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Abstract: *Thermal treatment techniques for fruit juices have been extensively investigated, primarily to improve the control of process variables and ensure the preservation of product quality. Among these techniques, ohmic heating stands out due to its high energy efficiency, as it generates thermal energy directly within the material through an applied electrical potential. However, maintaining product quality requires precise temperature control capable of adapting to variable conditions. This study characterizes the thermal performance of a bench-scale ohmic cell and presents the experimental results of applying on-off, Fuzzy, and a proposed cascaded Fuzzy control techniques to regulate the temperature of an orange juice solution. The results indicate that the proposed cascaded Fuzzy controller proved to be more robust by combining primary and secondary controllers, maintaining the temperature stability of the cell even when subjected to thermal disturbances, while also reducing energy consumption. These findings reinforce the potential of Fuzzy control for industrial applications.*

Keywords: *food heat treatment, cascade control, energy efficiency, Joule effect*

1. Introduction

With the increase in the scale of industrial processes, the need has arisen to develop mechanisms capable of controlling parameters in large systems while preserving the quality of the end product. This is the case with pasteurization processes, which can present different temperature gradients as the volume increases. Faced with problems like this, new techniques have emerged to increase the efficiency of heat treatments, preserving food quality and eliminating contaminating microorganisms.

Ohmic heating is one of the heat treatment methods that stands out the most for its high energy efficiency, homogeneous heating, low cost, and applicability to various types of food, solids, or fluid [1]. This method generates energy inside the material as an electrical potential is applied, which provides better heat dissipation and temperature homogeneity [2]. Physical and chemical properties have a major influence on the rate of energy generation. Thermal conductivity, specific heat, and specific mass are some of these properties, the most important of which is electrical conductivity [3, 4]. [4] reported that orange juice treated by ohmic heating has higher concentrations of aromatic compounds and a sensory duration twice as long, as well as demonstrating that treatment by ohmic heating at high temperatures can be effective for pasteurizing fresh orange juice, with minimal sensory deterioration. For their part, [5] experimentally proved, in the case of pitaya juice (*Hylocereus undatus*), that ohmic heating results in less degradation of bioactive compounds, total phenol content and antioxidant activity compared to conventional heating.

Despite being a very efficient and fast method, ohmic heating may not be the best option when the material to be treated has significant differences between the components of its structure. This makes monitoring the process more inaccurate and can cause regions with different temperature values. The presence of these zones can facilitate the non-elimination of contaminating microorganisms [6].

To ensure that the product does not lose quality during ohmic heating, it is essential to monitor intensive properties, such as temperature and electrical voltage, to enable the

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system to be manipulated in such a way as to avoid exceeding limits that could damage the structure of the material. [7] found a 69 to 95% reduction in the ascorbic acid content of guava pulp (Psidium guajava) when subjected to heat treatment via ohmic heating for prolonged periods.

To mitigate negative effects on juices or pulps during ohmic heating, it is essential to use control mechanisms. They measure, make decisions, and send signals to actuators, which adjust the process variables. In this way, it is important to avoid reducing the nutritional power of juices and pulps, ensuring their essential properties are maintained during the process.

Controllers on-off are usually applied in processes where the response to a given input is relatively quick because they are simple to program. In this case, a certain action is taken entirely (on) when the measured value exceeds the set-point, and the action is completely stopped (off) when the measured value becomes less than the set-point. For processes with more disturbances or when the response is slow, the on-off controller may not be the best option, and it is suggested that more complex control systems or more comprehensive control logic be used.

Fuzzy logic was introduced in 1965 by Lotfi Zadeh and aims to make rational decisions based on uncertain and imprecise data [8], classified as an Artificial Intelligence technique. Fuzzy logic is based on imprecise fuzzy sets, which assess how "true" or "false" something is [9]. Several differences between classical logic and fuzzy logic were made by [10], and they are summarized in the ability to solve problems in a way closer to the real world, which guarantees the definition of a fuzzy system as an intelligent system.

The use of cascade control systems, when one control logic evaluates set-point values for another logic, makes it possible to improve the system response to noise and intense disturbances. However, most existing studies in the literature rely on simulations or simplified mathematical models rather than experimental validation. For instance, [11] used fuzzy logic to determine the parameters, Kp and Ki, of a PI controller for temperature control in a continuous stirred reactor, where the reactor dynamics were modeled using simple model of two equations. Similarly, [12] compared a non-adaptive fuzzy controller, an adaptive fuzzy controller, and a cascade PID controller for superheated steam temperature control—all tests were conducted in the APROS simulation environment (Advanced Process Simulator), without experimental verification. Additionally, the work of [13] focuses on the development of different cascade control configurations for temperature control in a multiproduct semibatch polymerization reactor. The master controller regulates the reactor temperature by manipulating the mean cooling jacket temperature, while the slave controller adjusts the valve opening to control the mean jacket temperature. However, their results were derived from a theoretical mathematical model consisting of only four ordinary differential equations, which can limit the generalization and practical applicability of their findings to real-world scenarios. This reliance on simplified models is a common characteristic in the existing literature, often sacrificing system complexity for ease of analysis. [14] applied cascade control with Fuzzy and adaptive PID to an industrial furnace, with their study based on theoretical dynamic models rather than experimental validation.

In contrast to these simulation or model-based approaches, the present work provides experimental results obtained from a bench-scale ohmic heating cell, applying closed-loop on-off control, conventional fuzzy control, and cascaded fuzzy control to regulate temperature in a real system. The cell contains an orange juice solution, with cooling water flow rate as the manipulated variable. To the best of the authors' knowledge, there is limited research on temperature control in ohmic heating systems, with most existing studies focusing on continuous flow systems and not exploring intelligent control techniques. Moreover, the experimental validation of fuzzy-based controllers in ohmic heating, as presented here, has not been previously reported in the literature.

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2. Materials and Methods

The study began with the preparation of the orange juice solution and the development of the ohmic heating cell in a jacketed container, enabling the application of a closed-loop control system to regulate the temperature of the orange juice by adjusting the flow rate of the cooling liquid through an external casing (cooling jacket) around the main vessel. The water flow through the jacketed part of the vessel was determined by the power of the water pump, which was controlled using different control techniques. The results allowed for the determination of key parameters in heat treatment processes and enabled a comparison of the applied control strategies.

2.1. Preparation of the orange juice samples

Fresh Pear oranges (*Citrus sinensis L. Osbeck*) were purchased from a local business in Apucarana, Brazil, and stored at 4°C. The oranges were sanitized and then squeezed manually with a metal squeezer. The pulp was filtered using a sieve, which allowed the liquid to pass through by gravity. The extract was prepared sufficiently to formulate new solutions if the one used showed unwanted changes, such as contamination or a color change.

2.2. Ohmic heating cell

The configuration of the ohmic cell developed is shown in Figure 1, in which a schematic of the cell is shown. The heating system consists of a jacketed glass beaker with a capacity of 600ml, sealed by an airtight lid containing four specific inlets. One inlet is used to insert a calibrated thermocouple, which measures the temperature and is connected to a computer data acquisition and monitoring system. Two inlets are intended for the electrodes, while an additional inlet is provided to collect samples during the heating process. The electrodes used in the cell are made of platinum and have a rectangular shape, measuring approximately 2 x 3 cm, and are arranged about 6 cm apart. The electrodes were connected to an alternating, 60 Hz, constant electrical potential supply of 127 V. The set was positioned on a DiagTech stirrer (model: DT3120H, 22 Voltz), whose function is to ensure the homogenization of the juice during heating.

The data acquisition system was designed to monitor and record variables such as electrical consumption and the temperature of the slurry and coolant at the system outlet as a function of time, while the temperature control system regulates the flow rate of the cooling fluid.

Data acquisition and the calculation of control actions were implemented on an Arduino Uno platform, chosen due to the low cost of this hardware and the relative slowness of the system's thermal dynamics. The manipulated variable, i.e., the action of the controller to control the set point temperature of the juice, was carried out by controlling the rotation of a RhondaMaq water pump (model: CF-2201A), powered by a 12 V supply via an H-bridge - BTS7960 (FC see Figure 1)

A supervision system was developed using Matlab software, in which the Arduino Uno operates as a slave and a notebook acts as a master. The supervision interface was designed to be intuitive, allowing temperature monitoring and control. The system offers a graphical display of the juice temperature history and set point and allows the desired temperature to be set and the control action and offset to be monitored.

One of the biggest challenges in implementing temperature control is temperature measurement accuracy. Sensors such as thermocouples and PT100 resistors provide low-amplitude electrical signals that can be disturbed by the electric field present in the environment, making it difficult to capture and process the signal correctly. This interference can directly affect the effectiveness of the control algorithm. In addition, direct contact between the sensors and the heated environment can cause unwanted

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electrochemical reactions, which affect the sensor's response time and the accuracy of the measurements. To mitigate these problems, the juice temperature sensor, TT1 (model: DS18B20), was encapsulated in a glass container, and the empty spaces were filled with highly conductive thermal paste to optimize heat transfer. After these modifications, the sensor was properly calibrated. Two more temperature sensors of the same model were used to determine the temperature of water in the jacket (TT2) and the jacket inlet (TT3).

