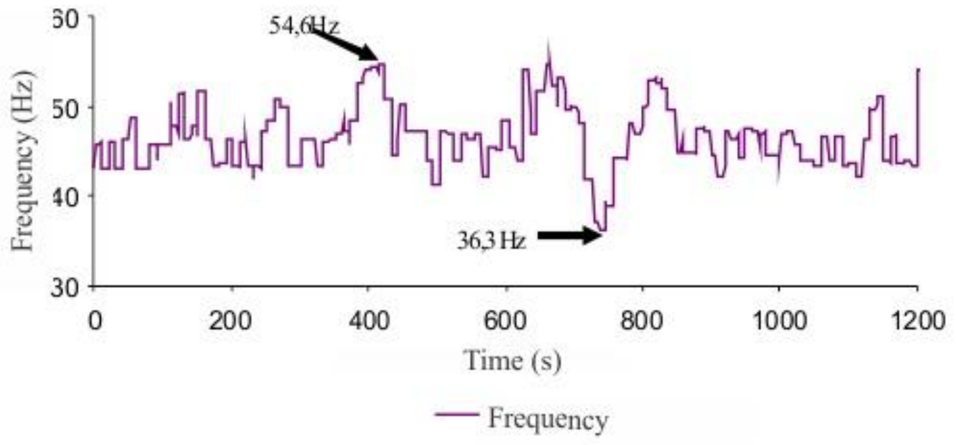
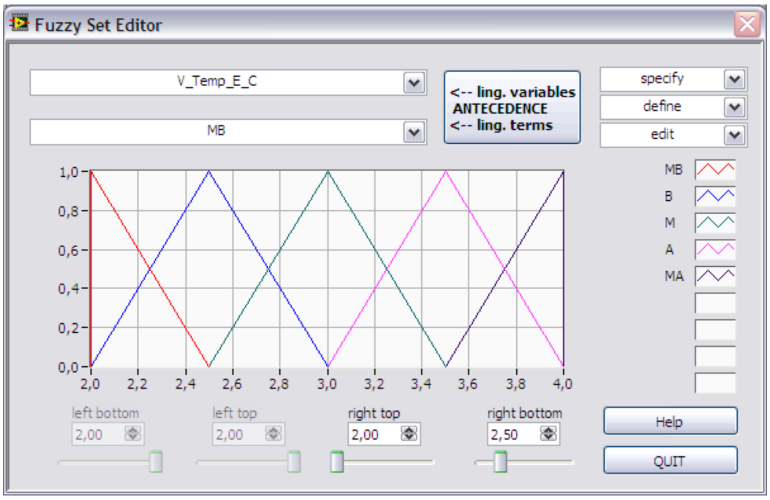


FIGURE 5. Action of the system with control PID – electrical frequency.

Fuzzy control strategy

In the operation of this control strategy, the fuzzy controller adjusts the reference value of the PID controller, allowing a controlled variation of no more than 1 ºC for the reference value originally selected for the controller. This mode of operation aimed to consider small variations of the thermal load, which occur due to the difference between the air temperature at the center of the storage chamber and the air temperature at the evaporator inlet (V_Temp_E_C), and also the variation of the error between these two temperature measurements (Dif_Error_Temp). This control strategy has changed the reference value when the difference between the air temperature at the center of the storage chamber and the air temperature at the evaporator inlet reached the range of 2 °C to 4 °C (range in which the fuzzy controller operates), and the differential of the error was zero or negative. Otherwise, the reference value remains the same as pre-set for the PID controller.

The input variable that represents the variation of air temperature between the center of the chamber and air inlet of the evaporator (V_Temp_E_C) receives, every second, the value of the difference of the temperatures cited above, and admits values in the range of 2 °C 4 °C, divided into the following linguistic terms: Very Low (MB), Low (B), Medium (M), High (a) and Very High (MA). It can be seen in Figure 6 the relationship between the linguistic terms for variable V_Temp_E_C.


