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Automatic Control System for Cane Honey Factories in Developing Country Conditions

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Citation: Mejía, V.C.; Mejía, G.C.; Rubio, O.G.; Cortes, I.B.; Yordi, E.G.; Tenezaca, B.O.; Miño Valdés, J.; Suárez, E.G.; Martínez, A.P. Automatic Control System for Cane Honey Factories in Developing Country Conditions. *Processes* **2022**, *10*, 915. https://doi.org/10.3390/pr10050915

Academic Editors: Seung-Jun Shin and Jong-Ho Shin

Received: 2 January 2022
Accepted: 15 April 2022
Published: 6 May 2022

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Abstract: (1) Background: A proposal for the automatic control of sugar cane honey factories based on simulation with real data is presented. (2) Methods: The P&ID diagram of the artisanal process is designed, as well as the measurement and control systems of the different process variables. A data acquisition and monitoring system is proposed with all the required equipment. Using GNU Octave software, the process was simulated, where the transfer functions and parameters of the different stages were determined. The transient responses of these systems are determined before step-jump type disturbances, as well as that of the controllers. (3) Results: A correct adjustment of the controllers is obtained, indicating those that work in a stable way before disturbance variations in the real ranges of plant work. (4) Conclusions: Simulation of controllers before different forcing functions in the ranges of the operating parameters allowed for establishing dynamic responses of each one, demonstrating that they are capable of adjusting the value of the variable of interest or the control, and determining control of the main operating variables.

Keywords: plantwide control; sugar cane honey; data acquisition system

1. Introduction

Sugarcane, predominantly grown in tropical and subtropical "developing countries" in Asia, Latin America and Africa, will continue to be the main crop used to produce sugar [1]. Per capita consumption of sugar-derived calories is expected to increase by 2030. As a result, global sugar consumption is projected to continue to grow at around 1.4% per year and consumption of alternative caloric sweetener to increase by 1.9 Mt to reach 15 Mt by 2029 [1,2].

Food systems will have to adapt to changing diets and consumer preferences, as high levels of refined sugar consumption can contribute to diseases and health problems, including diabetes, overweight and obesity, while per capita consumption in high-income countries is expected to decline as a result of changes in consumer habits with respect to refined sugar consumption [1].

The production of Minimally Processed Sugarcane Derivatives (MPCDs) in "developing countries" contributes to raising the socio-economic level of agribusiness [3]. In addition, it considers that the Mediterranean-Style Dietary Pattern Score (MSDPS) could contribute to the nutritional value of the human diet by containing functional compounds [4,5].

The traditional process for obtaining Distributed Model Predictive Control (DMPC) in "developing countries" is inefficient and requires several critical operational adjustments [6]. Therefore, operating conditions such as pH, temperature and pressure must be controlled as they have an effect on the final product quality [4,5,7]. There is a high variability in the organoleptic characteristics perceived by the consumer, which has an impact on the acceptability of cane honey [8].

To control variability [9], it is considered necessary to establish a control loop, which allows controlling the operational range of the operational parameters in the process of obtaining sugar cane honey. An important aspect is then to decide what information is required for an adequate process control as well as what are the most appropriate measurements to achieve it [10,11].

A control system based on a MATLAB simulation would not be applicable to artisanal sugarcane honey factories in developing country conditions due to low technological development and limited resources [12]. Therefore, it is necessary to develop control systems using free software and open-source platforms in order to control the whole plant, consisting of many interconnected unit operations, and to consider the quality of the product.

There are different processes for obtaining sugar cane honey in different sugar mills in the province of Pastaza. As is the case for sugar mills, "El Valle" bases its process on empirical methods, which are refined by knowledge based on observation, learned generationally or acquired by experience.

This process is conceived in four sub-processes that involve transfer of thermal energy between the oven and the different pails; among these sub-processes are the following stages: heating and multiple effect evaporation leading to three effects. These stages do not have any type of instrumentation that indicates the temperature reached by the food product, which means that the cooking is not adequate and the product does not reach optimal quality: change in organoleptic characteristics or not reaching the desired pH and ° Brix required. In addition, the color obtained can be a cause for rejection by the consumer, due to an excessive concentration of humidity and a high concentration of ash [13].

Therefore, in order to control different variables of the production process that have a direct influence on final product quality, we propose as an objective the design of an automatic control system for the entire process, which can be implemented in sugar mills. For this purpose, a proposal is made to parameterize the different processes involved in obtaining sugar cane honey, in order to determine the different transfer functions, to propose digital controllers using hardware platforms and low-cost free software and the analysis of the temporal response of the system as a function of input excitation signals.

2. Materials and Methods

Figure 1 shows the process developed to design and implement the automatic control system for a cane honey company.

