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ORIGINAL ARTICLE

On the effects of the temperature control at the performance of a dehydration process: energy optimization and nutrients retention

Norma-Francenia Santos-Sánchez[1] · Raúl Salas-Coronado[1] · Omar-Jacobo Santos-Sánchez[2,4] · Hugo Romero[2] · Erick Garrido-Aranda[3]

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Abstract In this article, we study the effects of the temperature control on a dehydration tomato slices process when two control strategies are considered: PID controller and optimal linear control when inherent input time delay is considered. The first controller is tuned by D-partitions method and a numerical procedure in order to minimize a quadratic performance index, the second one considers a state predictor to compensate the effects of the input delayed. The energy savings and the intrinsic characteristics in the tomato slices (vitamin C, total phenols, and lycopene levels) are quantified in order to conclude advantages of the two controllers under study.

✉ Omar-Jacobo Santos-Sánchez
omarj@uaeh.edu.mx

Norma-Francenia Santos-Sánchez
nsantos@mixteco.utm.mx

Raúl Salas-Coronado
rsalas@mixteco.utm.mx

Hugo Romero
rhugo@uaeh.edu.mx

Erick Garrido-Aranda
erick.garrido@mytec.com.mx

1 Universidad Tecnológica de la Mixteca, Huajuapan de León, Oaxaca, Mexico

2 CITIS-ICBI-Universidad Autónoma del Estado de Hidalgo, Hidalgo, Mexico

3 MYTEC, Querétaro, Mexico

4 Ciudad del Conocimiento, Carretera a Tulancingo km. 4.5, CITIS-ICBI-UAEH, C.P. 04280, Mineral de la Reforma, Hidalgo, Mexico

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1 Introduction

The dehydration of the fruits and vegetables is a process consuming a high quantity of energy, in fact, around 10–25 % of energy consumption into industry is linked with dehydration processes [5]. As it is exposed in Dufour [5] and Haley [8], optimal control strategies could be the best option in order to drive the temperature of the drying chamber. This issue has been dealt in Ryniecki [18], where an optimization procedure for a dehydration process was applied on an atmospheric dryer, it has produced a significant reduction of the energy consumption rate and consequently the production cost was reduced around 34 %. The Proportional Integral Derivative (PID) controller is considered in this work, because as it was exposed in Astrom [2], 90 % of the industrial control loops are regulated by these controllers and 20 % of these controllers are tuned and used with the default factory gains, without applying any kind of optimization technique, then the obtained results are very conservatives and with great opportunity to be improved, including those applied in dehydration processes.

Another important issue in dehydration process is that the quality of product can be affected by temperature changes and velocity deviations of the hot air flow [11]. Then, two important topics could be addressed in the dehydration processes: the operation cost related with energy consumption and the quality of the product (retention nutrients and color).

In that sense, some works had been reported about the optimization of the energetic efficiency and retention of nutrients in dried fruits and vegetables, see, for example, Jin [9] and Olmos [15], where an optimization approach is applied to dehydration process for broccoli and paddy rice, respectively. In these works, the degradation mathematical model was analyzed for some specific characteristic (vitamin C or a head kernel yield, respectively) of the dried product, and it was combined with the optimization algorithm to determine the drying conditions. In Chua [4], the effects on the quality of bananas and guava were studied applying different temperature-time profiles in a tunnel heat pump dry. The experiments were developed using step functions to vary the temperature of drying air and considering appropriate starting temperature and cycle time. Under this conditions, it was possible to significantly reduce the drying time to reach the desired moisture content with improved product color.

In addition to this, a delay appears in the input (temperature of the hot air) which affects the control loop, this is produced by the distance between the heating source and the product to be dried, this causes that the measurements of the air temperature in a neighborhood of the product are not the same as the air temperature in a nearby region to the heating source. This delay could be modeled as a deviation in the argument of the input and as it is very well know, delays in the input are equivalent to state delayed in closed loop and they produce oscillations or instability [14] in the plant. Then, the compensation of this delayed input is a very important issue for the control loop. In fact, there are a lot of techniques to compensate this delay [16]. A popular technique in food process [8] and in general in the industry is the Smith predictor [8, 16], which is included as a programmable option in some industrial PID controllers. Other advanced techniques to compensate delays affecting the input signals are based on the knowledge of the analytical solution of a linear model of the plant [1]. The use of advanced delay compensation techniques are not generalized in the industry; however, experimental results over temperature process have been presented recently in Santos-Sánchez [19] and Rodríguez-Guerrero [17]. The delay compensation technique also could be mixed with optimal control strategies for linear and nonlinear plants [10]. Nevertheless, the industrial application of these advanced control techniques is not easy, because it requires to incorporate new hardware and software in the control loop.

It is important to emphasize that in the best knowledge of the authors, no quantitative studies about the effects produced by the different kind of controllers regulating the air temperature on the quality of dried tomato (vitamin C, lycopene, and total phenols) have been reported yet, and much less if it is combined with an advanced delay compensation and energy optimization techniques. In this paper, the effects of temperature control on the quality of dried sliced tomatoes (vitamin C, lycopene, and total phenols) are analyzed, which constitute the main contribution of this work. In this study, two controllers were considered: on the one hand, an industrial PID controller Honeywell DC1040 with programmable dead band, and on the other hand, a predictive optimal linear control, following the suggestion of McGrath [12], the optimal control was implemented on LabView Software by using a low cost data acquisition module (Data Acquisition module USB6008 National Instruments) and a personal computer. According to the obtained experimental results, the tested controllers produce a very important reduction in the energy consumption, and they increase the food quality of the final product, consequently the production cost is also reduced.

The article is disposed as follows: in Section 2, the control strategies are presented, after in Section 3, the description of the used experimental platform is exposed, and then in Section 4, the experimental results using the classical and modern controls in the plant, the nutrients retention analysis and energy savings are presented. Section 5 is devoted to final comments.

2 Control strategies

2.1 PID controller

This section briefly recalls the control algorithms used in this article. The PID controller is widely used in the dehydration process due to its simplicity, flexibility, and the large number of trademarks and enterprises manufacturing and selling this industrial device, so the use of them is a powerful tool. For these reasons, this controller is used in the comparative study developed in this work. Then consider the following equation representing the PID algorithm:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt}, \tag{1}$$

where $e(t) = SP - PV$ and SP is the Set Point and PV the process variable [2]. There exists a lot of algorithms in order to select the gains K_p, K_i, and K_d, each one of these set of gains defines a specific behavior and performance of the plant. One of these techniques is the very well know D-partitions method [13, 22], which performs a robust tuning of the PID controller. This method subdivides the parameters space in stable and unstable regions, and we can choose a specific set of parameters in order to increase the robustness of the characteristic equation with respect to deviations of these parameters; a similar idea is used in the industry by the software Expert-Tune [6] on its product PIDLoop Optimizer, based on classical result as given by Ziegler [23], which uses linear models (first and second order) with a delayed input. We briefly recall some important aspects of the D-partitions method. Consider the following stable delayed first-order model in frequency domain:

$$G(s) = \frac{Ke^{-sh}}{Ts+1}, \tag{2}$$

where K, h, and T define the plant gain, the amount of delay and the time constant for the plant, respectively. This equation will be used later to represent the mathematical model of dryer, where both the input voltage applied to the electrical heater and the temperature of the air applied to the product are considered.

