

CONTROL SYSTEM FOR FORCED-AIR COOLING OF HORTICULTURAL PRODUCTS¹

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ABSTRACT: This work is a study of the implementation of a classical controller using a tuning method referred to as IMC (Internal Model Control) and aimed at the reduction of electrical energy consumption by the appropriate relation between energy consumption and the cooling time with forced air. The supervisory system installed was able to manipulate the variable of frequency of the signal power of the exhaust fan engine (forced air module), to accelerate or decelerate the loss of heat from the product to be cooled by airflow variation that passes through the mass of the produce. The results demonstrated a reduction in energy consumption from 64% and an increase of only 8% in the cooling time to the system using PI/IMC (Proportional - Integral with IMC) tuning method compared with the system in its operating nominal condition. This PI/IMC control may be implemented directly in a frequency converter, without the need to purchase a computer or PLC (programmable logic controller) to run the dedicated application, increasing its economical viability.

KEYWORDS: instrumentation, controller tuning, IMC method, cooling time, supervisory system.

SISTEMA DE CONTROLE PARA O RESFRIAMENTO COM AR FORÇADO DE PRODUTOS HORTÍCOLAS

RESUMO: Este trabalho consiste no estudo da implementação de um controlador clássico utilizando o método de sintonia denominado por Controle de Modelo Interno, visando à redução do consumo de energia elétrica que decorra na adequada relação entre este consumo e o tempo de resfriamento do processo de resfriamento com ar forçado de produtos hortícolas. Para isto, o sistema supervisão instalado manipulou a variável de frequência do sinal de alimentação do motor de indução trifásico do exaustor (módulo de ar forçado), para acelerar ou desacelerar a perda de calor do produto a ser resfriado por intermédio da variação da vazão de ar que perpassava a massa deste produto. Obteve-se como resultado uma redução no consumo de energia elétrica de 64% e um acréscimo de apenas 8% no tempo de resfriamento para o sistema utilizando um controle proporcional e integral associado ao método de sintonia promovido por Controle de Modelo Interno, quando comparado ao sistema em seu funcionamento nominal. Esta estratégia de controle é passível de ser implementada diretamente em alguns modelos de inversores de frequência, sem a necessidade de compra de um computador ou controlador lógico programável para executar o aplicativo dedicado, tornando-o mais viável economicamente.

PALAVRAS-CHAVE: instrumentação, sintonia de controlador, método IMC, tempo de resfriamento, sistema supervisão.

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INTRODUCTION

The expansion and widespread use of microelectronics and computer point out the role of a possible transformation of the agricultural production process. This role, in one of its aspects, aims to adequate the energy efficiency of processes. The application of instrumentation, automation and control techniques has become increasingly common in agriculture, being used in various processes and systems in this sector, as to monitor and control climatic variables to environment of plant and animal production, as studied by SILVA et al. (2007), and to evaluate an automatic control system of drip irrigation for tomato production, as studied by STEIDLE NETO et al. (2009). The application of these techniques proved to be feasible in both cases.

The process of forced-air cooling is the first procedure for storing horticultural products, and among those is the Cold Chain. This process is usually carried out in tunnels coupled with exhaust fans inside the cooling chamber, and allows the decrease in temperature of these products to the levels recommended for each produce type, cultivar and variety, thus contributing to increase its shelf life. PINTO & JORGE (2007) associated techniques of forced-air cooling with the application of the 1-methylcyclopropene and obtained firmer peaches (cultivar 'Natal'), with low levels of soluble solids, and reduced respiratory rate, compared to peaches of the control treatment, which were cooled slowly in a cold chamber, i.e., without the use of cooling techniques.

A microprocessor machine with human-machine interface (HMI) was developed by TERUEL et al. (2008), aiming to open loop control of systems with forced air cooling of vegetables, with the function of providing variable airflow rates according to the amount of produce to cool, in order to keep within the range of the recommended values to ensure an appropriate cost-benefit. The development of this equipment was based on the fact that the existing cooling systems currently operate in accordance with the airflow pre-determined in the project depending on the amount of product to cool.

In recent years there has been a growing interest in the control of cooling processes applied to the area of manufacturing microchips. XING et al. (2008) studied the advanced control method called Smith – *Fuzzy* – *Expert* – PID (proportional - integral - derivative) and its application in processes of air cooling to test environments and microchips simulations; aiming at control strategies to increase the adaptability of the control system, its robustness, contiguously to the security process. The experimental results suggested its suitability to the requirements of the system, and that it is of easy implementation.