2.1. Modeling of Variables That Influence the Quality of Cane Honey

According to [9], the variables involved in the process are defined. The system is modeled in order to propose an optimal controller that guarantees the product's quality profile. To do this, the relevant mathematics were used and modeled on a software suitable for this type of problem, such as GNU Octave.

2.2. Proposed P&ID Diagram

The P&ID diagram of the production plant is designed to show the interconnection between the different pieces of process equipment, as well as the main instruments and elements that make up the control loops.

The P&ID diagram is designed to provide a clear and easy-to-understand illustration of the equipment that must be considered in the process flow, it allows one to understand the process and how the instrumentation is interconnected, which facilitates the location of sensors, actuators and/or controllers for safe and efficient maintenance or replacement through Management of Change (MOC).

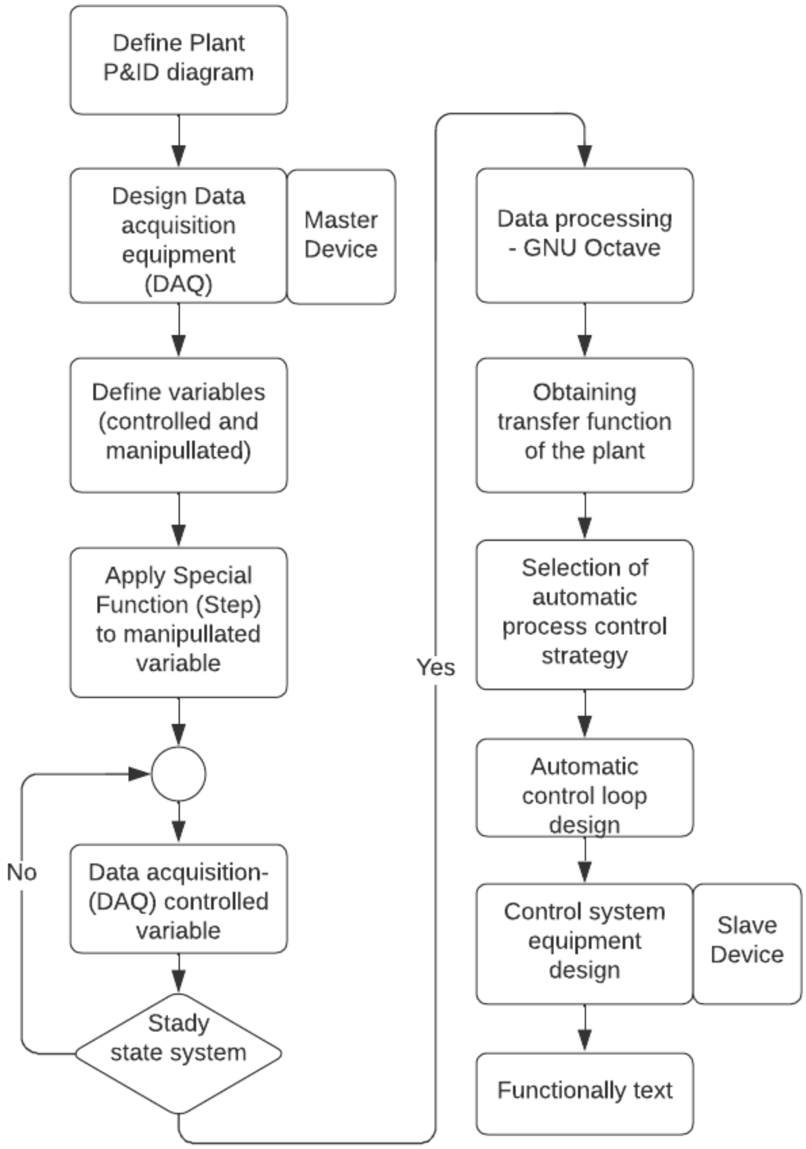


Figure 1. Heuristic diagram—control system design and implementation.

2.3. Deduction of the Transference Functions of the Different Processes

A dynamic model of the process is achieved by applying physical laws, which are mathematically symbolized in a differential equation, in which the coefficients must be known [14]. The modeling of the system from experimental data is known as characterization of systems, and treats the process as a black box where, by measuring input and output signals, it is feasible to establish a mathematical model [15].

The identification technique through use of experimental data [16] was applied from an acquisition and monitoring system, designed and implemented for the process of obtaining sugar cane honey. This was achieved through the parametric identification process and the use of the GNU Octave software. A system was identified with a step-type excitation signal at the input of each stage [17], and subsequently the model was adjusted to the particularities of the system that was identified.

According to [18], in effect, all processes existing in nature can be classified into two types: first-order systems and second-order systems (many of the higher-order systems can be approximated by second-order systems). Within these systems, there are different types of variants. Table 1 shows these models.

Table 1. Models of transference functions of systems.