V_Temp_E_C

MB

left bottom 2,00

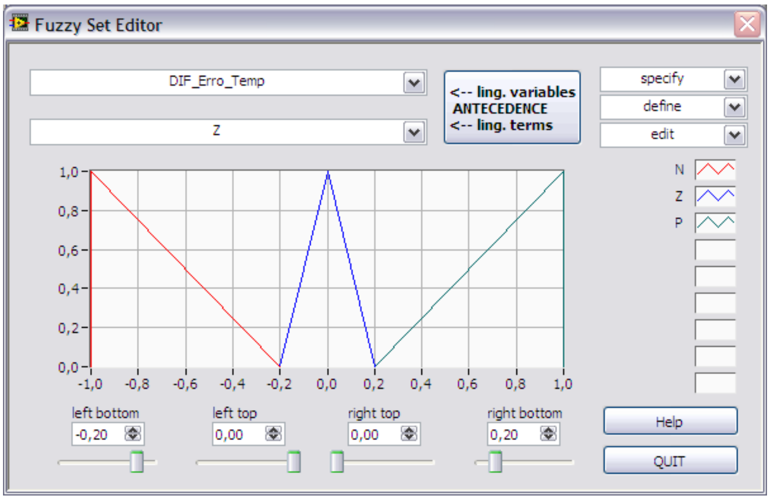
left top 2,00

right top 2,00

right bottom 2,50

FIGURE 6. Linguistic terms for the variable V_Temp_E_C.

The differential variable of the error between air temperatures at the center of the chamber and the air temperature at the evaporator inlet (DIF_Error_Temp) admits values between -1 and 1, divided into the following linguistic terms: Negative (N), Zero (Z) and Positive (P). A range of values from -0.2 to 0.2 led to a kind of "dead band" (Figure 7), preventing unwanted oscillations in the actuator.


Fuzzy Set Editor

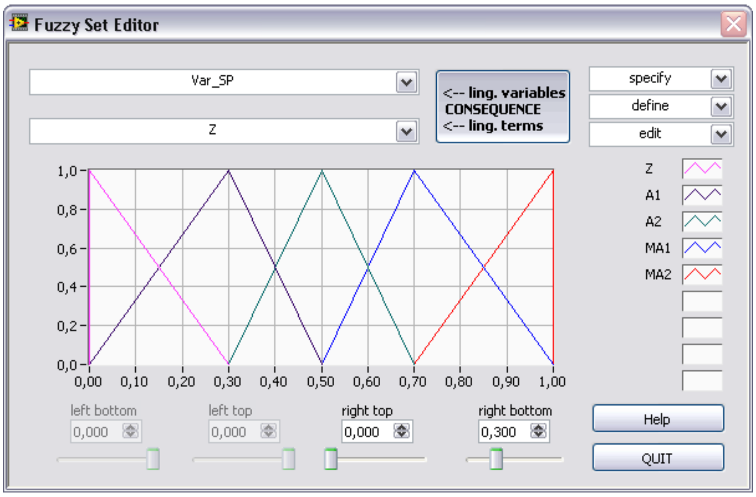
DIF_Erro_Temp

Z

left bottom -0,20
left top 0,00
right top 0,00
right bottom 0,20

FIGURE 7. Linguistic terms for the variable DIF_Erro_Temp.

The output variable linguistic, the variation in the set point (Var_SP), represents the value to be added to the reference value of the PID controller. This variable allows the output values in the range of 0 to 1, and has the following linguistic terms: Zero (Z), High 1 (A1), High 2 (A2), Very High 1 (MA1) and Very High 2 (MA2), as can be seen in Figure 8.


Fuzzy Set Editor

Var_SP

Z

left bottom 0,000
left top 0,000
right top 0,000
right bottom 0,300

FIGURE 8. Linguistic terms for the variable Var_SP.

The rule base (Table 3) has 15 rules, built taking into account the knowledge of an expert, and has a group of fuzzy propositions that are in the form "if… then", which would be activated as the values of the input linguistic variables, grouped by a logical operator "and", generating an *defuzzificated* output value through the center of gravity method.

The developed fuzzy controller acted consistently, corroborating with the results observed by SILVA et al. (2006), inter-relating the linguistic variables determined by a expert, allowing a controlled deviation of the reference value of the PID controller. This deviation is larger, the smaller the difference between the air temperature at the evaporator inlet (T_air_Evap) and the air temperature at the center of the chamber (T_Center).

TABLE 3. Rule base of the fuzzy controller.

Rule Number	V_Temp_E_C	DIF_Error_Temp	Var_SP
1	MB	N	MA2
2	MB	Z	MA2
3	MB	P	A2
4	B	N	MA1
5	B	Z	MA1
6	B	P	A1
7	M	N	A2
8	M	Z	A2
9	M	P	A2
10	A	N	A1
11	A	Z	A1
12	A	P	Z
13	MA	N	Z
14	MA	Z	Z
15	MA	P	Z

The fuzzy control strategy has enabled a shift in the reference value of 2 °C for a maximum of 2.5 °C, as shown in Figure 9. Regarding the air temperature in the center of the chamber, there was a slight variation of up to 0.3 °C. Regarding the air temperature at the evaporator inlet, this followed the fixed reference value. The electrical frequency applied to the compressor motor, which represents the controlled variable, ranged from 30.5 Hz to 51.4 Hz (50.8% to 85.7% of rated), as shown in Figure 10.