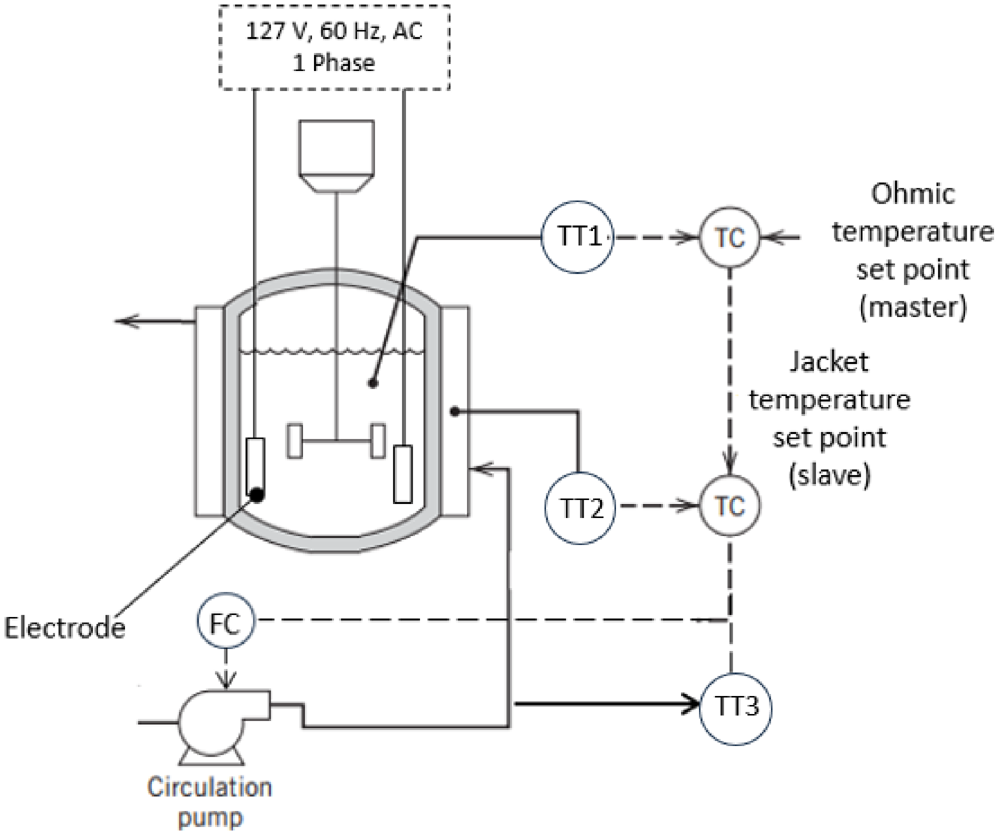

Figure 1: Experimental bench-scale composition of the ohmic heating cell.

The energy efficiency of the ohmic cell was calculated based on the electrical energy provided and the energy used to raise the juice temperature to the set point value. Thermal efficiency is an important parameter to determine, as it can help assess the technical feasibility of ohmic heating. Energy efficiency was calculated using Equation (1).

$$\eta = \frac{(m_g Cp_g + m_j Cp_j)(T_f - T_0)}{E_c} \quad (1)$$

where m_g is the mass of the glass (kg) present in the ohmic cell, Cp_g is specific heat (J/kg K), m_j is the mass of the juice (kg), Cp_j the specific heat of the juice (J/kg K), T_f is the maximum temperature reached, T_0 is the initial temperature of the juice, and E_c is the electrical energy provided (J).

2.2 Electrical conductivity

Electrical conductivity (σ) is a physical property that quantifies a material's ability to conduct electrical current, representing the efficiency with which it allows electrical discharges to flow through its structure, especially in the context of ohmic heating. Voltage and current data were used to determine the samples electrical conductivity (in S/m). The calculation was carried out using the following equation:

DOI: https://doi.org/10.71058/jodac.v9i5020

$$\sigma = \frac{i\,L}{V\,A} \tag{2}$$

where: i represents the electric current (A), L the distance between the electrodes (m), A the electrode face area (m^2) and V the applied potential difference (Volts).

2.3 Control techniques

Control techniques are essential for guaranteeing the stability and efficiency of dynamic systems, especially in processes involving temperature control. This work implemented three different approaches: on-off control, fuzzy control, and cascade fuzzy control, each with specific characteristics and applications.

2.3.1 On/off controller

On-off controllers are used when the system responds quickly to a given disturbance or control action. For systems where the inertia of the process is more significant, it may be necessary to use controllers with more complex logic to prevent the manipulated variable from suffering significant variations. For the on-off controller, a simple script was developed in Matlab software, in which the cooling flow rate is maximum (on) when the juice temperature (T1) exceeds the set point value and zero (off) when the temperature is below the desired value. The turn-on and turn-off temperatures were deliberately made to differ by a small amount, known as hysteresis, to prevent noise from rapidly and unnecessarily switching the heater when the temperature is near the set point. The hysteresis band h was set to ±0.5°C based on the sensor's noise levels and the system's thermal time constant.

Figure 2 presents the block diagram of the on-off system, where only the temperature sensor TT1, shown in Figure 1, was required for control. At the same time, TT2 and TT3 were used solely to monitor potential disturbances.

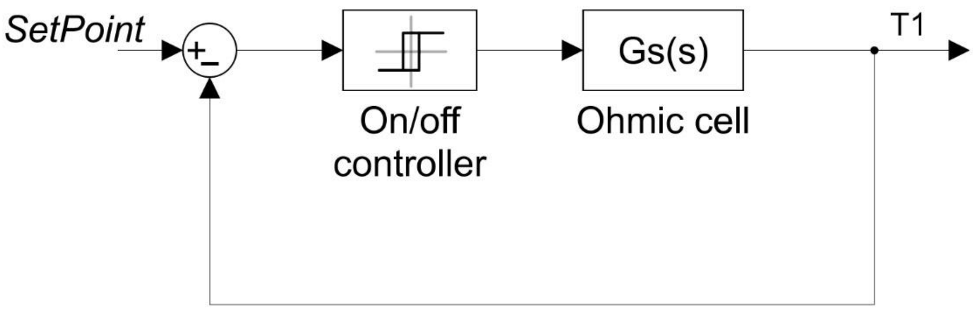

Figure 2. On-off control block diagram for the ohmic cell.

2.3.2 Fuzzy controller

The fuzzy control logics were developed using a set of Mamdani rules with response parameters adjusted according to the intensity of the error and the variation of the error between the measured temperature and the setpoint value. The Mamdani method is particularly suitable for food thermal processing because it allows a more intuitive

DOI: https://doi.org/10.71058/jodac.v9i5020

representation of expert's heuristic knowledge, facilitating the formulation of understandable fuzzy rules.

In processes such as ohmic heating, which are subject to disturbances like variations in product composition or electrical fluctuations, this method demonstrates greater robustness, contributing to the thermal stability essential for pasteurization. The centroid defuzzification, characteristic of the Mamdani approach, generates smoother responses in cooling water flow control, reducing equipment wear and preventing thermal shock in food products. The choice of this method is further supported by extensive literature proving its effectiveness in similar thermal contexts. For example, [15]developed a control system with two inputs — error and error variation — using fuzzy logic based on the Mamdani system to control the drying temperature of coffee beans in a rotary dryer. The results showed that the system was effective in maintaining the desired temperature, contributing to the quality of the drying process.

[16] also developed a Mamdani - based fuzzy controller with two inputs — error and error variation — to regulate the output temperature of an electric air heater. A PI-like algorithm was incorporated to enhance the controller's performance, resulting in minimal overshoot and a fast response time.

According to [17], a Mamdani fuzzy controller was implemented to regulate the temperature of a horizontal autoclave for food sterilization. The controller maintained the temperature within ±0.5 °C and resulted in smoother control actions with reduced oscillations.

The membership functions and rule sets for both simple and cascade fuzzy controllers were defined based on expert knowledge about the thermal behavior of the ohmic heating system, considering open-loop response data and following classical guidelines from [18] and [19] for thermal systems. The design of the input and output membership functions and the specification of the fuzzy controller rules depend on the designer's knowledge of power supply and pumping device constraints, intuitive and practical aspects related to the thermal mechanism's dynamic behavior, and successive experiments to ensure process robustness and reliability [20, 21]

The rigorous development of the controllers ensures that the obtained results represent the true potential of each evaluated strategy, allowing valid conclusions about their relative advantages and limitations in the specific context of temperature control in ohmic heating processes. The controller was developed using two key parameters: the error, e(k), defined as the difference between the setpoint and the measured value, and the error variation, Δe(k), which accounts for the rate of change in the error over time.