An intelligent temperature control of environments for systems of heating, ventilation and air conditioning was developed by SOYGUDER et al. (2009), with variable airflow. The models and correlations between the airflow and temperature of the system were obtained in Simulink (computational tool for mathematical simulation executable under the platform MATLAB R2009a®) with PID-*fuzzy* controller compared with the application of PD (proportional - derivative controllers) and PI (proportional - integral). The results showed a better system response in terms of error, stability and resolution when using PID-*fuzzy*.

Algorithms applied to the cooling system to control the evaporator fan and condenser in order to improve the system performance and lower power consumption were presented by YEH et al. (2009). The results indicated an improvement in the system response, both transient and steady state, modulating the speed of a single fan, and keeping the other with constant rotation.

This study aimed at evaluating the performance of a classic controller in relation to power consumption of produce cooling process, by using the method of controller tuning called IMC (Internal Model Control). The implementation of this controller aimed at improving the relationship between the electricity consumption of the forced-air cooling system and the produce cooling time.

MATERIAL AND METHODS

The physical system studied was composed of a cold room with 34.4 m³, a cooling system with forced air (through a centrifugal extractor) and a cooling vapor compression system (R-22).

Description of the cooling system with forced air

The cooling system with forced air consisted of a exhaust fan (brand Artcom, model EC4-TAR), with flow of 2,900 m³ h⁻¹, rated speed of 3,485 rpm, 60 Hz frequency, 3.73 kW (5 HP) power, 220 V voltage, 12.9 A current, 0.88 cos ϕ , and 32 kg weight. This exhaust fan worked by sucking air from the chamber to the cooling tunnel, and backing it to the ejecting chamber by a side exit.

The cooling system is comprised of two independent parts: the cooling tunnel and the base. The cooling tunnel measured 80 cm (length) x 66 cm (width) x 32 cm (height), with 28 cm in length and width of 33 cm at the end of the tunnel, and the base of the tunnel was 60 cm elevated from the floor of the chamber by a bracket. The exhaust fan/electric motor set, likewise, had a mobile support.

The cooling system was installed inside the cold room, as shown in Figure 1a, where the cooling tunnel was attached to the exhaust fan. Figure 1b shows the control room of the cold room and its forced air system. In this room, there were connection frames, the data acquisition board and the computer where the supervision software was installed.



FIGURE 1. (a) Cooling system with forced air. (b) Computer of the control room.

Sphere instrumentation

To determine the cooling time, it was used plastic spheres (70 mm in diameter made of polyethylene) distributed in a uniform layer and instrumented with a Pt100 temperature sensor inserted into its geometric center. The instrumented sphere was prepared previously, and filled with a gel made by blending water with and a seaweed-based compound extract (Agar-Agar, a dry powder dissolved in hot water at 1.5%), a method widely used in this research field to simulate fruits such as oranges (DELELE et al., 2009).

Instrumentation of the cooling system

The behavior of the cooling system with forced air was monitored by sensors according to Figure 2. Instrumented spheres were placed in the center of the transverse and longitudinal product package (Pkg), and this package had the dimensions of 50 cm (length) x 30 cm (width) x 25 cm (height), comprising 70 spheres in total.