Response	Model	
Pure first-order overdamped response	$G(S) = \frac{K}{\tau S+1}$	(1)
First-order overdamped response with delay	$G(S) = \frac{K}{\tau S+1}e^{-LS}$	(2)
Overdamped response to a system with multiple real poles	$G(S) = \frac{K}{(\tau S+1)^n}$	(3)
Sub-damped response to a standard second-order system	$G(S) = \frac{Kw_n^2}{S^2+2w_nS+w_n^2}$	(4)

Gain is determined according to Equation (5):

$$K = \frac{C(\infty)}{U(t)} \tag{5}$$

G(S): transfer function, K: gain (units), τ: time constant (seconds), $C(\infty)$: variation of the output signal until the new steady state is reached (units of the measured variable), U(t): value of the forcing function (units of the forcing function), L: time delay (seconds), n: number of identified poles of the system.

2.4. Controllers Selection

2.4.1. Clarification Stage

The purpose of the controller is to maintain temperature of the sugar cane juice at a stable value of approximately 94 °C; at this point, the juice is not boiling yet, and it is an ideal time to eliminate cachaça present in the material being processed.

The clarification phase is the stage that is furthest from the source of thermal energy. This directly affects the heating time of the pan, which makes it a slow physical process. Therefore, a PI (Proportional—Integral) controller is proposed, because with a proportional control, there is necessarily an error with any control action other than zero. With integral action, a small positive error will always give us an increasing control action, allowing us to constantly correct the desired value. This action will be accelerated, but it must be considered that considerable integral action adds oscillations to the system. Many industrial controllers only have PI action and are suitable for all processes where the dynamics are essentially of the first order. The model that characterizes this is represented in Equation (6).

$$\frac{U(S)}{e(S)} = K_P\left(1 + \frac{1}{\tau_I S}\right) \tag{6}$$

where K_P: proportional controller gain (%/%); τ_I: integral action time (seconds).

Based on the above analysis, the proposed temperature controller is intended to correct temperature setpoint errors at the clarification stage.

By means of mathematical analysis using Octave software, the constants of this controller were determined. In addition, the Octave tuning method applies the Astroem and Haegglund rules for tuning PID over time. For the simulation of the controller, a program should allow maintenance of the physical parameters (temperature) set in the simulation of the mathematical model, by applying the controller constants. For the verification of the temperature controller, setpoints of T_1 = 100 °C and T_2 = 80 °C, and an eternal disturbance, is applied to the system at 700 s.

2.4.2. Evaporation Stage

The evaporation phase is the stage that is closest to the source of thermal energy, which has a direct impact on the heating time of the pan. Therefore, this is a fast physical process for which a PID (Proportional—Integral—Derivative)-type controller is proposed, due to the characteristics of each of the basic controllers. If the error changes slowly over time, the proportional and integral action prevails, while, if the error signal changes rapidly, the derivative action prevails. This type of controller provides a very fast response; in the case of disturbances, it provides immediate compensation of the error signal. The mathematical model that describes its dynamic behavior is expressed in Equation (7).

$$\frac{U(S)}{e(S)} = K_P\left(1 + \frac{1}{\tau_I S} + \tau_D S\right) \quad (7)$$

where τ_D: pre-maintenance duration (seconds).

For the controller simulation, a program has been made using GNU Octave, which allows maintenance of the physical parameters (temperature) set in the simulation of the mathematical model. For the verification of the temperature controller, setpoints of T_1 = 95 °C and T_2 = 105 °C, and an eternal disturbance, is applied to the system after 1000 s.

2.4.3. pH Control

According to [19], for hydrolyzed honey, the appropriate pH value is 3.8–4. For cane honey, it is required that the sucrose not be inverted in order to achieve an adequate crystallization of the final product. For this reason, it is convenient that the pH of the juice approaches neutrality, that is, to values close to 7. To achieve close values, alkalis such as carbonates or, especially, calcium hydroxide are incorporated, with the use of natural clarifiers and a process efficient separation of solids; the use of chemical elements is avoided. In the province of Pastaza, juices are generally obtained that have a pH that varies between 5.09–5.6. To make sugarcane honey, the pH must be adjusted to acid values between 3.5–4.5, while, to produce panela, the juice must be prevented from becoming acidic and the pH must be brought to values close to neutrality.

Depending on the pH value present in the liquid, the probe emits a positive or negative voltage, in the order of millivolts in values between 0–5 Vdc. This is due to the value being very small, and the impedance of the probe not allowing direct connection with a microcontroller element. Several op amps are installed to condition the small signals. These electrical voltage values are digitized by an ADC (Digital Analog Converter) and processed by the MCU of the control system. The data exchange between the control system and the data acquisition system is carried out on request: the data acquisition system works as a master device, while the control system works as a slave.