This approach enhances control precision while maintaining system stability under varying operational conditions. The controller was developed using two key parameters: the error, e(k), and the error variation, Δe(k). The error is defined as the difference between the setpoint and the measured value, given by $e(k) = T_{sp} - T$. The error variation is determined as the difference between the current error and the error from the previous step: $\Delta e(k) = (e(k) - e(k-1))/\Delta t$. This parameter makes it possible to characterize heating situations, when it is positive, cooling, when it is negative, and stagnation, when it is null, for example.

The rules evaluate the e(k) and Δe(k) values for simple fuzzy logic, which generate the PWM value as a response. Figure 3 shows the set of error pertinence functions for simple fuzzy control logic, where was used the following notation EL = Extremely Low, VL= Very Low, L = Low, H = high, VH = Very High and EH = Extremely High.

DOI: https://doi.org/10.71058/jodac.v9i5020

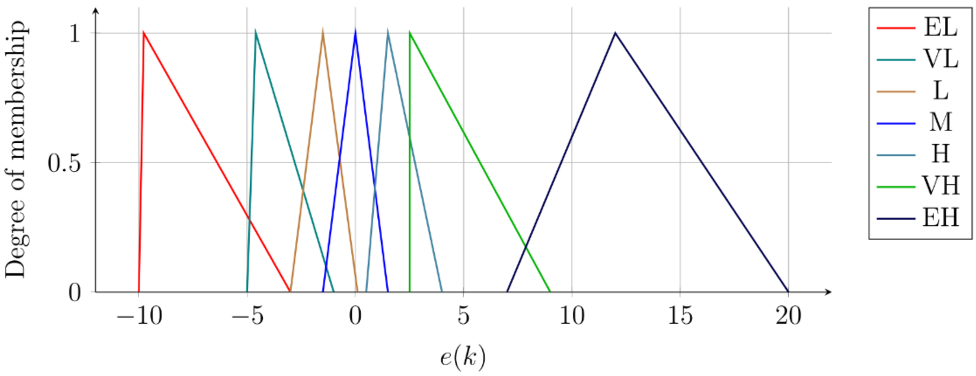

Figure 3. Parameters of the error e(k) - Fuzzy Logic.

Figure 4 shows the set of error variation pertinence functions for simple fuzzy logic, defined as VN = Very Negative, N = Negative, Z = Zero, P = Positive and VP = Very Positive.

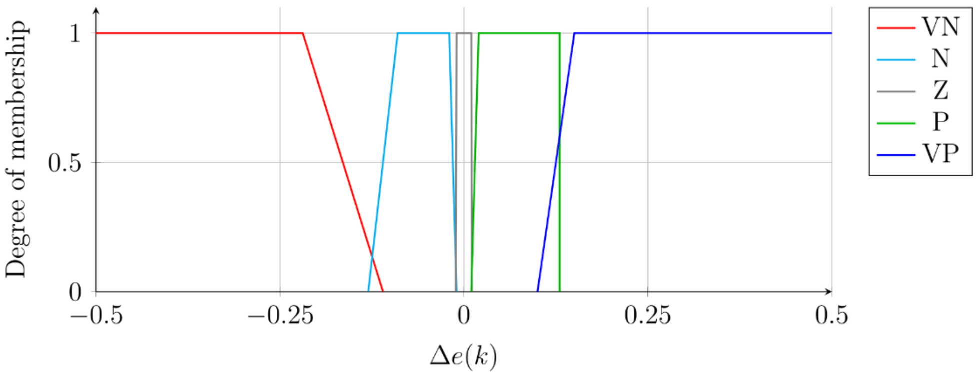

Figure 4. Parameters of the Δe(k) - Fuzzy Logic.

Figure 5 shows the set of pertinence functions for the PWM response of simple fuzzy logic , where the following notation was used as EW = Extremely Weak, VW = Very Weak, W = Weak, M = Medium, S = Strong, VS = Very Strong and ES = Extremely Strong.

Table 1 shows the control rules for simple fuzzy logic based on the fuzzy associative matrix system.

Figure 6 presents the block diagram of the fuzzy control, where only the temperature sensor TT1, shown in Figure 1, was required for control. At the same time, TT2 and TT3 were used solely to monitor potential disturbances.

Table 1. **Set of rules – Fizzy Logic**

$\frac{e}{\Delta e}$	EL	VL	L	M	H	VH	EH
VN	ES	VS	W	M	VW	VW	EW
N	ES	VS	S	M	W	VW	EW
Z	ES	VS	S	M	W	VW	EW
P	ES	VS	S	M	W	VW	EW
VP	ES	VS	VS	M	M	VW	EW

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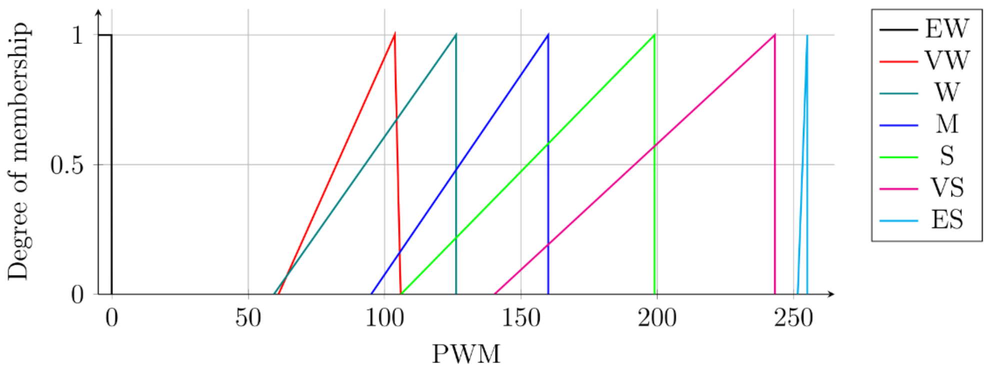

Figure 5. PWM response parameters - Fuzzy Logic

2.3.3 Cascaded fuzzy controller

The inlet temperature of the cooling liquid in the jacket (Tj in = T3) can vary significantly, see Figure 1 For example, reducing the water temperature in the cooling jacket may require a decrease in the flow rate of the cooling liquid. To mitigate the effects of this disturbance in the cooling temperature, an effective approach is to measure the temperature of the cooling fluid at the outlet of the jacket (T2). This process variable, called the internal secondary, is chosen as part of constructing a nested cascade control architecture.

The addition of a temperature sensor to measure the outlet temperature of the cooling water (T2) provides an early warning of any disturbances in the temperature of the liquid entering the jacket (T3), allowing a rapid response before these variations impact the temperature of the juice (T1) contained in the ohmic cell. Adding a second temperature controller completes the cascade control structure for the ohmic cell, as shown in Figure 15.

In the internal secondary control loop, the temperature of the coolant at the outlet of the jacket (T2) is monitored, and a signal is sent to the water pump (FC), which adjusts the flow rate of the coolant. Depending on the need, the pump increases or decreases the flow rate to reduce or increase the jacket's temperature (T2).

The outer loop maintains the juice temperature (T1), the primary process variable of interest. As shown in Figure 15, the output of the primary controller defines the set point of the internal secondary controller. In this way, variations in the temperature of the cooling liquid entering the jacket are quickly compensated for by the internal secondary loop, ensuring the stability of the juice temperature.

The controller was designed using the previously mentioned parameters: error e(k), error variation Δe(k), and the second-order error variation, Δ2e(k). The latter is defined as the difference between the error variation in the current iteration and that of the previous iteration: $\Delta 2e(k) = (\Delta e(k) - \Delta e(k-1))/\Delta t$. This parameter helps mitigate noise caused by minor fluctuations in the error, ensuring more precise and stable control.

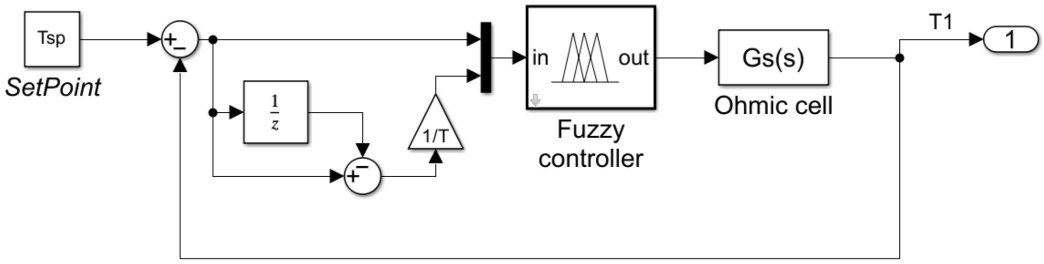

Figure 6. Fuzzy control block diagram for the ohmic cell.