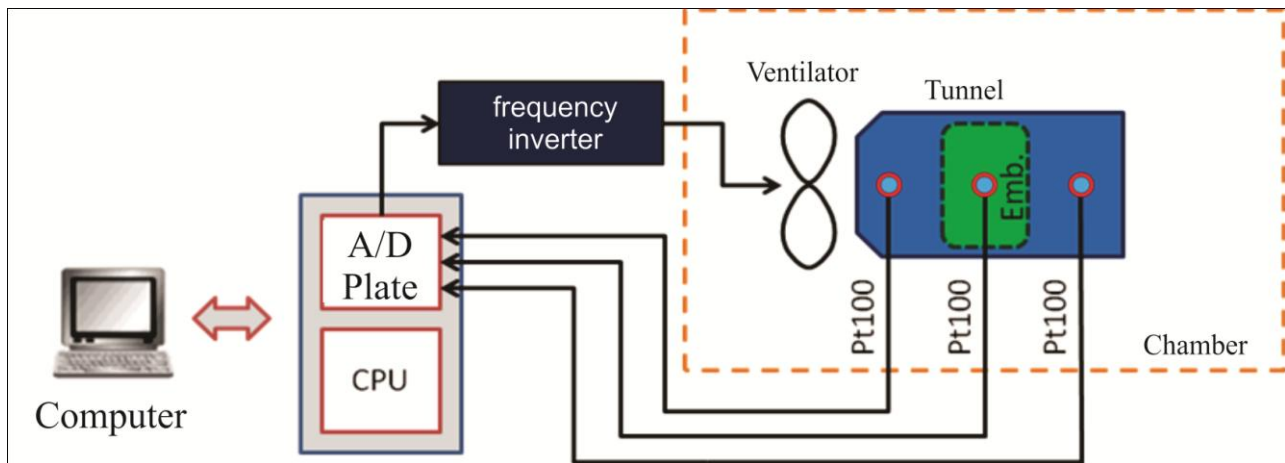


FIGURE 2. Flowchart of the cooling instrumentation system.

Figure 2 shows the temperature sensors, which used Sensym RTDs, type Pt100, model TR106, with connecting wires in three dimensions, 2 mm diameter and 30 mm length (with PVC cable). These RTDs were connected to the temperature transmitters with 4-20 mA output. The transmitter models used do not require calibration procedures of Pt100 (as reported by the manufacturer), and have the following specifications: overall accuracy of 0.20% of maximum range for RTD, operating temperature from -40 to 85 °C, brand Sensym, microprocessor type, model TT-100 and with output resolution of 0.005 mA (15 bits).

The temperatures of the instrumented gel sphere and the inlet and outlet air of the cooling tunnel were measured by the respective Pt100 sets and temperature transmitter. Measurement of the temperature in the external environment to the camera was carried out in the same way, in order to monitor the temperature outside to the system.

A frequency inverter (WEG brand, model CFW09) was the equipment responsible for variation in voltage frequency of the electric motor in the exhaust fan. The inverter used had three-phase voltage of 220-230 V, input with single 8-bit resolution, and linearity error lower than 0.25% (0 to 10 V). The electrical transducer used was Kron, model MultK-05, 0.2% accuracy and with supply voltage of 220V, and had the function to return data to the electrical system on the engine exhaust fan, such as tension, current, active power, reactive power, apparent power, power factor and power consumption. This transducer had a communication interface type RS485 (2 wires) speed 9600; 19200; 38400 or 57600 bps (configurable), data format 8N1, 8N2, 8E1, 801 (configurable), address 1 to 247 (configurable) MODBUS-RTU and n standard IEEE-754 information encoding floating point.

The processing computer, located in the control room, was used to collect data from all temperature sensors and electrical transducer, and in parallel, to store the collected data into files, as well as to control the actuator, which in this case was the frequency inverter. This computer was in the control room located next to the camera.

Calculating the cooling time

The cooling time was determined by calculating the rate called Dimensionless Temperature (TAT) of equation 1, and this is defined by the parameters: temperature of the produce in a given time (T), initial produce temperature (T_i) and the temperature cooled through the (T_A). The half-cooling time ($t_{1/2}$) and time of seven-eighths cooling ($t_{7/8}$) is reached when this ratio (eq.(1)) equals 0.50 and 0.125, respectively:

$$TAT = \frac{T - T_A}{T_i - T_A} \quad (1)$$

These ($t_{1/2}$ and $t_{7/8}$) are related to the time required to cool the produce commercially, as illustrated in Figure 3:

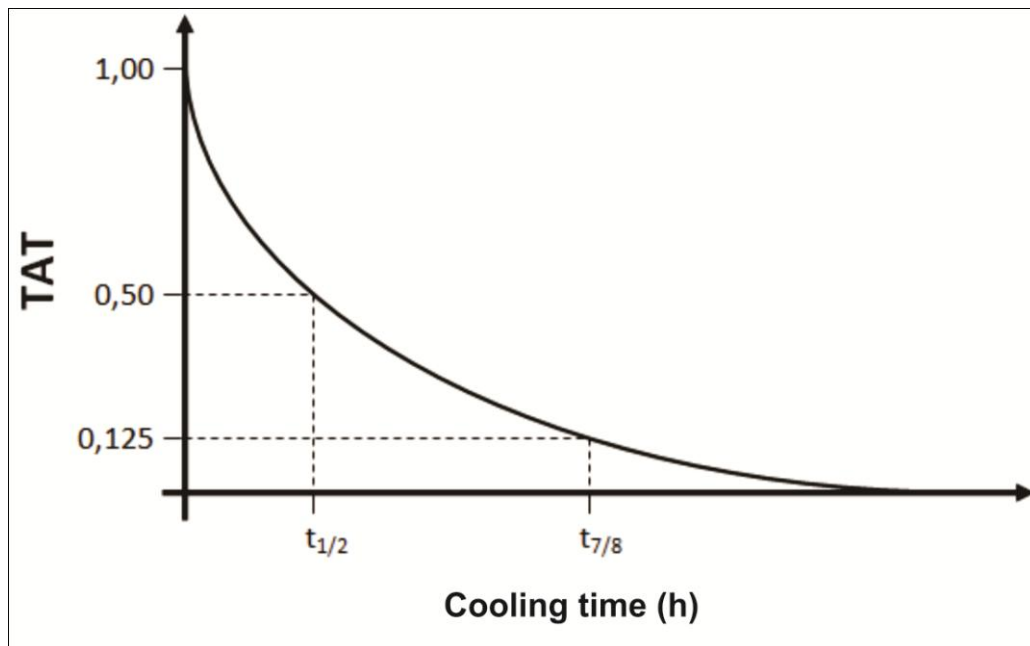


FIGURE 3. Characteristic cooling curve.

Simulation of the control system

The behavior of produce temperature ($^{\circ}\text{C}$) as a function of time results in the cooling curve of the process, from where it was analyzed the cooling time to a pre-established initial produce temperature, air velocity and produce quantity. For this, it was used Simulink/MATLAB[®] blocks for the control and the inclusion of transfer functions representing the cooling process. The cooling process was estimated to a first order system with the addition of a dead time.

After identifying the parameters of the system, tuning of the PID controller was made by the IMC control structure (based on the classical method). For the IMC tuning method, the PI and PID controller was designed, however, the time constant of the first-order filter (λ) was previously calculated as described below:

1. An operation range of the manipulated variable of the system was determined. The frequency of the signal power of the electric motor was 30 to 60 Hz;
2. The parameters K (gain of the process), τ (time constant) and θ (dead time) of the system were used at peak levels to determine the transfer function of the plant. Peak level, system operating at 60 Hz. The tangent method was applied to the identification of system parameters;
3. K_p (proportional gain) of the controller was defined by the difference between the maximum and minimum levels of the system. Operating system from 30 to 60 Hz, then $K_p = 30$;
4. λ for K_p was calculated using Table 1, and it was verified that λ is within the recommended levels;
5. From Table 1, τ_i (full time) and τ_d (derivative time) were calculated for later obtain all gains of the controller.

Table 1 shows the parameters of PID controller, adjusted by the IMC method; recommended values were also found for λ (time constant of the first-order filter). For a function of first order with dead time as a model, the IMC control structure can be used to design PI and PID controllers. This methodology was introduced by GARCIA & LIVING (1982).

TABLE 1. The IMC method.

	PI	PI (improved)	PID
K_p	$\frac{\tau}{\lambda K}$	$\frac{2\tau + \theta}{2\lambda K}$	$\frac{2\tau + \theta}{2K(\lambda + \theta)}$
τ_i	τ	$\tau + \frac{\theta}{2}$	$\tau + \frac{\theta}{2}$
τ_d	—	—	$\frac{\tau\theta}{2\tau + \theta}$
Adicional filter	$\frac{\lambda}{\theta} > 1,7$	$\frac{\lambda}{\theta} > 1,7$	$\frac{\lambda}{\theta} > 0,25$

Thus, the PID controller is given by eq.(2), where G_c is the transfer function of this controller:

$$G_c = K_p \left(1 + \frac{1}{\tau_i s} + \tau_d s \right) \quad (2)$$

Implementation of the control system to the cooling process

The supervisory system was performed using the LabVIEW ® software, which was developed to allow supervision of the cooling system in real time, to monitor the temperature variation inside the chamber, as well as to recognize the interface with the frequency inverter to control the rotation speed of the exhaust fan in the forced air system.