2.1.1 D-partitions method for tuning PID controllers

The D-partitions method could be used in order to find the stability boundaries of PID controllers for delayed systems. Consider the system (2) in closed loop with a PI controller (in this step, derivative part is set to zero). The closed loop characteristic equation of the plant (2) with a PI controller is given as follows

$$p(s, e^{-sh}) = Ts^2 + \left(1 + K_p K e^{-sh}\right) s + KK_i e^{-sh}. \tag{3}$$

According with the definition given in Niculescu [14], this is a delayed quasipolinomial and it has an infinity number of roots, then to find the values K_p, K_i which assure the stability in closed loop, it is not a direct and easy task. The strategy is to consider K_p and K_i are unknown gains, while the parameters K, T, and h are given (obtained from the dynamic response of the plant). Then, we want to compute the region for the pair K_p–K_i where the system (2) in closed loop with this PI controller is stable. In order to find the borders for this region, replace $s = 0$ in the characteristic quasipolinomial (3) (according with the D-partitions method it represents a root of Eq. 3 crossing to complex right half plane). Setting it to zero we get:

$K_i = 0$, for any value of K_p.

In this point, it is relevant to realize that one of the most important restrictions for the industrial PID controllers is that they accept only positive gains for programming. So, the first border is $K_i = 0$ and $K_p \geq 0$. Now replacing $s = j\omega$ in Eq. 3 and equating to zero, separating the real and complex parts and solving for K_p and K_i we get

$$\begin{aligned} K_p &= \tfrac{1}{K}\left(-\cos h\omega + T\omega \sin h\omega\right) \\ K_i &= \tfrac{1}{K}\left(\omega \sin h\omega + T\omega^2 \cos h\omega\right). \end{aligned}$$

Taking arbitrary values for ω, but excluding zero (it implies that we consider all possible intersections of roots with imaginary axis), we can obtain a closed region which contains the stable pair $K_p = K_i = 0$, then according with the D-partitions method, this region is stable. In this region, assume that we choose (according with some criteria) a pair K_p, K_i, then we have the following quasipolinomial in closed loop:

$$s^2\left(T + K_d K e^{-sh}\right) + \left(1 + K_p K e^{-sh}\right) s + KK_i e^{-sh}, \tag{4}$$

once again replacing $s = 0$ and $s = j\omega$ in the quasipolinomial (4) in order to find the stability interval for K_d value, being $K_d \geq 0$. Then, for $s = 0$, any value K_d satisfies the equation $KK_i = 0$ (because $KK_i \neq 0$). When $s = j\omega$, we get

$$\begin{aligned} -\omega^2 T - \omega^2 K_d K \cos \omega h + K_p K \sin \omega h + KK_i \cos \omega h &= 0, \\ \omega^2 K_d K \sin \omega h + \omega - K_p K \omega \cos \omega h - KK_i \sin \omega h &= 0, \end{aligned} \tag{5}$$

in these equations we can solve for K_d and ω, using the restriction that $K_d \geq 0$, the stability interval is $\left[0, \bar{K}_d\right]$, where $\bar{K}_d$ is founded using the first value of ω which satisfies the simultaneous equations (5) and gives a value of K_d greater to zero. In the parameter space K_p–K_i and the interval $\left[0, \bar{K}_d\right]$ (call to this Ξ), we want to find a triplet K_p^*, K_i^*, K_d^* which minimizes a given performance index J_1 defined as follows:

$$J_1 = \int_0^T (e^2(t) + u^2(t))dt, \tag{6}$$

where $e(t) = SP - PV$ is the error and $u(t)$ is the control signal generated by the PID controller. Observe that a setting of the triplet K_p^* , K_i^*, K_d^* produces a different signal $u(t)$ and a different error $e(t)$. We will deal this problem by the numerical optimization method proposed in Santos-Sánchez [20]. First, a maximum number of iterations was fixed, then the parameters K_p, K_i, K_d were collected in a three-dimensional vector defined as follows

$$\bar{K} = \left[\, K_p \;\; K_i \;\; K_d \,\right],$$

then the components of the vector $\bar{K}$ were initialized randomly. This first chosen vector was denoted $\bar{K}^*$ and the value of the performance index $J_1\left(\bar{K}^*\right)$ was computed, where $\bar{K}^*$ denotes the initial value for $\bar{K}$ and the error $e(t)$ was also computed with the numerical solution of the system (2) in closed loop with the PID controller $u(t)$ with the parameters given by the entries of $\bar{K}^*$. This vector was updated [20] according with an uniform random variable δ as follows

$$\bar{K} = \bar{K}^* + \delta,$$

notice that the value of the performance index (6) depends of the value of $\bar{K}$, and consequently: $J_1 = J_1(\bar{K})$. If the value of the performance index $J_1(\bar{K}^*)$ is strictly greater than the $J_1(\bar{K}^* + \delta)$ and $\bar{K}^* + \delta$ is in the stable zone Ξ, then $\bar{K}^* = \bar{K}^* + \delta$. Moreover, if the maximum number

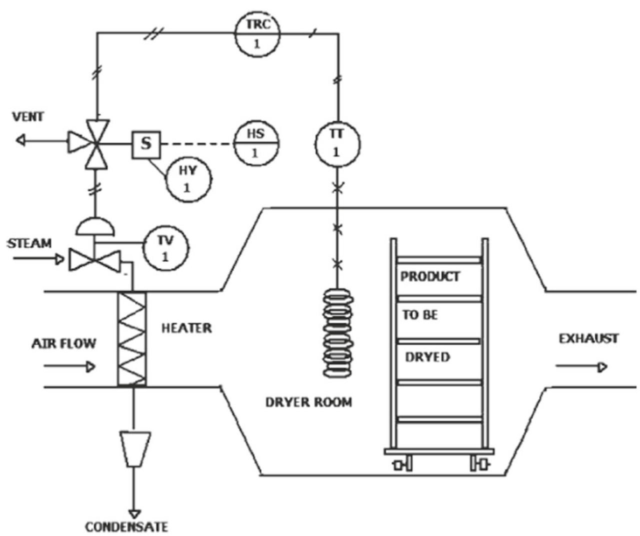


Fig. 1 Batch industrial dryer

of iterations was reached, then the best value for $\bar{K}$ is $\bar{K}^*$, if not, the vector $\bar{K}^* + \delta$ is calculated again [20]. In this way, a Honeywell DC1040 PID controller was tuned and experimentally tested to control the temperature of the air in tomato slices dehydration process.

2.2 Optimal linear control

The second considered control technique in this paper is the optimal linear control with time delay compensation. Some related works with this approach have been published in Rodríguez-Guerrero [17] and Santos-Sánchez [19], where the optimal regulation problem of the airflow temperature for a dryer platform was considered. However, in those works, any nutrients retention analysis has been reported and the control was applied to the ventilator and not to heater. The optimal control problem could be established as follows: Find a control law u such that minimizes the following performance index defined by

$$J = \int_0^{\infty} \left(x^T Q x + u^T R u \right) dt, \tag{7}$$

subject to

$$\dot{x}(t) = Ax(t) + Bu(t-h),$$
$$u(\theta) = \mu(\theta), \text{ for all } \theta \in [-h, 0], \tag{8}$$

where $x(t) \in R^n$, $u(t) \in R^m$, $A \in R^{n\times n}$, $B \in R^{n\times m}$, $Q \in R^{n\times n}$, $R \in R^{m\times m}$, $Q \geq 0$, $R > 0$, $h > 0$, and $\mu(\theta)$ is a piecewise continuous function. Note that a time delay in the input is considered in the model because in a dryer process this appears as a transport delay [17] due to the distance between the heat source and the product. The control problem for delayed input systems has been widely dealt in the literature, see, for example, Alekal [1] and Krstic [10]. As is exposed in Alekal [1], the optimal control law with time delay compensation is defined by