JOURNAL OF DYNAMICS AND CONTROL
DOI: https://doi.org/10.71058/jodac.v9i5020

External control logic: The cascade fuzzy control system is structured with both external and internal control logics, each evaluated through specific pertinence functions. Figures 7, 8, and 9 illustrate the pertinence functions for the external logic, representing the error e(k)e(k)e(k), its variation Δe(k)\Delta e(k)Δe(k), and the second-order error variation Δ2e(k)\Delta^2 e(k)Δ2e(k), respectively. These functions are essential for assessing the external control behavior and determining the necessary adjustments. Figure 10 presents the response ranges of the external logic, which generates the new set point temperature values for the internal control logic. The control rules for this external logic, based on the "If-Then" system, are summarized in Table 2.

For the internal logic, Figure 11 shows the pertinence functions for evaluating the internal error, while Figure 12 presents the corresponding error variation functions, forming the core of the internal control evaluation within the cascade structure.

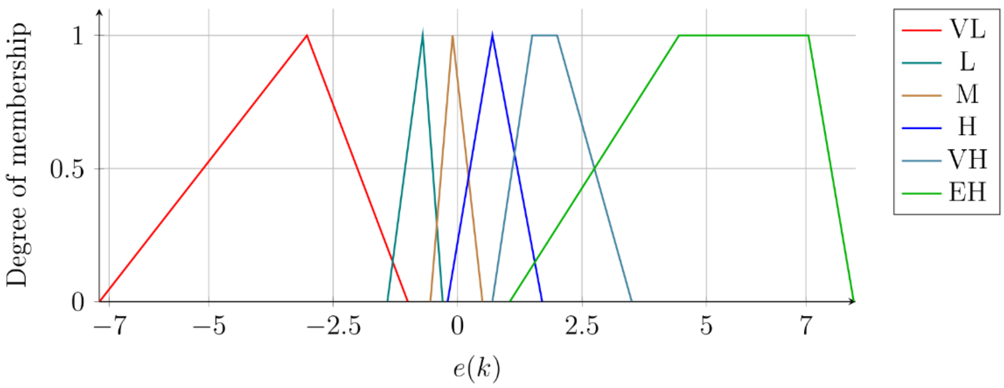

Figure 7. Parameters of the error e(k) - External Fuzzy Logic.

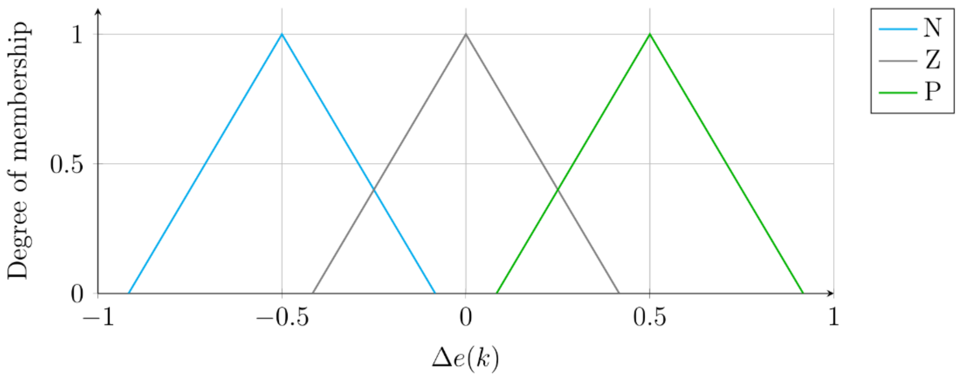

Figure 8. Parameters of the error variation, Δe(k) – External Fuzzy Logic.

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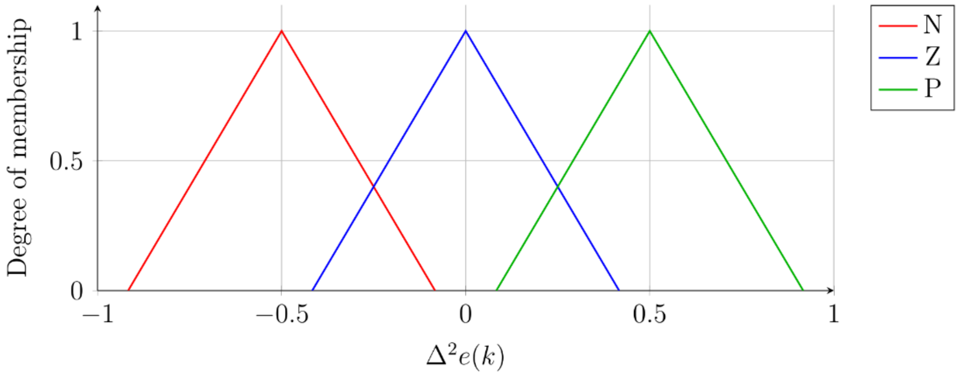

Figure 9. Parameters of the second-order error variation, Δ2e(k) - External Fuzzy Logic

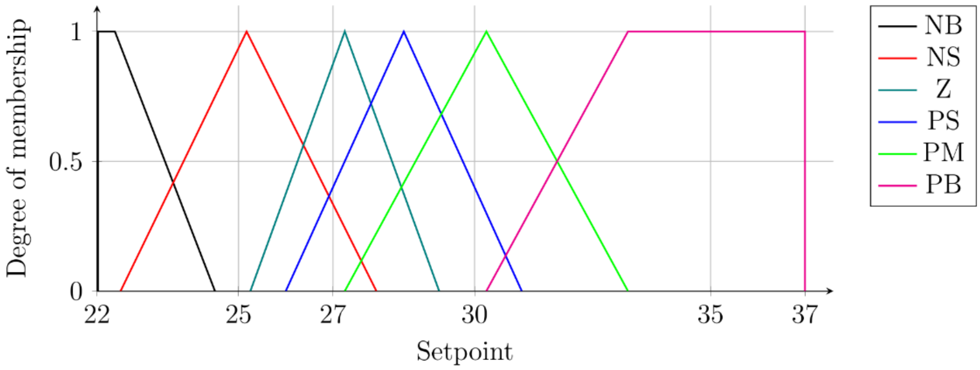

Figure 10. Tj sp response parameters - External Fuzzy Logic

Table 2. Set of rules – External Fuzzy Logic.

$\Delta e/e$	VL	L	M	H	VH	EH
N	NB	NS	PS	PS	PM	PB
Z	NB	NS	Z	PS	PM	PB
P	NB	NS	NS	PS	PM	PB
$\Delta^2 e/e$	VL	L	M	H	VH	EH
N	NB	NB	Z	PS	PM	PB
Z	NB	NB	Z	PS	PM	PB
P	NB	Z	Z	Z	PM	PB

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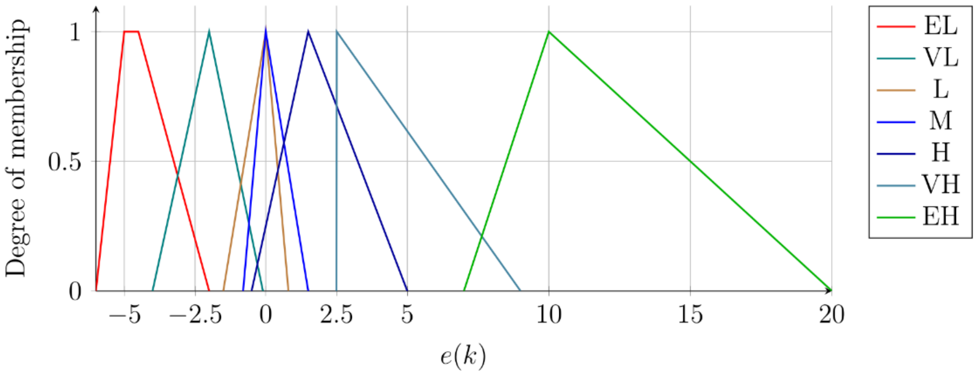

Figure 11. Parameters of the error e(k) - Internal Fuzzy Logic

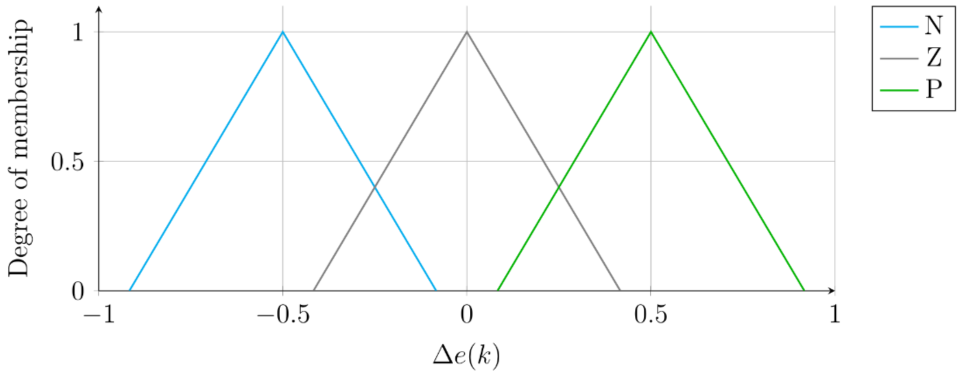

Figure 12. Parameters of the error variation, Δe(k) – Internal Fuzzy Logic

Figure 13 shows the pertinence functions of the second-order error variation for the internal fuzzy logic.