The supervisory application was installed on a computer at the control room that had a National Instruments data acquisition board, NI PCI-6221 model (with the optional CB-68LP), with 16 inputs and 2 analog outputs with a resolution of 16 bits and range of ± 10 V, and 24 digital channels. This board had the function of receiving information from all transducers and acting on the frequency inverter. Data were collected and stored in files for analysis.

RESULTS

Supervision application

Figure 4 displays the graphical output, in LabVIEW ®, to oversee the process of cooling with forced air.

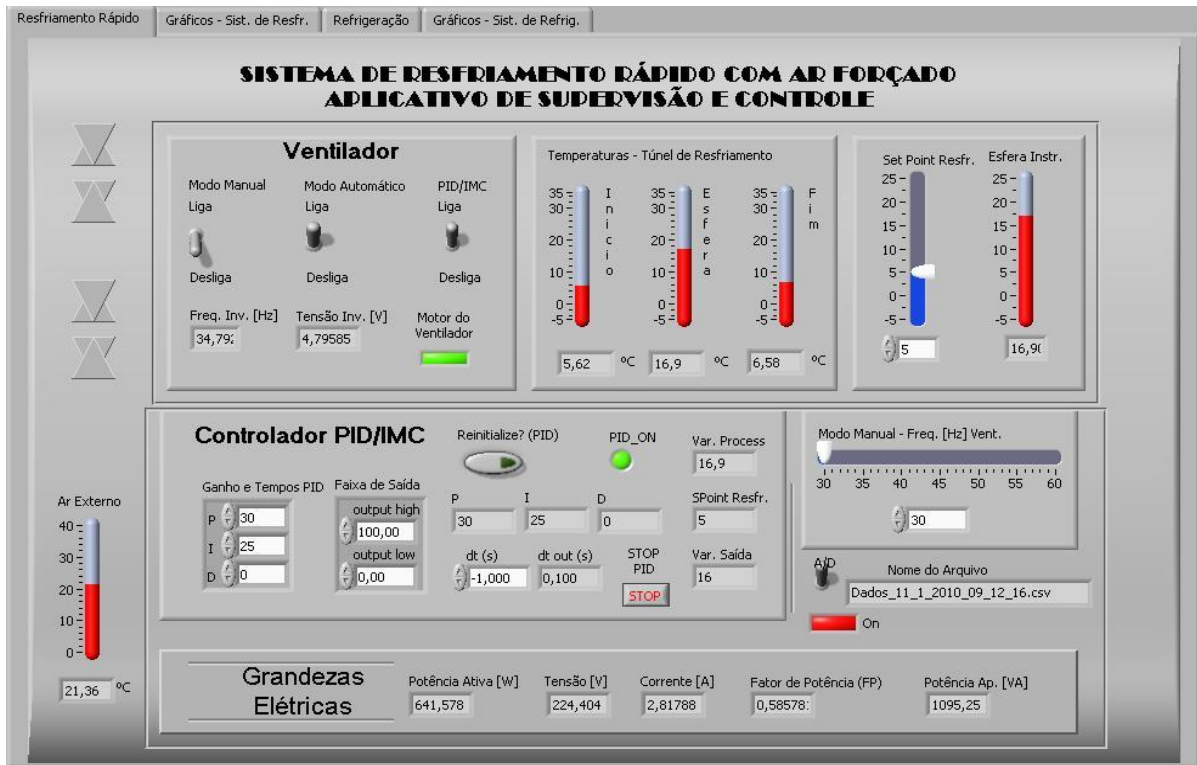


FIGURE 4. User interface of the cooling process.

Implementation of the PI/IMC controller

Figure 5 represents the behavior of the produce cooling curve and the frequency of the electrical signal power of the exhaust fan along the process, with the cooling system operating with the designed IP/IMC controller (this showed the best result, with calculated gains K_p equals to 30 and K_i equals to 0.0212). These data were collected in triplicate, on December 30, 2009, in which the average temperature was 22.7 ± 0.27 °C.