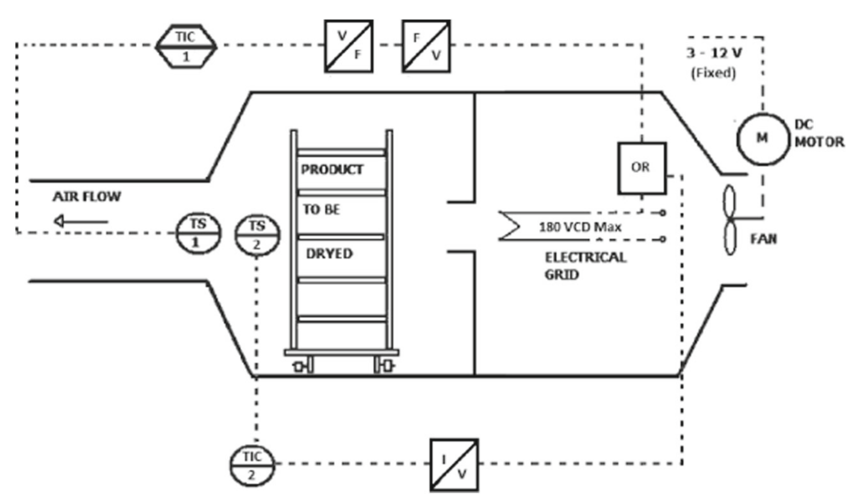
$$u(t-h) = -Fe^{Ah}x(t-h) - F\int_{t-h}^{t} e^{A(t-\theta)} Bu(\theta - h)\, d\theta + K_{ss}, \tag{9}$$

after some direct manipulations [1, 17], we get

$$u(t-h) = -Fx(t) - 2FA\int_{-h}^{0} e^{A\theta} x(t+\theta)\, d\theta + K_{ss}, \tag{10}$$

where $F = R^{-1}B^T P$, and P satisfies an Algebraic Riccati Equation (ARE) [1]. Notice that the control law (10) is a feedback state, and it could represent a more robust control scheme compared with the control law (9), [17]. If we want to reach a set point different to zero, we can compute the adjust term K_{ss} of the control which holds the process variable (PV) in this set point (SP) [19]. The implementation

Fig. 2 Proposed prototype



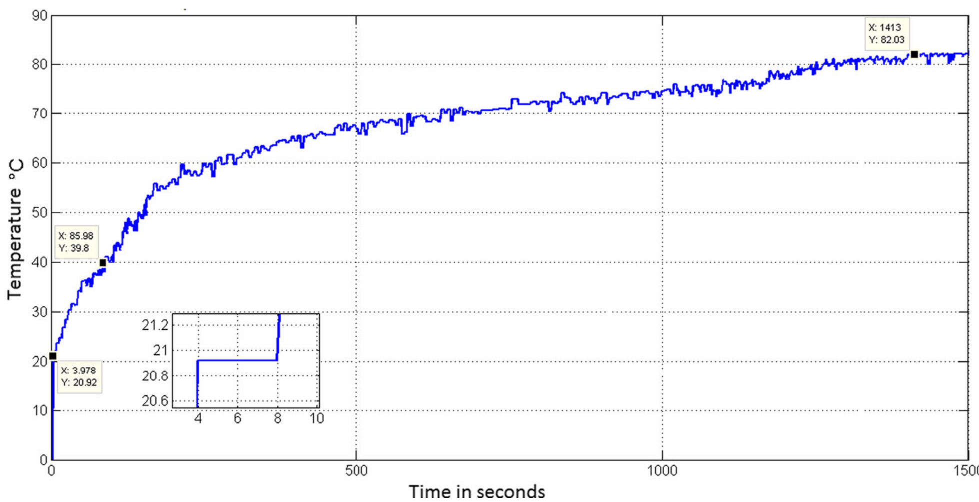


Fig. 3 Step response of the prototype

of the control law (10) could be addressed by numerical methods or discrete techniques. In this paper, numerical methods are used to implement this control law. Notice that the optimal control strategy could be used to improve the dryer fluid behavior and therefore the performance of the dryer platform. The performance improvement is a crucial issue for nutrient retention [5], and as was mentioned above, it is under analysis in the present work. Using this control strategy, the time delay h present in the control u is compensated.

2.2.1 Numerical Implementation

One of the important issue to be considered is how the integral term of the control law is implemented. In this case, the implementation of the integral term of the control law (10) is done by quadrature numerical methods. Then, the control law can be expressed as follows:

$$u(t-h) = -Fx(t) - 2FA\left[\frac{h}{n}\left(\frac{x(t)}{2} + 2\left[\sum_{i=1}^{n} e^{A\frac{ih}{n}} \times x\left(t - i\frac{h}{n}\right)\right] + e^{Ah}x(t-h)\right)\right], \tag{11}$$

where the step $\Delta = \frac{h}{n}$, and n is the number of subintervals dividing the interval $[-h, 0]$. Using Lyapunov-Krasovskii Stability theory and Linear Matrix Inequalities (LMI) approach [14], it is possible to find sufficient conditions in order to conclude the stability of the system (8) in closed loop with the approximated control law (11) [7]. However, due clarity of exposition, it was not included in this work.

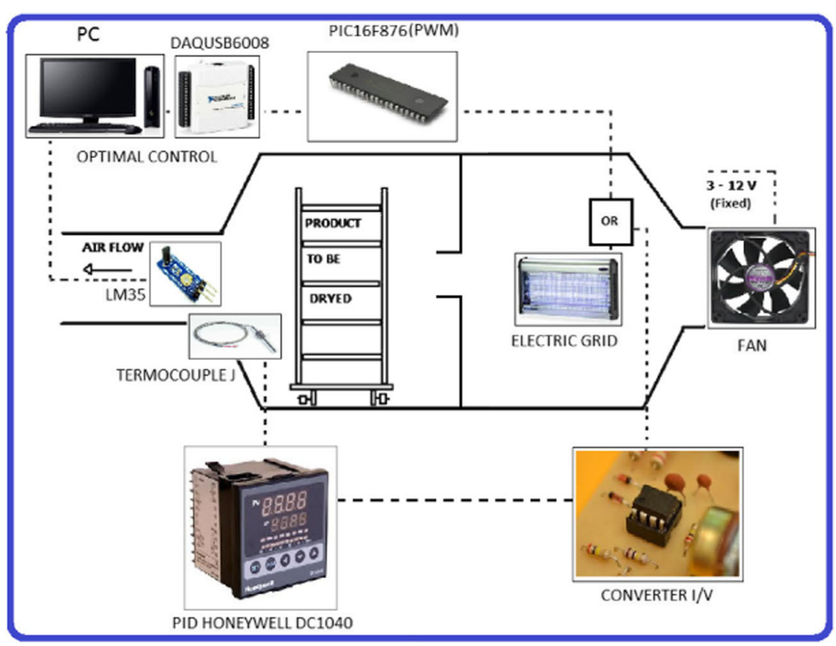


Fig. 4 Schematic diagram of the dryer prototype

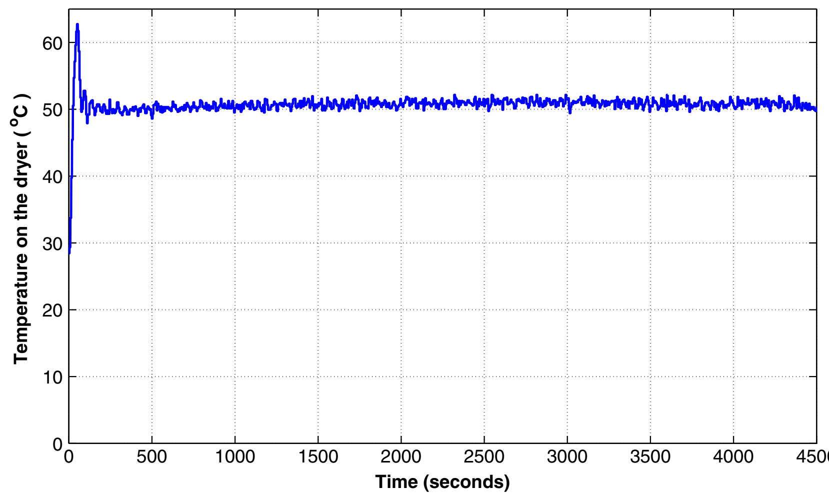


Fig. 5 Temperature of the air flow, set point chosen in 50 °C using a PID robustly tuned