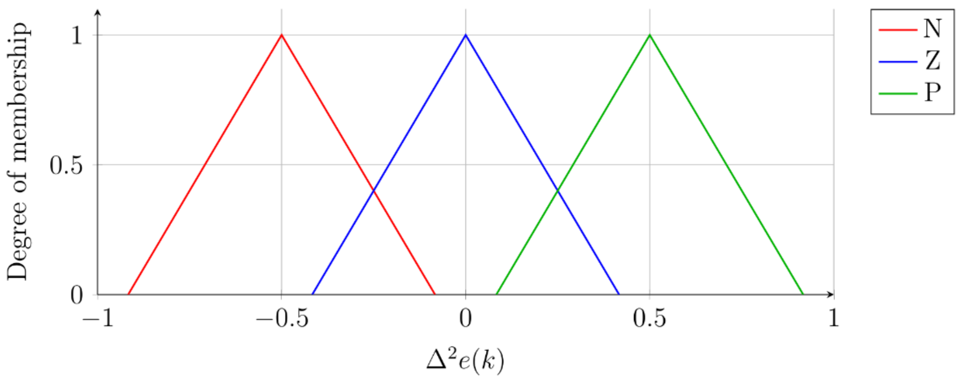

Figure 13. Parameters of the second-order error variation, Δ2e(k) - Internal Fuzzy Logic

Figure 14 shows the pwm response of the internal fuzzy logic, where the following notation was used as Z = Zero, VS = Very Small, S = Small, MS = Medium Small, ML = Medium Large, L = Large, VL = Very Large and F = Full.

JOURNAL OF
DYNAMICS AND CONTROL
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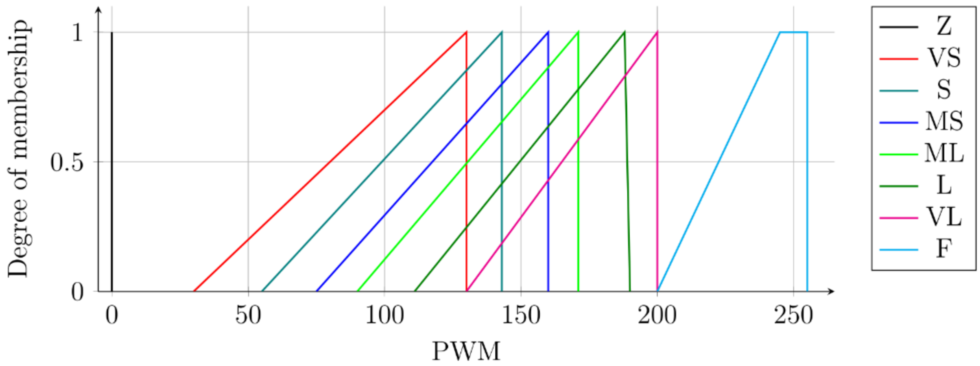

Figure 14. PWM response parameters - internal fuzzy logic

Table 3 shows the set of internal fuzzy logic rules.

Table 3. Set of rules – Internal Fuzzy Logic

$\Delta e/e$	EL	VL	L	M	H	VH	EH
N	F	VL	L	MS	VS	VS	Z
Z	F	VL	L	MS	S	VS	Z
P	F	VL	L	MS	S	VS	Z
$\Delta^2 e/e$	**EL**	**VL**	**L**	**M**	**H**	**VH**	**EH**
N	F	F	L	ML	S	VS	Z
Z	F	VL	L	ML	S	VS	Z
P	F	L	L	S	S	VS	Z

Figure 15 illustrates the control loop of the cascade fuzzy system.

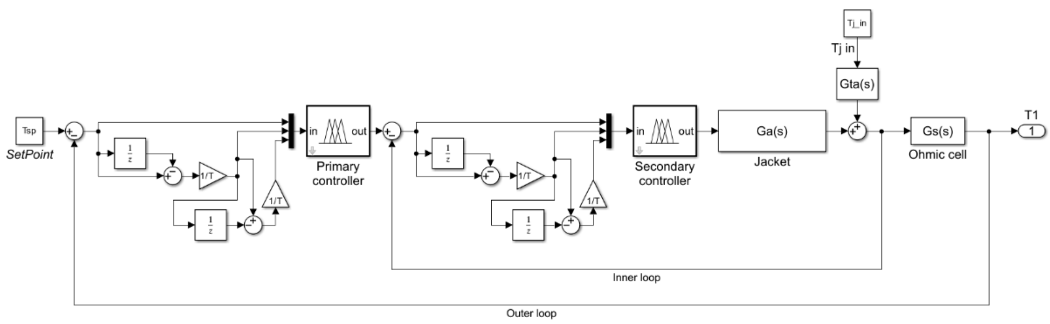

Figure 15. Cascade fuzzy control block diagram for the ohmic cell.

Scripts and the Fuzzy Logic Toolbox in the MatLAB software were also used to develop the fuzzy and fuzzy cascade controllers.

3. Results and discussion

Initially, systematic temperature measurements were taken and correlated with the electric current and energy consumption during the ohmic heating process. This data was

DOI: https://doi.org/10.71058/jodac.v9i5020

used to determine the energy efficiency of the cell, as well as the electrical conductivity of the orange juice solution.

Comparative temperature control tests were then carried out using two strategies: on/off controllers and fuzzy logic-based controllers. The main objective was to assess the ability of these controllers to avoid and minimize disturbances in the system.

In addition, to demonstrate the influence of external disturbances on control systems, fuzzy and fuzzy cascade control strategies were implemented in a system subject to variations in cooling water temperature. Ice stones were added to the inlet tank after the temperature had stabilized at the set point to simulate these disturbances. This approach made it possible to analyze the performance of the controllers in dynamic and non-ideal conditions, providing information on their robustness and effectiveness in practical scenarios.

3.1 Thermal efficiency and electrical conductivity

Energy efficiency is important in determining whether a system is commercially viable. In this regard, the energy efficiency of the ohmic cell in the orange juice heat generation process was analyzed. Based on the values of the thermo-physical properties available in [22] and [23], the average energy efficiency via the Joule effect obtained experimentally was 94.1%, calculated from Equation (1).

The efficiency value obtained is close to that expected for ohmic heating, at over 90% [24].[25] obtained an energy efficiency of 94.2% for ohmic heating in treating model solutions representing heterogeneous foods. [26] valuated the energy efficiency of ohmic heating applied to the concentration of agraz (also known as verjuice). The energy efficiency obtained ranged from 71.27 to 75.22%, depending on the electrical potential applied. [27]evaluated the efficiency of the ohmic heating system for orange juice, varying the concentration of the juice and the electrical potential gradient applied. The results indicated that the efficiency is strongly influenced by the electrical potential gradient, being reduced for higher values of V/cm. For 60 V/cm, the efficiency varied between 52% and 59%, while for 20 V/cm, the values were between 88% and 92%.

To determine the electrical conductivity of the orange juice, measurements were made of the electrical current associated with the temperature of the ohmic cell, Figure 16 The mathematical relationship between electrical current and temperature was obtained with these values, Equation (3).

$$i(T) = 0.02684T + 0.7505\ [A] \tag{3}$$

Using Equations (2) and (3), the electrical conductivity of the juice was determined as a function of temperature, obtaining the following linear relationship:

$$\sigma(T) = 0.0097T + 0.2713\ [S/m] \tag{4}$$

For a temperature of 25ºC, the electrical conductivity obtained is 0.5138 S/m and 1.047 S/m for 80ºC. The values obtained for conductivity are close to 0.343 S/m at 25ºC and 0.971 S/m at 80ºC, consistent with the results reported by [28]for orange juice produced by extracting tropical Thai mandarins, *Citrus reticulata*.

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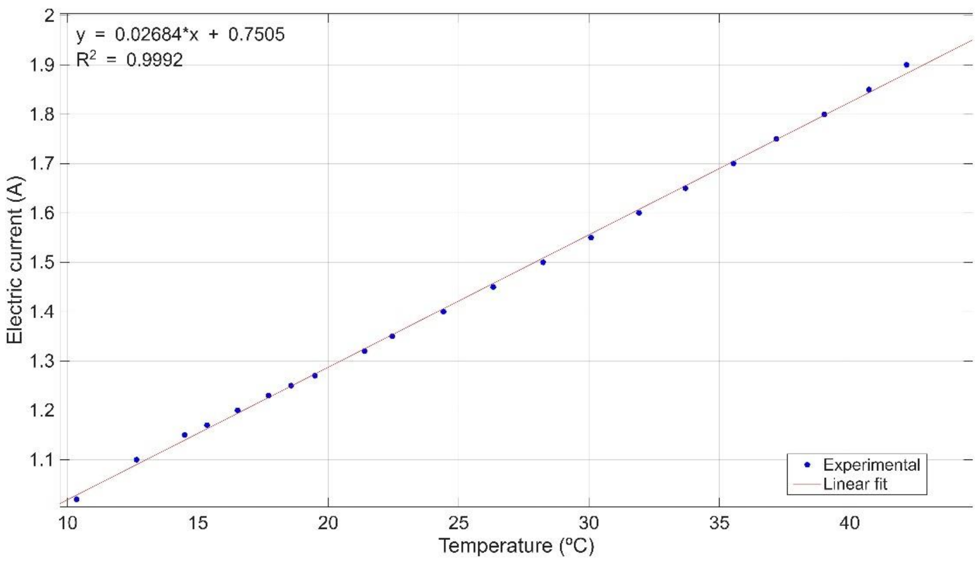

Figure 16: Electrical current as a function of temperature.