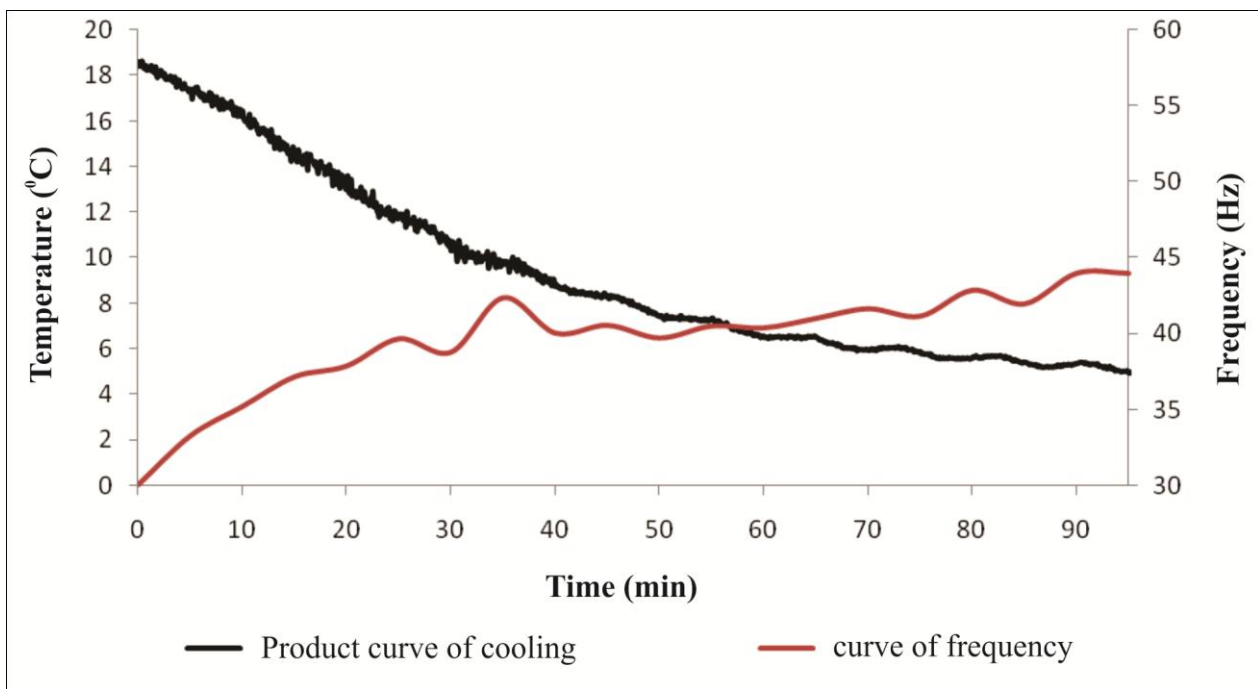


FIGURE 5. Curve of cooling and frequency for PI/IMC.

The curves shown in Figure 5 are relative to the data collected and stored (in tables) by the supervision application, which makes acquisition in one second intervals, i.e., every second to collect temperature data from the instrumented sphere and electrical power and frequency of the exhaust fan (real-time process).

The electrical power of the exhaust fan is a function of the cube of the frequency, as described in Equation 3:

$$P = 0.0233f^3 - 1.5901f^2 + 64.484f - 678.47, \text{ with } R^2 = 100 \tag{3}$$

Where,

P - the amount of power consumed (W), and

f - the value of the frequency of fan power (Hz).

This function is an estimate with respect to numerical regression of experimental data collected in survey of the characteristics of the cooling process based on 30; 40; 50 and 60 Hz frequency levels. Therefore, the higher the frequency applied, the more power demanded by the electrical appliance. The electric power exhaust fan, in turn, is directly related to electricity consumption, because it equals to the integral of electric power curve over time (AUC).

There was a reduction in power consumption when the system operated with the IP/IMC controller implemented, compared to the system in its nominal operation (Figure 6).