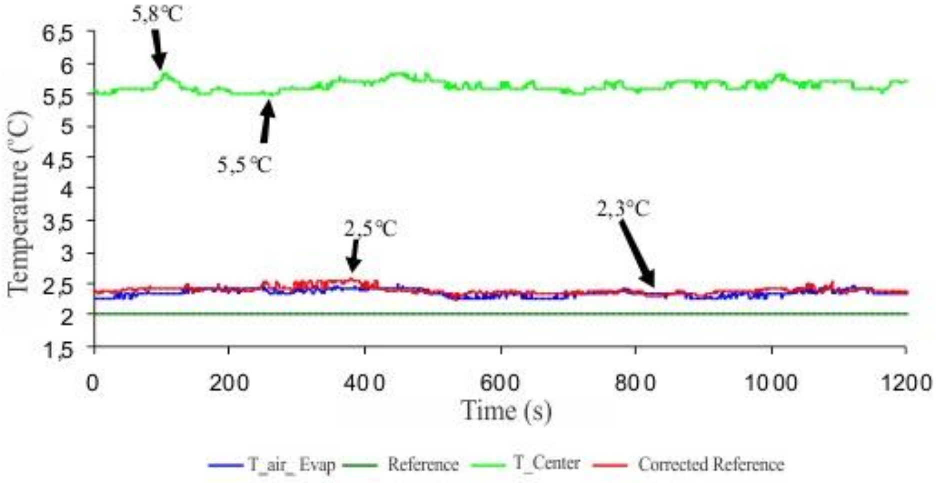


FIGURE 9. Action of the system with fuzzy control - temperatures.

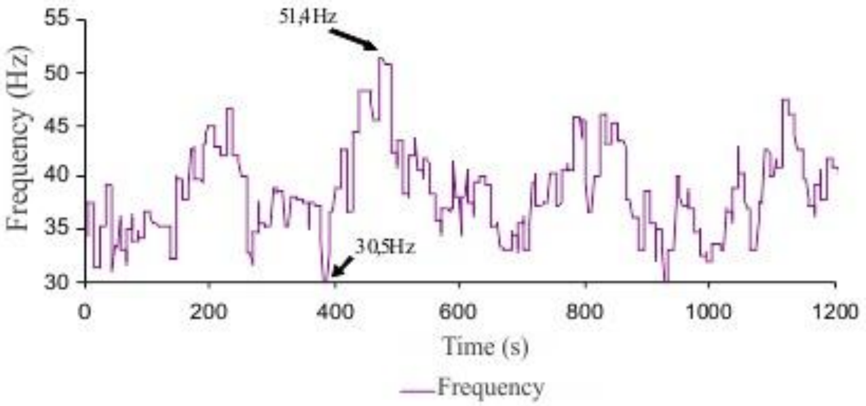


FIGURE 10. Action of the system with fuzzy control - electrical frequency.

Regarding the consumption of electricity in the compressor, the fuzzy control got the best result, requiring 1.87 kWh, followed by on-off system of 2.01 kWh, and 2.07 kWh for PID, during the tests. The best performance of a cooling system when using the fuzzy control strategy was also observed by HUANG et al. (2010).

It is observed that the use of on-off and PID controllers resulted in similar levels of energy consumption, but the PID practically does not cause oscillation of the controlled variable, which can improve the conservation of stored products, as well as the preservation of the electric motor of the compressor. On the other hand, the fuzzy control strategy, besides getting the lowest power consumption, showed no significant oscillations of the controlled variable. The I_{MSE} value calculated for the fuzzy control strategy was the lowest (I_{MSE} = 0.002) when confronted with that obtained with the use of PID control strategy (I_{MSE} = 0.019), and the one obtained with the control strategy on-off (I_{MSE} = 0.170).

The behavior of the control strategies in terms of energy saving, oscillation of the controlled variable and also the error in steady-state, was similar when compared to simulations made by MENEGHETI (2009), in the mathematical models that represent the cooling system.

CONCLUSIONS

With the acquisition system, monitoring and developed control, it was possible to evaluate the performance of different control strategies in a cooling system.

The results indicate that the PID control strategy has kept the controlled variable without major changes, and with less error in relation to the reference value when compared with the controller on-off, still maintaining the power consumption in similar levels of this controller.

On the other hand, the fuzzy control strategy obtained a best compromise solution when we evaluate the set of indices: temperature variation in the chamber; error in system and electricity saving, because in their range, had a lower error in steady-state and a lower oscillation of the controlled variable, when compared to the other two control strategies, besides providing a lower power consumption.

The results indicate that the developed system is valid for studies of control strategies applied to refrigerated storage.

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