3.2 On/off Control

Figure 17 and 18 illustrate the performance of the on/off controller. Figure 17 displays the inlet and outlet temperatures of the cooling water, the set point, and the juice temperature, represented using the dimensionless temperature defined as T*= T/T setpoint, plotted as a function of time. Figure 18, on the other hand, presents the control action in terms of the mass flow rate of the cooling water.

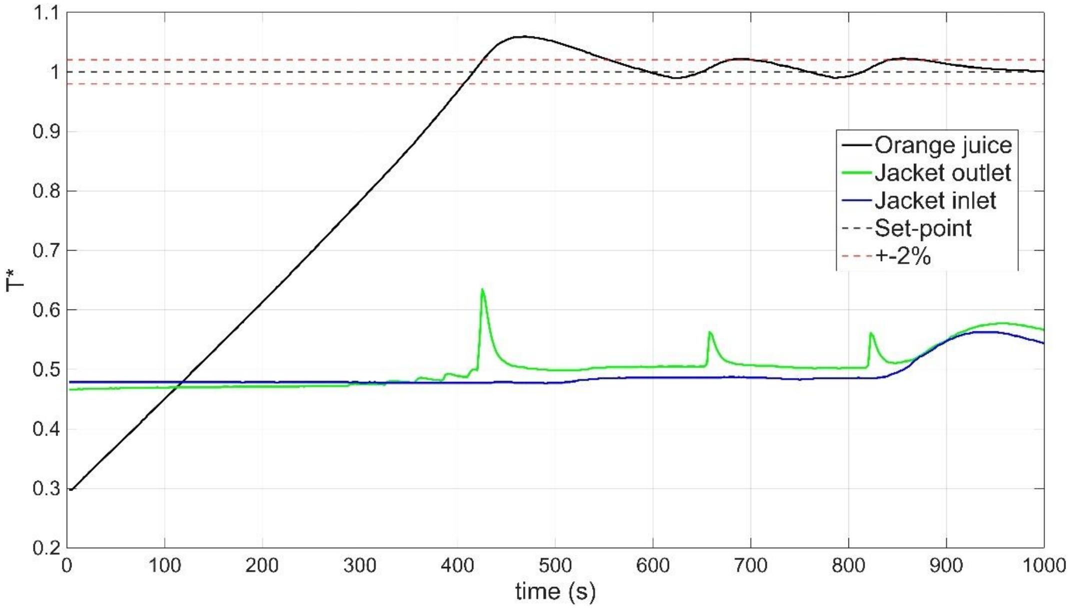

Figure 17. Closed-loop responses obtained with the on-off controller

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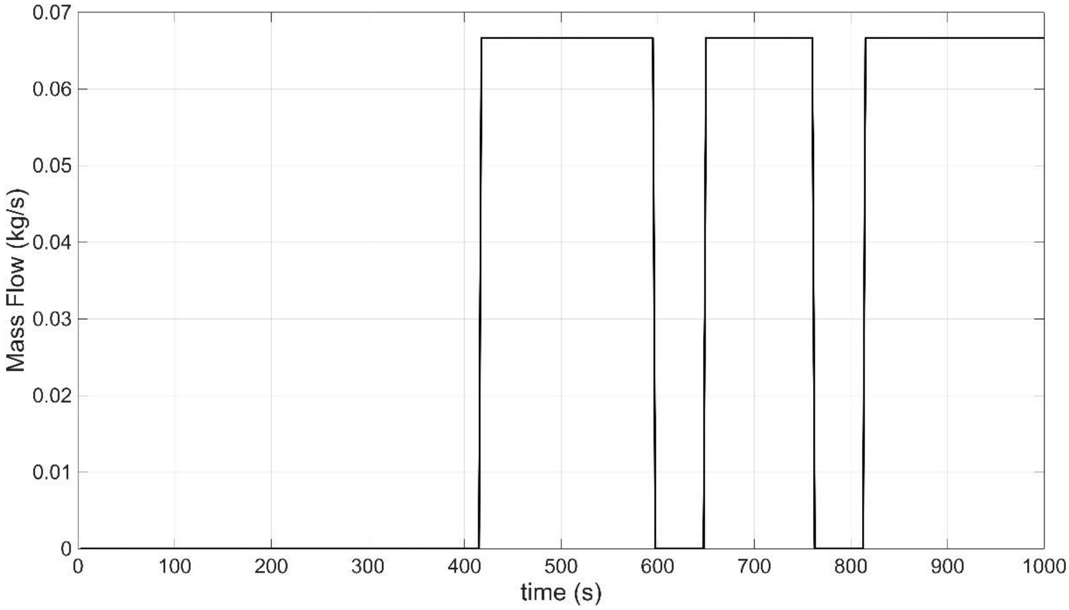

Figure 18. Controller on-off action.

It can be seen that the inlet water temperature remained practically constant during the initial phase of the process, with a rise in temperature towards the end. There are also temperature peaks in the outlet water caused by the water stagnating in the ohmic cell jacket when the water pump is switched off.

As expected, in the initial period of the process, the juice temperature increased linearly over time due to the Joule effect. When the temperature reached the set point, at around 410 s, the control system was activated, reducing the juice temperature. However, a 106% overshoot of the set point was observed. Subsequently, as the control action switched between the turn-on and turn-off, the juice temperature did not remain constant, oscillating T* between 0.99 and 1.06. This variation may be acceptable depending on the specific requirements of the process. This apparently satisfactory behavior was possible because, as illustrated in Figure 3, the inlet water temperature remained practically constant during the initial phase of the process, rising only in the final moments.

It can be seen that the inlet water temperature remained practically constant during the initial phase of the process, with a rise in temperature towards the end. There are also

temperature peaks in the outlet water caused by water stagnating in the ohmic cell jacket when the water pump is switched off.

Table 4 summarizes the main performance indices obtained specifically for the on-off controller and the data that will later be presented for the other control techniques explored in this work. The parameters considered include delay time (τd), rise time (τr), peak time (τp), maximum overshoot (MO), settling time (τs), and consumption in kWh. These parameters are essential for assessing the control quality, especially in thermal systems, where a fast and precise response is essential, as in orange juice processing, where excessive overshoot is highly detrimental. It significantly reduces ascorbic acid (vitamin C) content and total phenol concentration, thereby compromising the nutritional quality. The concentration of vitamin C in orange juice is one of its most important attributes for consumers [4]. Even prolonged heating at subpasteurization temperatures can cause undesirable changes in pH and juice color, affecting product acceptability [29]. For now, the results presented refer exclusively to the on-off controller, with a detailed analysis of the other techniques being discussed in the next section.

JOURNAL OF DYNAMICS AND CONTROL
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Table 4. Set of rules – Internal Fuzzy Logic

	τd (s)	τp (s)	τr (s)
OnOff	53	146	470
F ND	31	126	737
F WD	0	92	647
C WD	0	92	580
	τs (s)	MO (%)	C (kWh)
OnOff	880	105.9	0.03391
F ND	485	100.7	0.02901
F WD	1222	101.6	0.04768
C WD	1122	101.2	0.04511

Note: F ND: Fuzzy With No Disturbance; F WD: Fuzzy With Disturbance; C WD: Cascade Fuzzy With Disturbance; MO: Max Overshoot; C: Consumption.

3.3 Fuzzy Control

The results of the experiments using the fuzzy controller were analyzed under two conditions: operation without disturbance and introduction of a thermal disturbance by adding ice to the cooling water.

In the undisturbed experiment Figure 19, the temperature curves showed that the fuzzy controller kept the juice temperature within a deviation range of less than 2% from the set point. The maximum value recorded was T*=1.01, indicating good control precision. The cooling water inlet temperature stabilized at around 26.26°C and 26.62°C, reflecting a scenario with practically no thermal disturbance.

The mass flow rate provided by the pump (Figure 20) showed constant adjustments, with small oscillations, to compensate for minor variations in the thermal system. The energy consumed by the pump was 0.02901 kWh, lower than that recorded by the on-off controller, which consumed 16.89% more energy, implying that the controller consumes more cooling fluid. The system's characteristic times are summarized in Table 4.