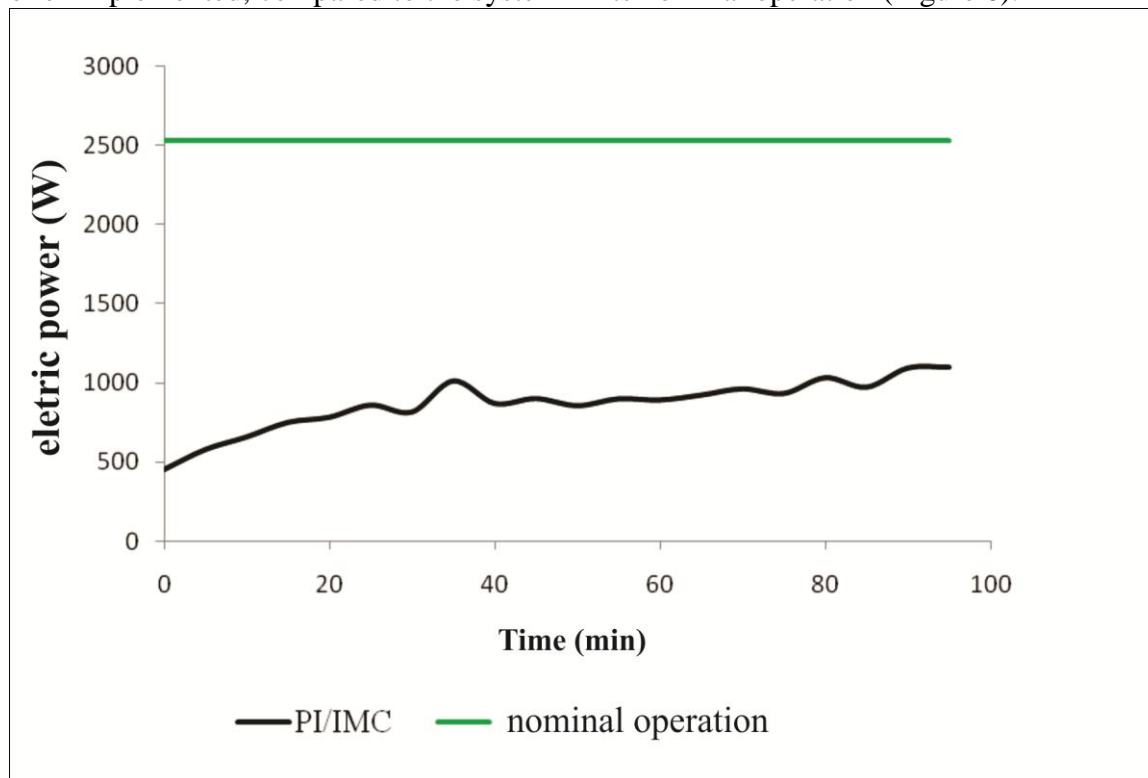


FIGURE 6. Comparison of nominal potency operation with the PI/IMC controller.

Table 2 presents the mean values of three repetitions of the experiments for the system in its nominal operation and the operating system with the PI/IMC controller implemented.

It was found that the reduction of energy consumption is possible while maintaining adequate relation to cooling time. That is, when the system works in its nominal operating condition, the equivalent consumption is 2.41 kW.h to cool the produce from an initial temperature of 19 °C to 6.75 (for $t_{7/8}$, to air cooling at 5 °C) in 58 minutes. However, when the IMC controller was implemented, the consumption was 0.87 kW.h, and cooling time took 63 minutes (with the same initial and final temperature conditions of the sphere). This reduction in energy consumption, around 64%, only caused an increase in cooling time of five minutes (about 8% increase), which is

a value that does not affect produce quality, but in terms of energy consumption it would fully justify the use of this technology.

TABLE 2. Operation of the cooling system.

	Nominal	PI/IMC
Outside Temperature (°C)	20.7	22.7
Electric Power Consumption (kWh)	2.41	0.87
1/2 Cooling Time (min)	27	28
7/8 Cooling Time (min)	58	63

For produce cooling time, the seven-eighths cooling time ($t_{7/8}$) was adopted, with the cooling air at a temperature of 5 °C, as it is done commercially in cooling processes of produces (fruits and vegetables). The half-cooling time ($t_{1/2}$) could be adopted in the same way, but in this case we chose $t_{7/8}$ as the process was intended to be studied in a comprehensive way.

The supervisory system developed here can be used both to monitor the process, as in the dynamic study of produce cooling, and it can be used to implement various control strategies.

The PI/IMC controller can be implemented directly in some business models of frequency inverters, without the need to purchase a computer or PLC (Programmable Logic Controller), as a feasibility analysis might be of interest to be carried out from an economic standpoint before investing in this technology.

CONCLUSION

The development of the classical PI controller, using the IMC tuning method, was suitable for using in cooling processes with forced air of produce.

A 64% reduction of electricity consumption was reached in return for an increase of 8% of cooling time with the implementation of this control strategy.

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