3 Experimental platform description

In this section, we describe the experimental platform. Figure 1 shows a typical industrial atmospheric dryer, which could be described as follows: The control system uses a temperature sensor. An air-to-open valve (TV) is the regulatory element to avoid overheating of the product. A controller (typically a Proportional Integral Derivative) compensates the load changes due to variations in air flow rate. Moreover, a hand switch (HS) activates a solenoid valve (HY) in the air line between the controller and valve. When HS is open, HY vents air from the valve motor closing TV. When HS is closed, HY is switched to close the vent and connect the controller output directly to the valve [17]. Another configuration of this control system could be made with a electrical grid and a power electric system. Once the product is loaded in the dryer, automatic start-up is initiated when the operator closes the hand switch on the control panel. Then, temperature is increased and it is held high during a pre-established time measuring on this period in a direct or indirect way the humidity of product, which indicates if the drying is done and the product can be extracted. If it is assumed that a batch has been completed and the operator has opened HS, the steam flow shunts off to the heater, the product is removed, and a new batch is loaded. When this happens, temperature decreases and may even approach ambient conditions. When the operator closes HS for starting a new cycle, the steam flow is maximum (it also depends of the tuning of control) and the temperature increases fast. The signal error should decrease and the signal control should decrease too [17]. But, consider that it is important to have a reasonable distance between of heat source and the product (if the product is very closely to the heat source may be damaged). This distance produces cause a transport delay in the system, which could be modeled as a deviation in the argument of the signal control. As it is very well know, delays in the plants could produce instability, poor performance, oscillations, and/or excessive waste of energy. Therefore, the temperature of the air flow could be affected and it could produces a poor performance of the plant, affecting the retention of nutrients in the product. However, a good tuning of the PID controller or the use of an advanced control strategy to regulate the temperature of the air flow could avoid the poor performance or

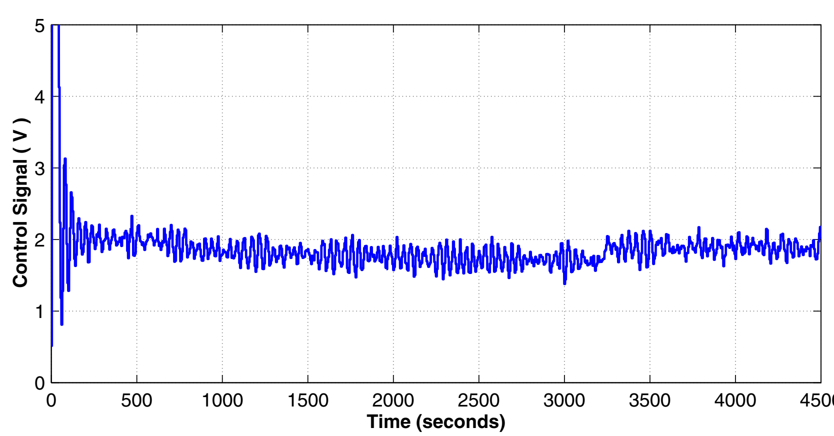


Fig. 6 Control signal of the PID before of the power stage

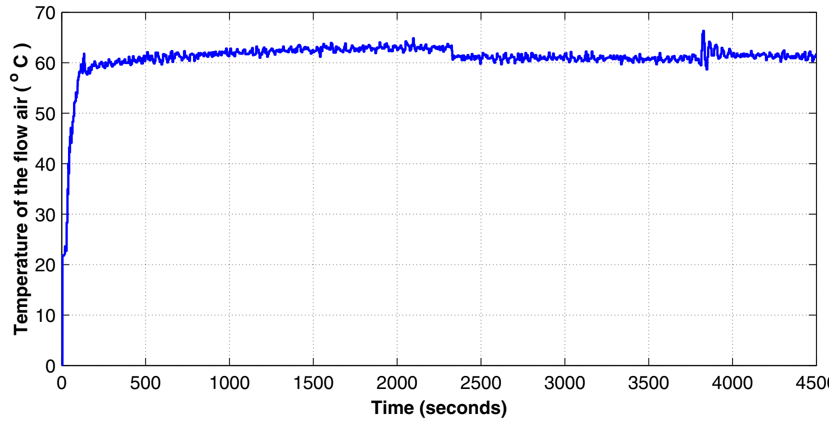


Fig. 7 Temperature of the air flow (SP chosen to 60 °C), using a PID robustly tuned

excessive waste of energy [17]. So, one of the main objective in this work is quantify the effects of the use of different control strategies in the temperature control system of the dryer process and simultaneously reduce the energy consumption by the heat source. In order to test the proposed controller and obtain experimental results, a prototype was constructed with an electrical grid as a heat source.

Is important to realize that in Rodríguez-Guerrero [17] the control signal is applied to the air flow (control in inverse mode), whereas in this contribution the signal control is applied to the heat source. It allows the control of the quantity of energy applied to the process. Additionally, the PID was numerically optimized and operated in direct mode.

3.1 Dryer prototype description

The batch dryer prototype is composed by two sections: a drying chamber and a heating chamber. The heating chamber has an fan powered by a DC motor **(3-12 V)**, which produces an airflow crossing through an electrical grid (180 V DC as maximum voltage level and 20 Ω of resistance) acting as the heating source, which achieves until 95 °C). Also, an electronic power system is required to regulate the voltage level applied to the electrical grid. The drying chamber is composed by a static tray to place the product and a tunnel for the flow of hot air. The dimensions of this prototype are 60 × 40 × 30 cm (length, wide, and height). In the prototype, the actuator is the electrical grid and the fan remains always with a constant voltage producing a continuous and constant air flow. However, it could be also regulated varying the voltage level and consequently the velocity of the air could be controlled, but this configuration is not used in this work. The instrumentation diagram of the prototype is displayed in Fig. 2.

As in the industrial dryer showed in Fig. 1, a transport delay also appears in the control loop in our prototype. Notice that when an electric grid is used, the conversion of electrical energy to heat energy could be inefficient, consequently, an optimization method over the controller used is necessary. Now, applying the energy conservation principle together with some concepts of heating systems [3],

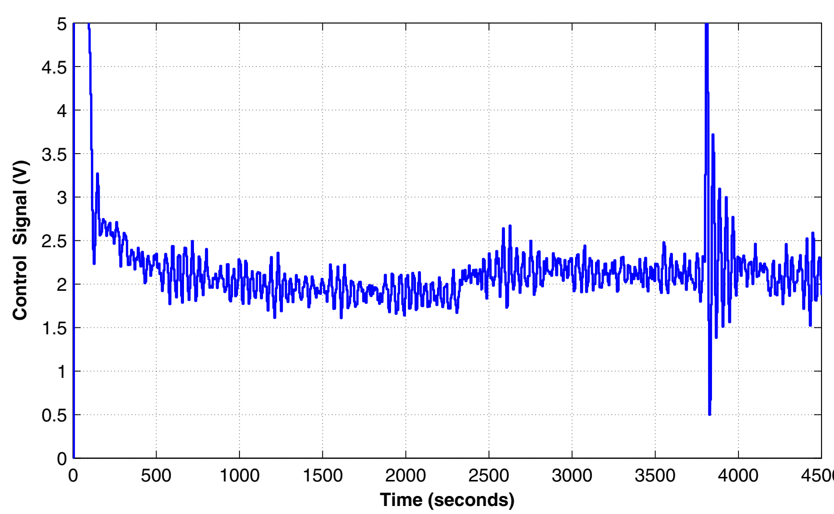


Fig. 8 Control signal of the PID Honeywell DC1040 (SP chosen to 60 °C)