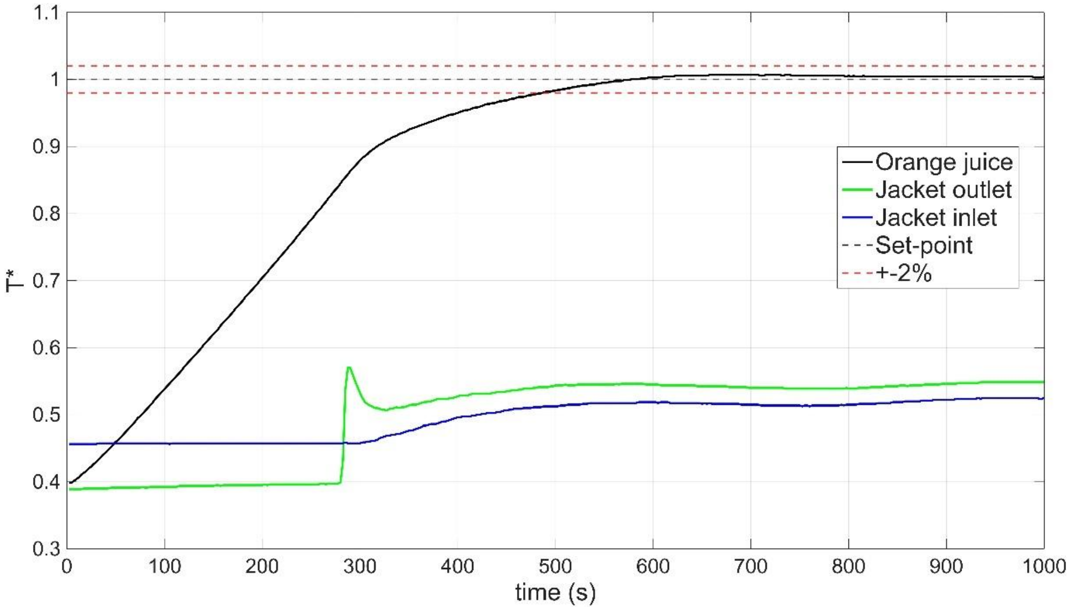

Figure 19. Closed-loop responses obtained with the Fuzzy Controller.

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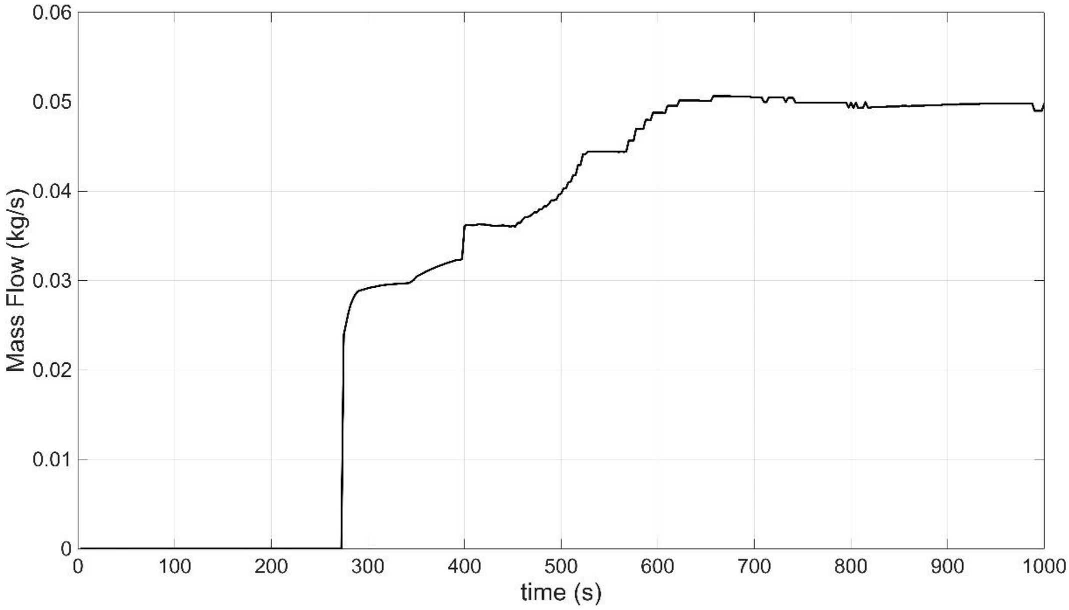

Figure 20. Action of the Fuzzy Controller.

In the experiment with disturbance (Figure 21 and 22), after initial stabilization, ice was introduced to the cooling water, which caused a significant drop in the temperature of the cooling water from 27.19°C to 16.06°C, and there was also a rapid thermal response in the temperature of the outlet water. The results show that the fuzzy controller responded by adjusting the mass flow rate in the pump, as shown in Figure 22. However, the juice temperature of T*=1.01 was reduced to 0.91, reflecting the higher heat removal rate resulting from the increased temperature difference between the juice and the cooling water. Although the controller adjusted the flow rate in response to the disturbance, it could not keep the juice temperature within the tolerated deviation range, signaling that fuzzy logic alone could not compensate for disturbances in the cooling water temperature.

The estimated energy consumption of the pump was 0.04768 kWh, which was higher than in the undisturbed experiment. This increase was expected since the duration of the experiment was significantly longer. The characteristic temporal parameters of the system, summarized in Table 4, indicate a dynamic response with significant oscillations before stabilizing at the desired set point.

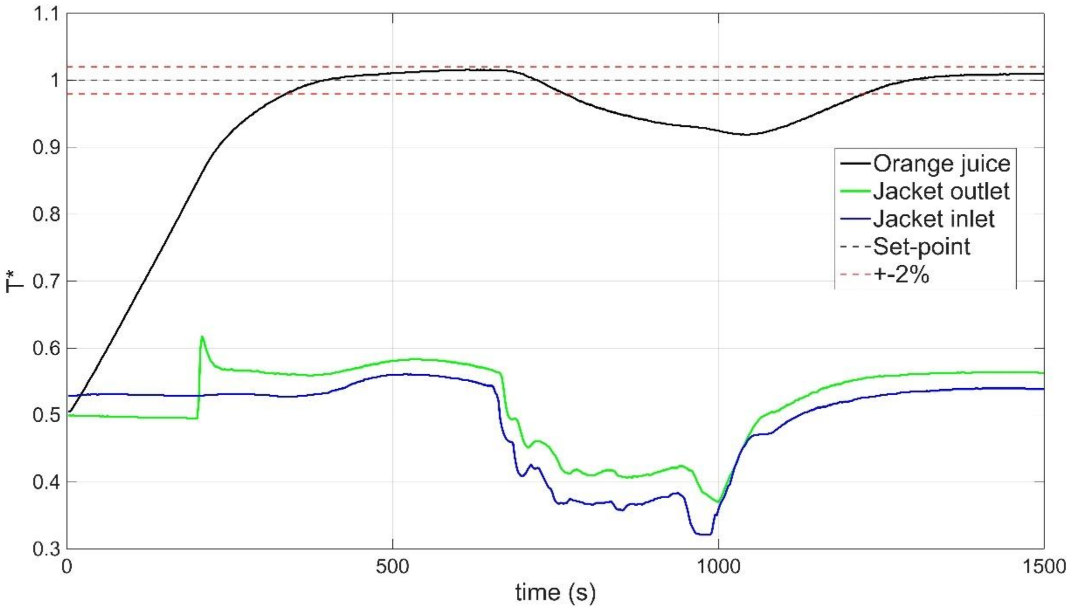

Figure 21. Closed-loop responses obtained with the Fuzzy Controller with disturbance.

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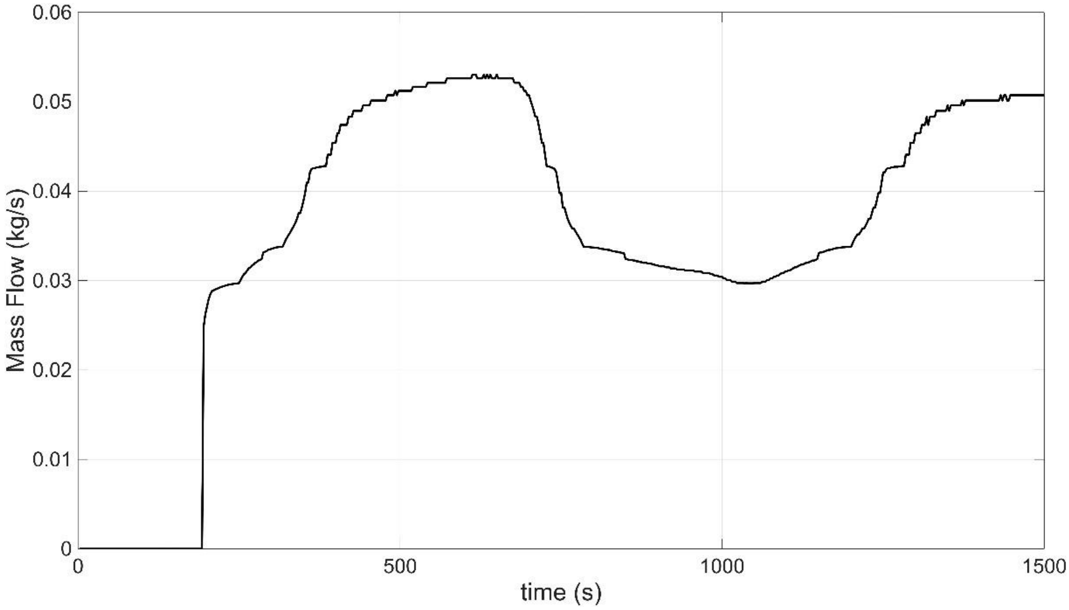

Figure 22. Fuzzy controller action with disturbance.