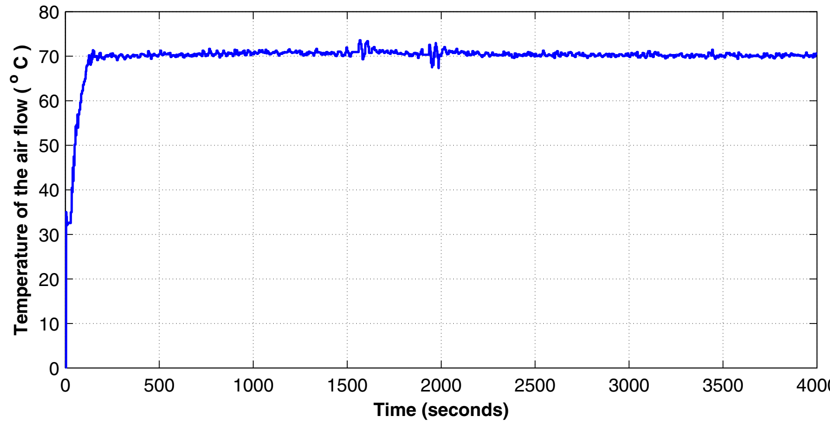


Fig. 9 Temperature of the air flow (SP chosen to 70 °C), using a PID robustly tuned

the mathematical model for proposed prototype could be defined as follows:

$$RC\frac{d\theta\,(t)}{dt} + \theta\,(t) = Rh_i(t),$$

where $\theta\,(t)$ is the temperature (°C) of the air flow, C is the heat capacitance (Kcal/°C) of the device, R is the heat resistance $\left(°\mathrm{C}\frac{\mathrm{sec}}{\mathrm{Kcal}}\right)$ of the device, and $h_i(t)$ is the input heat flow $\left(\frac{\mathrm{Kcal}}{\mathrm{sec}}\right)$. Assuming a linear relationship between the input heat flow, the voltage applied to electric grid ($u(t)$), and the temperature transducer, we have that

$$u(t) = K_{grid}h_i(t), \quad y(t) = K_{sensor}\theta(t).$$

where $u(t)$ and $y(t)$ are the input and output signals, respectively. Finally, if we consider the distance between the heating source and the product, a deviation $h > 0$ in the argument of the input $u(t)$ appears. The magnitude of this deviation depends mainly of this distance, then we can obtain the transfer function as follows:

$$\frac{Y(s)}{U(s)} = \frac{ke^{-sh}}{\tau s + 1},$$

where $\tau = RC$, $k = \frac{RK_{grid}}{K_{sensor}}$, and h is the input delay of the plant. These parameters could be identified easily by the very well known step response method [23]. In this work, three operation zones are considered, and they are defined at: 50, 60, and 70 °C. In order to obtain this mathematical model, a constant voltage equivalent to 70 % of maximum voltage (126 V DC) is applied to the electrical grid to obtain the temporal response of the plant (Fig. 3 shows the temporal response produced by the plant), and this voltage level is considered the unitary step of the plant. Although it is clear that the plant has a nonlinear behavior, but around a specific operation zone, it could be considered linear.

For the experiments, the environment temperature (initial condition of the plant) was 20 °C and the stable temperature was fixed at 82 °C. Therefore, the obtained model plant is defined as follows:

$$\frac{Y(s)}{U(s)} = \frac{0.62e^{-4s}}{86s + 1}. \tag{12}$$

This input–output mathematical model is used in order to design both the PID and optimal control strategies. It is important to realize that this mathematical model is only

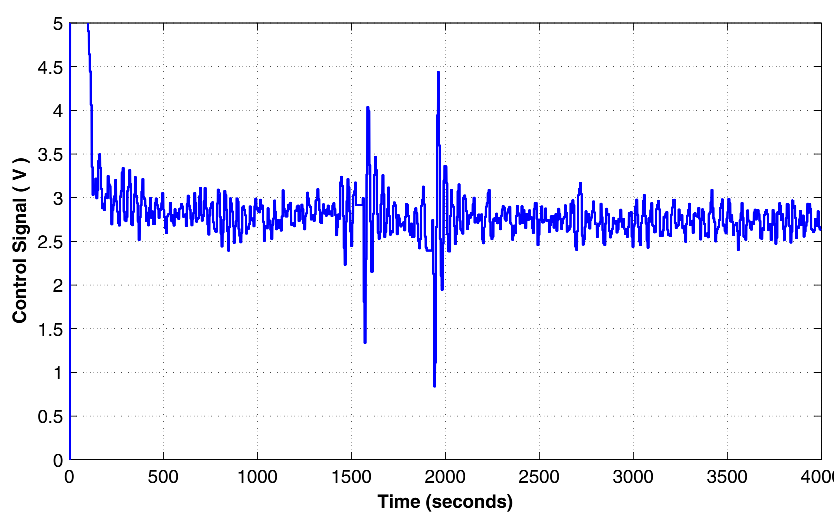


Fig. 10 Control signal of the Honeywell PID controller robustly tuned

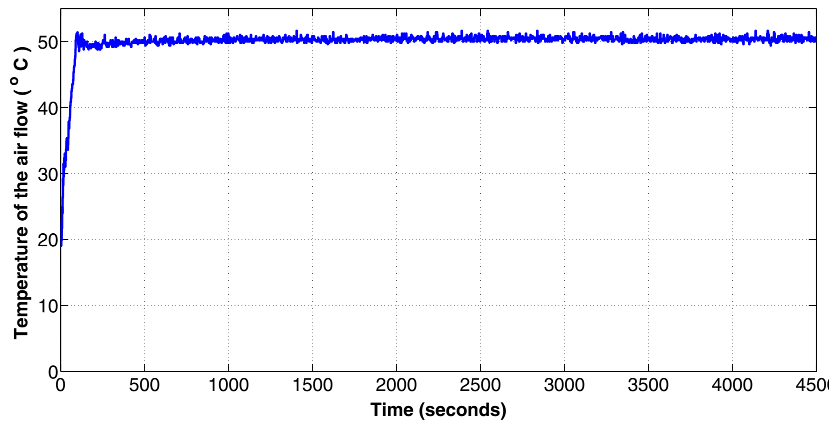


Fig. 11 Temperature of the air flow when an optimal control is used (SP was 50 °C)

an approximation of the real plant and the couple of controllers must be sufficiently robust to adequately drive the temperature of the air flow.

4 Experimental results

The main objective in this paper is to synthesize and test an optimal control strategy to drive the temperature in a dryer chamber in order to increase the nutrients retention for tomato slices and also reduce the energy consumption leading to lower production cost. Firstly, the PID controller is used on the prototype and the obtained experimental results are shown in the next section. In Fig. 4, the schematic diagram of our prototype is described.

4.1 Industrial PID control

The PID control used was a Honeywell DC1040 having maximum precision ±1 °C with cold junction compensation and linear output of 4–20 mA with ± 5 % of maximum deviation. Furthermore, it has automatic compensation of dead zone and the input used was a thermocouple type J of extended grade. For the experimental test, the PID controller was tuned using the Ziegler Nichols open loop method; however, due the poor performance obtained (8 % of overshot and decreasing oscillations until 600 s after the start of the experiment), we optimized those gains of PID controller. According with the exposed in Section 2, the numerical optimization approach for the controller gains (using the approximated model given by the equation (12)) gives the following values:

$$K_p = 50,\ K_i = 3,\ K_d = 50,\ (\text{ horizon } T = 4500 \text{ s}),$$

those gain values optimize the performance index (6). The numerical method applied to get the optimized gains considers those gains belonging to stability region Ξ given by the D-partitions method, briefly exposed in Section 2. It means that the selection of those values guarantees a local minimum of Eq. 6 and the stability of the closed loop. Figure 5 displays the controlled temperature of the air flow (set point fixed at 50 °C), while Fig. 6 shows the control signal just before to be adequate by the power stage of the prototype. All control signals (PID controller and optimal control) were scaled using the same factor and saturated to 5 V in order to convert these signals to PWM signals (PIC16F876), and then they are applied to the electrical grid through the power stage.

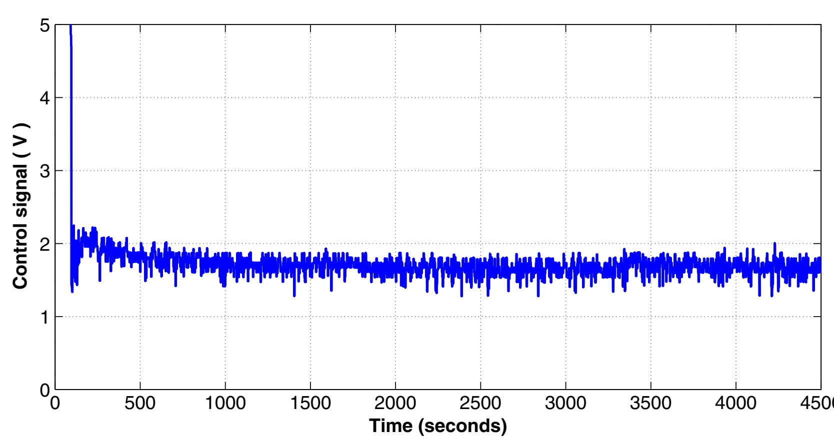


Fig. 12 Control signal using an optimal strategy (SP was 50 °C)

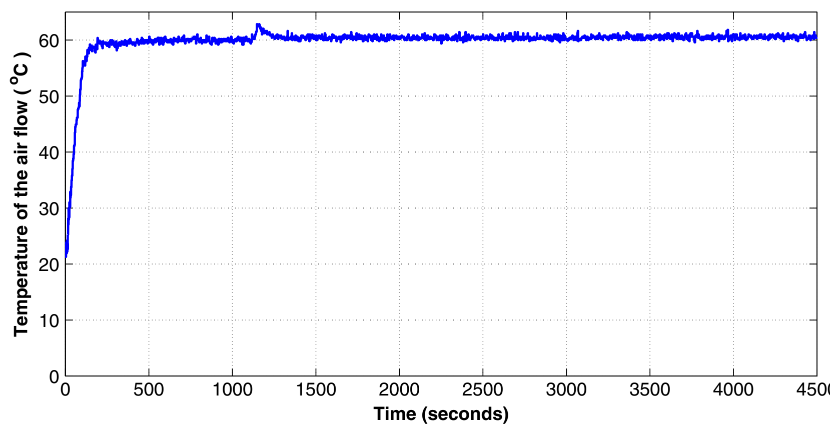


Fig. 13 Temperature of the air flow when an optimal control is used (SP was 60 °C)

The overshoot in the air flow temperature shown in Fig. 5, could be explained by the oscillations of the control signal caused by the specific tune of the PID.

Figure 7 displays the controlled temperature (set point fixed to 60 °C) of the air flow of the prototype, whereas the control signal before the power stage of the prototype is shown in Fig. 8.

Moreover, Figs. 9 and 10 show the controlled temperature of the air flow of the prototype when the set point was fixed at 70 °C and the control signal before the power stage of the prototype, respectively.

We can observe that the industrial PID controller presents some oscillations which causes deviations in the temperature of the air flow. These oscillations are due to the delay presents in the control loop, which is not completely compensated by the Honeywell PID controller. Obviously, this kind of behavior in any dynamic system always produce a degradation in the performance of the controlled system and therefore in the quality product.

4.2 Optimal controller

The optimal linear controller exposed en Section 2 was implemented in the LabView software version 7.1 on a PC with a processor running at 3.2 GHz using a low cost data acquisition module (USB 6008) and a low cost temperature sensor LM35 (see Fig. 4). The sample time was chosen to 1 s, which is small enough with respect to time constant of the plant estimated in 86 s according with the model given by Eq. 12. Using this sample time, the system can be considered a continuous system. The approximate model (12) was used in order to synthesize the optimal controller given by the equation (11). Three different experiments were made with set points adjusted to 50, 60, and 70 °C, respectively.

The following figures show the controlled temperature of the air flow and control signal using the optimal control strategy. Figure 11 shows the temperature of the air flow using an optimal control, the penalization values in the performance index given by Eq. 7 were adjusted as follows: $Q = 1100$ and $R = 3$. Figure 12 shows the control signal of the optimal controller with SP fixed at 50 °C.

Figure 13 shows the air flow temperature when the optimal controller is used and the SP was fixed at 60 °C. Figure 14 shows the control signal of the optimal controller with SP equal to 60 °C.

Figure 15 depicts the temperature air flow when the optimal controller is used and the SP was fixed at 70 °C.

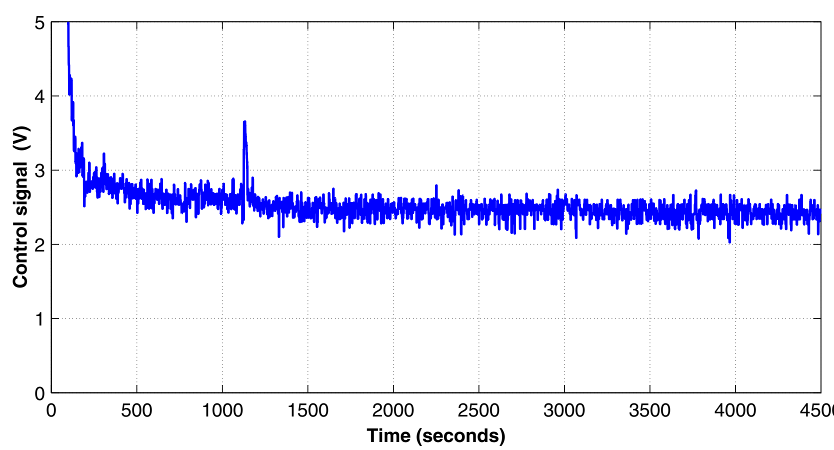


Fig. 14 Control signal using an optimal strategy (SP was 60 °C)

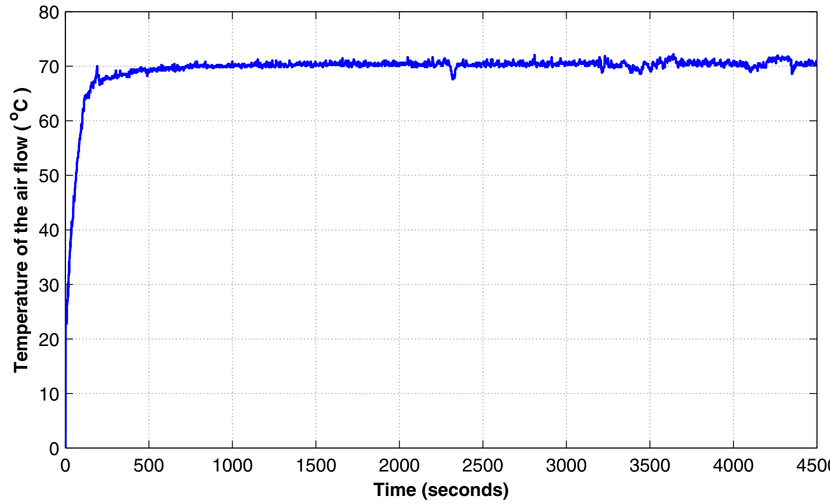


Fig. 15 Temperature of the air flow when an optimal control is used (SP was 70 °C)

Figure 16 displays the control signal of the optimal controller with SP equal to 70 °C.