The comparative analysis between the two scenarios shows the efficiency of the fuzzy controller in stable operating conditions, surpassing the on-off controller in terms of energy efficiency. However, the response to disturbances proved limited, indicating the need to implement complementary strategies to increase robustness and thermal stability under adverse conditions. One promising solution, presented below, is the adoption of cascade control.

3.4 Fuzzy Cascade Control

The results for the fuzzy cascade controller are shown in Figure 23, which indicates that the system could maintain the juice temperature close to the set point, even in the face of a significant disturbance in the inlet water temperature. The disturbance of the cooling water temperature from 27.12°C to 15.25°C between 600 and 1,100 seconds generated a rapid response from the controller and with greater amplitude than the simple fuzzy control, minimizing the error to values of less than 2% of the reference value. This behavior indicates the efficiency of the master and slave controller set in dynamically adjusting the system when it detects disturbances in the thermal conditions of the cooling fluid.

Figure 24 shows the mass flow rate response of the cascade control system. The curve shows quick and precise adjustments in response to the cooling fluid temperature drop, which ensures effective compensation for the disturbance. The flow rate variation indicates that the secondary controller was able to act directly on the cooling water flow, providing adequate adjustments until the system reached thermal stability.

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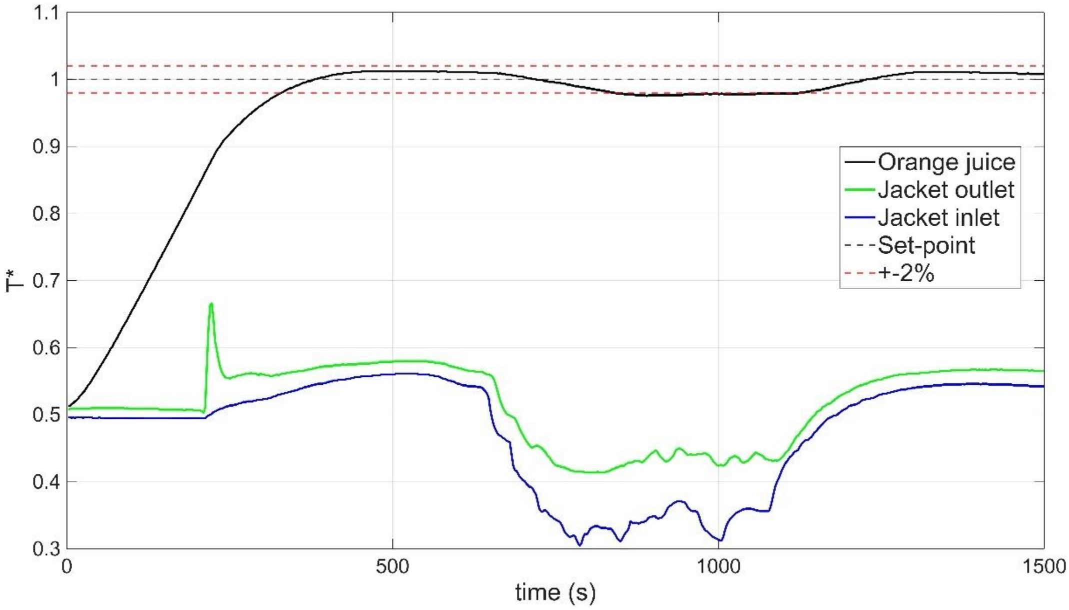

Figure 23. Closed-loop responses obtained with the Cascade Fuzzy Controller with disturbance.

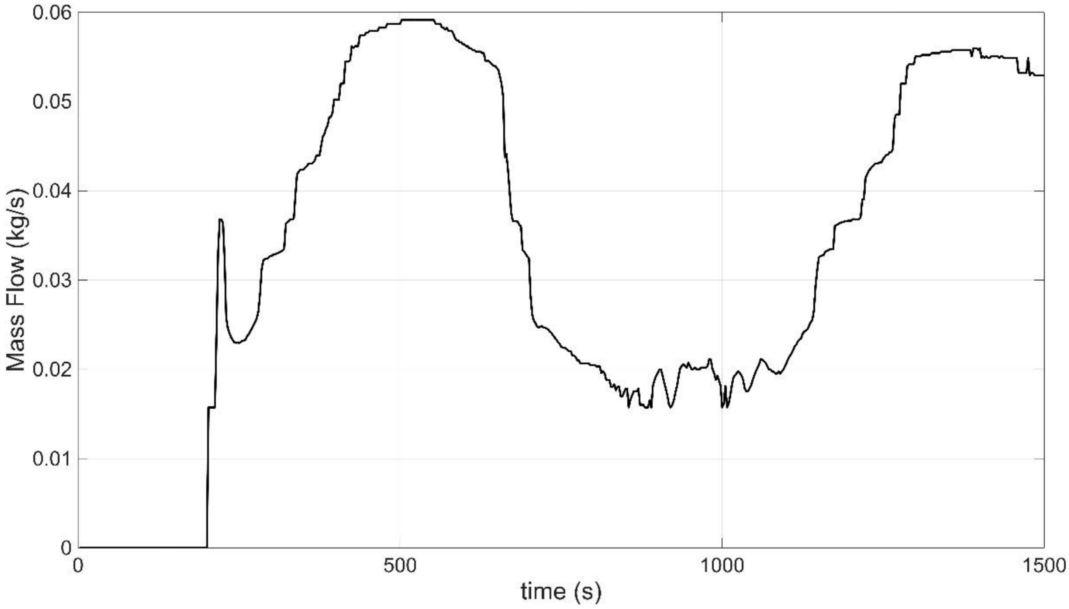

Figure 24. Action of the Cascade Fuzzy Controller with disturbance.

The energy consumption of the water pump was estimated at 0.04511 kWh during the experiment. Compared to the simple fuzzy controller under the same operating conditions, there was a 5.7% reduction in energy consumption. This decrease can be attributed to the lower volume of cooling water used since the average temperature of the cooling jacket was lower than that recorded in the undisturbed experiment.

The measured time constants, summarized in Table 4, indicate a significant initial oscillation, but one that was quickly controlled. This suggests that although the system was exposed to a sudden disturbance, the cascade control was effective in limiting prolonged oscillations and stabilizing the temperature.

Overall, the results indicate that the fuzzy cascade controller is more robust to external disturbances and more accurate and energy efficient. The implementation of this technique in ohmic heating systems can contribute to greater thermal stability and industrial applications that are sensitive to sudden temperature variations.

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4. Conclusion

This study thermally characterized a bench-scale ohmic cell for heating orange juice and compared temperature control techniques (on/off, fuzzy, and cascade fuzzy). The ohmic cell demonstrated high energy efficiency (94.1%) and variable electrical conductivity (0.5138 S/m at 25°C and 1.047 S/m at 80°C), consistent with the literature.

The cascade fuzzy controller, the first reported application of this type in batch ohmic systems, achieved a 5.7% reduction in energy consumption compared to simple fuzzy control while maintaining temperature stability even under significant thermal disturbances. The on-off controller exhibited significant oscillations, with a 106% overshoot of the set point, but managed to keep the temperature within acceptable limits, albeit with higher energy consumption (0.03391 kWh). The fuzzy controller proved to be more efficient under stable conditions, maintaining the temperature within 2% of the set point, but struggled with disturbances, resulting in higher consumption (0.04768 kWh) when ice was added to the cooling system.

In contrast, the cascade fuzzy controller stood out for its robustness, keeping the temperature close to the set point even with disturbances and reducing energy consumption to 0.04511 kWh. This demonstrates that, depending on the control requirements and in the absence of disturbances, both on-off control and simple fuzzy control can provide temperature control for the ohmic cell. However, among the control techniques explored in this work, cascade fuzzy control was the most effective for the studied ohmic heating system, offering greater thermal stability, energy efficiency, and the ability to handle external disturbances.

This approach presents promising potential for industrial applications that require precise temperature control and could enhance the quality of the final product and the efficiency of the process.

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