In all of these experiments, there are not overshoot (or it is very small for the case of the set point 50 °C); however, the settling time is greater than that obtained in dynamic responses generated by the PID controller. This is because the optimal control is synthesized to minimize some given performance index, although less energy applied to the plant implies a slower response but different choices of the parameters Q and R, could change it situation. The following table summarizes the performance of the plant when the two controllers are used, and Integral Absolute Error index (IAE) is considered to measure the performance of the closed loop plant. The settling time was calculated using the $\pm$ 2 % criterion [3].

The overshot more important in the plant is when the PID control was used (set point to 50 °C), the overshot depends of the choosing of control gains, however as the plant presents delays, unmodeled nonlinear dynamics and uncertain parameters, it is a not easy task to choice gains to graduate the overshot. Notice that the optimal control depends of the parameters of the plant and the performance of the closed loop system is affected by uncertainties present on control loop. Despite all this, the optimal control presents better performance with respect to the IAE index, this criterion gives us the process variable deviation with respect to the set point. The saturation times of the actuator are similar in most cases, except when the PID was adjusted with a set point of 50 °C, but it causes an overshot of 12.75 °C, even the saturation time are similar in the other cases, the optimal control consumes less energy because in stable state the signal control is smaller than the PID signal control.

The energy could be optimized by using the modern control strategy, but the question now is how to affect the quality of the product using this optimal control strategy?. This question will be answered in the next section, through a quantitative analysis of nutrient retention.

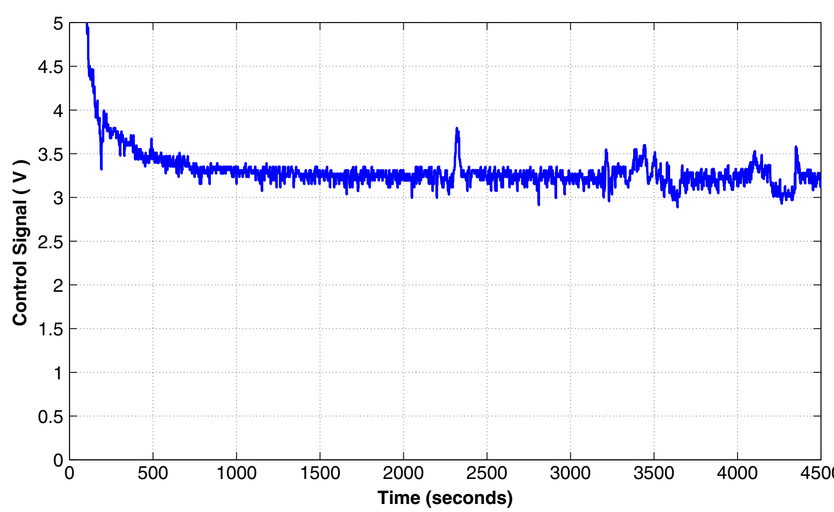


Fig. 16 Control signal using an optimal controller strategy (SP was 70 °C)

Table 1 Performance of closed loop plant

Controller	Overshot (°C)	Settling time (s)	Saturation time	IAE
$PID_{50\,°C}$	12.75	124.3	44.26	6090.53
$PID_{60\,°C}$	2	163.9	94.42	9456.78
$PID_{70\,°C}$	1.35	146	99.19	4646.87
Optimal $control_{50\,°C}$	0.9	101	102	4400.47
Optimal $control_{60\,°C}$	0	183	99.48	4733.01
Optimal $control_{70\,°C}$	0	379.5	104.5	3423.54

4.3 Nutrients retention and consumption energy

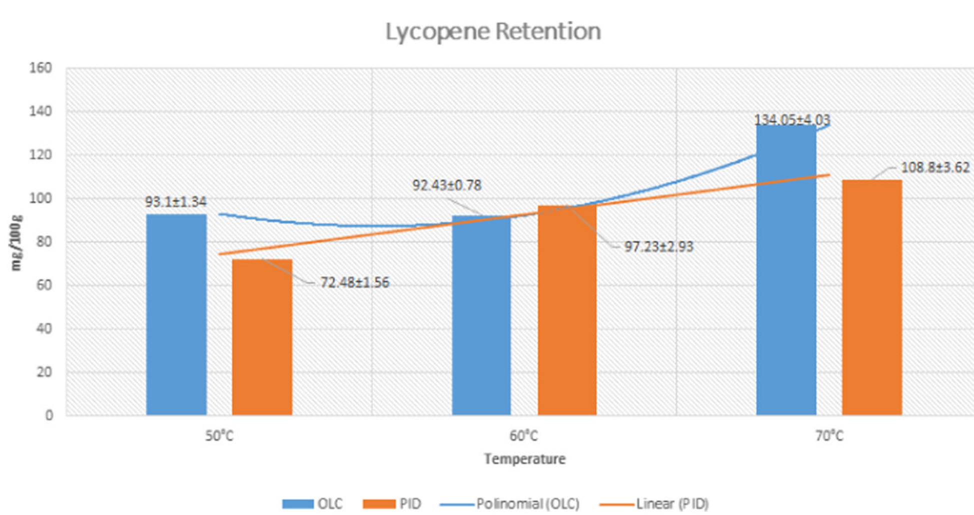
The dynamic responses given by the pair of considered controllers were compared using the energy consumption feature (the initial temperature was approximately 20–23 °C). The following comparative table shows the obtained results by both controllers with respect to the energy saving issue.

According with this table, the energy saving is evident. The energy saving could have variations due to the initial conditions and external disturbances.

However, despite the energy saving is an important aspect in the loop control, another considered issue in this paper, is the nutrients retention on the final product when two different strategies are used: PID and optimal control. According with specialized literature, for the case of the tomato is important to measure the lycopene, ascorbic acid, and total polyphenols contents, because they are quality indicators of the final product and the adequate drying process [21]. During drying process, these nutrients are modified, thus affecting the color, sensorial, nutritional, and functional quality of the dried product [21]. Using the same technique exposed in Santos-Sánchez [21], unbruised tomatoes with a similar mass (180–210 g) were used; tomatoes were cut into 6-mm-thick slices using a domestic manual slicer. Seeds were manually removed to prevent high variability in the weight measurements of dried product. Seedless tomato slices were immersed in a 10 g L^{-1} sodium metabisulfite solution for 10 min at room temperature [21]. The solution was then drained for 2 min. Drying of tomato slices was performed at 50, 60, or 70 °C, using air velocities of 0.6 or 1.2 m s^{-1}, with a static tray. The samples were weighed in an analytical balance every 15 min and finally averaged. The drying was continued until a final moisture content of 10^{-1} g per 100 g of fresh tomato was reached. The validation of the measurements (drying curves and effective diffusivity) was made via the mathematical models presented in Santos-Sánchez [21]. The experiments were executed three times (every experiment lasted 4500 s as maximum) in order to reduce the uncertain of each test. An statistical analysis was made, means standard deviation and analysis of variance (ANOVA) were obtained. Duncan's multiple range method was used for comparison of means, considering a confidence level of 95 % ($p < 0.05$). Following charts display the obtained results for nutrients analysis.

The trends of Lycopene and Phenol concentration for the PID controller are linear in contrast with the optimal control which is polynomial, the reasons are given below. The higher content of lycopene at 70 °C for optimal linear control (OLC) is attributed to stable dried conditions

Fig. 17 Lycopene retention



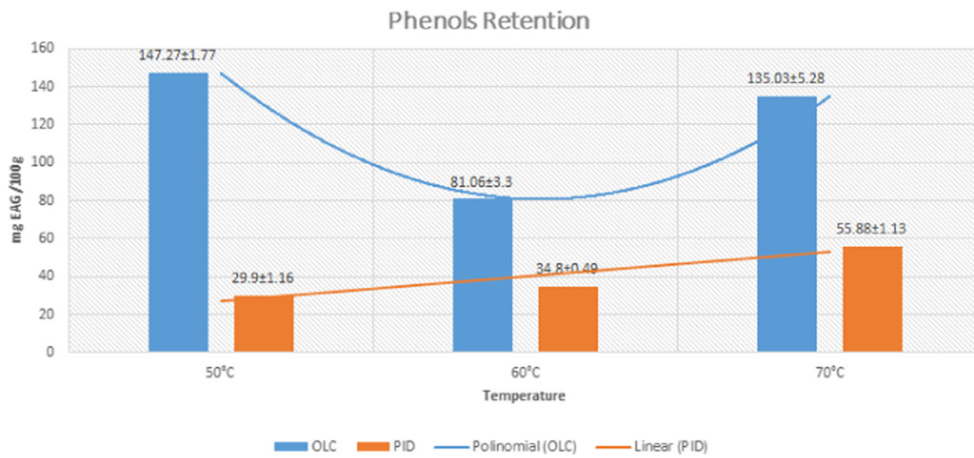


Fig. 18 Total phenols retention

(IAE = 3423.54, Table 1) generated by optimal control. The total phenols content was affected by the combination of temperature and IAE index. The total phenols retention was better at 50 °C with optimal controller.

Figure 19 shows the vitamin C behavior on the product for both tested controllers. The vitamin C is a hydrophilic compound highly sensitive to temperature and susceptible to temperature gradients. Therefore, the content of this bioactive can be influenced by the settling time and overshot during experiment temperature. In Table 1, it can be seen that optimal control experiments at 50 °C had the smallest settling time, obtaining the major vitamin C content, 359.84 ± 18.78 mg/100 g. While the higher overshot was observed with PID controller at 50 °C that yielded the lowest concentration of vitamin C of all treatments, 174.94 ± 4.17 mg/100 g.

The quantities which are added or subtracted in each quantity of the three nutrients represent the standard deviation calculated with the three experiments made in triplicate. According with the results showed in Figs. 17, 18, and 19, the optimal control with Set Point at 50 °C retained a greater amount of nutrients in the product and 80 % of saving energy, both with respect the PID controller working with equal conditions, see Table 2.

For the others temperatures, the use of the optimal control produces a better behavior at least two nutrients retention rates with respect to PID controller. But it is important to clarify that in all cases the energy consumption rate is lower when the optimal control is used. We can summarize the results of bioactives retention as follows:

1. According with the specialized literature, Chua [4], Marfil [11] and Santos-Sánchez [21], deviations on the temperature of drying air, affects the retention of nutrients. Notice that according with Table 1, bigger overshot corresponds to the plant response with a PID controller with set point of 50 °C, and this case presents the worst nutrients retention.
2. Observe that for the optimal control, settling time was increasing, this caused that the concentration of vitamin C in the product were decreasing (linear decrease), notice that the product exposed to large time of temperature deviations (transient response) of the set point could represent degradation of this bioactive [4]. The smaller settling time corresponds to optimal control when 50 °C was fixed as set point, and this was the controller with more vitamin C retention. Despite the PID

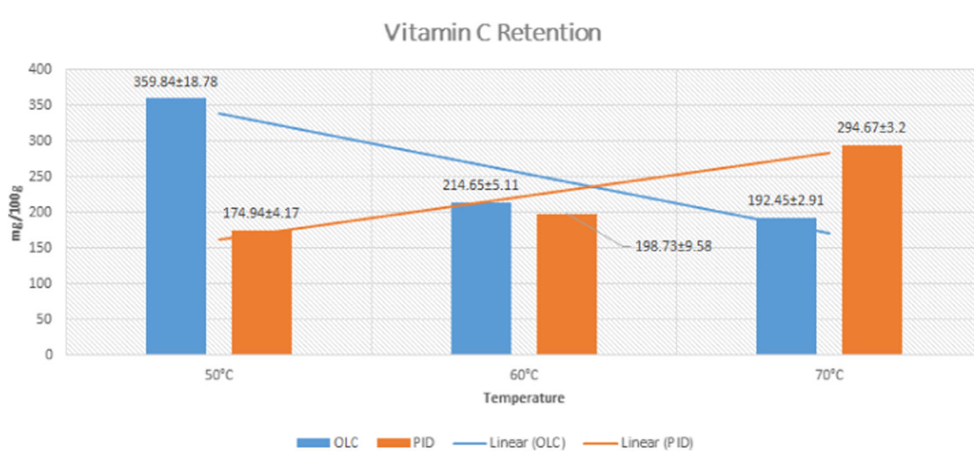


Fig. 19 Vitamin C retention

Table 2 Energy savings when the PID and the optimal control were used

Controller	Energy consumption (W/h)	Energy saving
$PID_{50\,^{\circ}C}$	170	–
$PID_{60\,^{\circ}C}$	185	–
$PID_{70\,^{\circ}C}$	202	–
Optimal $control_{50\,^{\circ}C}$	34	80 %
Optimal $control_{60\,^{\circ}C}$	40	78 %
Optimal $control_{70\,^{\circ}C}$	63	68 %

controller has settling times smaller than the optimal control (set points fixed to 60 and 70 °C), the vitamin C retention was less because the IAE index value was greater than the optimal control.

3. For the optimal control case, the worst performance with respect to IAE index was presented for the set point to 60 °C, this plus the uncertainties of plant, results in the lycopene and phenols retention with nonlinear behavior because the deviations in the temperature of the drying air causes the damage of the molecular structure of the product [4, 21].
4. For the PID controller, the set point fixed to 60 °C is the case with more IAE index value, however as the set point to 50 °C presented an important overshot, similar values in the three bioactive concentrations were obtained.
5. The parameters of the optimal linear control depends of the plant model, then when there exist uncertainties in the plant: uncertain parameters, nonlinear unmodeled disturbances and external disturbances, the performance of the optimal control could be poor, and consequently the bioactive retention behavior could be nonlinear. The PID controller does not present this disadvantages because its structure does not depend of the model of the plant, and consequently, the bioactive retention behavior is linear. The advantage to consume more energy is that we obtain more robust controllers.
6. The study showed that lycopene, total phenols, and vitamin C can be used as chemical sensors to evaluate the response of the control system performance during dehydrated tomato. This is because these bioactives are highly susceptible to temperature changes.

5 Conclusions

In this paper, we present a comparative analysis between an optimal linear controller with delay compensation and an industrial PID controller tuned by numerical optimization and D-partition method. The comparative analysis includes an energy consumption quantification and a study of retention of nutrients which give evidence that using advanced control techniques in this type of process it improves the quality of the final product and reduce the quantity of energy used in the plant. Notice that although the gains of the PID controller were found and optimized numerically, the optimal linear control strategy with delay compensation gave better results with respect to energy saving. Future works include the use of the nonlinear optimal control and to include in the optimization problem the degradation mathematical model of some nutrient of the product.

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