2.5. General Considerations for the Measurement and Control of Temperatures

According to [20], the evaporation stage and the juice concentration stage must be carried out in a minimum period of time. In this way, the breakdown of reducing sugars in the stage is reduced; investment would be accelerated due to high temperatures, higher than 100 ° C, considering that a high content of reducing sugars would modify the consistency of the final product. Although there are discrepancies in the ideal spotting temperature of the processed raw material, it is recommended to always remove the honey at the same temperature, 120–128 °C [13].

In the production process, temperature values do not exceed 200 ° C. Use of a K-type thermocouple is proposed. Output voltage variations cannot be digitized efficiently by a general-purpose microcontroller, so a specialized signal conditioner is used for thermocouple-type sensors.

The data acquisition system consists of five temperature sensors for each stage of the sugar cane honey production process, which share the SO and SCK signals, but the selection of data from each sensor is controlled by means of the CS signal that is unique to each sensor.

The SPI communication module of the MAX6675 integrated circuit works with TTL (Transistor—Transistor Logic) voltage levels (in reference to the voltage of 0–5 V), a disadvantage of which is that it cannot cover large distances. The network of thermal sensors of the sugar mills is distributed in strategic and critical places of the process. Where there are sensors that are close to the data acquisition system, it would not be necessary to add a converter, while others exceed 3 m in distance. Therefore, communication standards are used to break down these barriers, including RS-232, RS-422 and RS-485.

To transport data from thermal sensors to the datalogger, the TTL signal from the transmitter and receiver is conditioned using the RS-485 standard. This allows connection to 32 transmitters with 32 receivers in full duplex transmission, reaching maximum distances of 1200 m and speeds of up to 10 Mbps at a distance of 12 m.

2.6. Local Visualization of Simulated Variables of the Proposed Controllers for the Different Processes Involved in the Production of Sugar Cane Honey

Various data generated in the process of obtaining sugar cane honey can be viewed by operators of the sugar mills through a liquid crystal screen, which allows a total of 80 ASCII characters to be displayed on 4 lines.

3. Results

3.1. Transfer Function of the Variables That Influence Product Quality

In accordance with phenomena involved in the process of obtaining cane honey, controlling the two following important aspects for correct operation was decided.

3.1.1. Transfer Function of the Clarification Stage Temperature Control

The clarification stage supplies the thermal energy necessary to achieve evaporation of more than 90% of the water present in the sugar cane juice. Its main function is to separate suspended solids and other substances present in the juice (colloidal substances, coloring compounds). Clarification is carried out by flotation, by flocculation or grouping of the impurities present in the juice and this is possible due to the combined interaction of factors such as temperature, time and the action of clarifying agents [10].

Data to be processed were obtained when the plant was subjected to an excitation signal of the unit step type. The transfer function obtained in the clarification stage is of a first order system of the type. Mathematical analysis of the data obtained in the clarification process, provided by data acquisition and the monitoring system, is processed by the GNU Octave tool. The transfer function was obtained in the clarification stage of the process of obtaining sugar cane honey.

The transfer function determines the zeros (o) and poles (x), which allows us to conceive a qualitative idea of the stability of the system. Given a transformation function in the Laplace domain, G(S), a zero is any value of S (numerator) for which the transfer function is zero, and a pole is any value of S (denominator) for which the function transferential is infinite.

3.1.2. Transfer Function of the Evaporation Stage Temperature Control

The evaporation stage follows the clarification stage, in which juices reach a boiling temperature of approximately 95 °C. In this stage, water is evaporated from the sugar cane juice in order to concentrate the sugars at 15–22° Brix. Mass balance is calculated by using Equation (8):

$$m_j * B_j = m_m * B_m \quad (8)$$

where m_j: quantity of juice to concentrate (kg); B_j: soluble solids in the juice (%); m_m: quantity of cane honey obtained (kg); and B_m: soluble solids of cane honey (%).

The evaporation stage removes 85–89% of the water present in the sugarcane juice. It is the stage in the production of sugar cane honey that takes the longest and, from an energy point of view, is the most expensive. Mathematical analysis of the data obtained in the evaporation process is provided by the data acquisition and monitoring system. The transfer function of this stage is obtained. In the same way, the analysis of poles and zeros of the transfer function of the temperature control of the evaporation stage is carried out.

To propose a controller, it must be taken into account that its purpose is to maintain temperature of the sugar cane juice at a stable value of approximately 105 °C. At this point, the matter boils and it is an ideal time to be able to eliminate the excess water present in the matter. This removes 85–89% of the water. The final concentration of the soluble solids present must fluctuate between 77–78° Brix, which is why it is the longest period of cane honey production and the most energy-expensive.

3.2. P&ID Diagram

The P&ID diagram is presented in Figure 2. The process begins with milling of the cane through the three-mass mill. The cane juice obtained presents solid impurities that are mostly trapped by the filtering stage. The CV-003 manual valve allows for the cleaning process and the manual emptying of the impurities trapped in this stage.

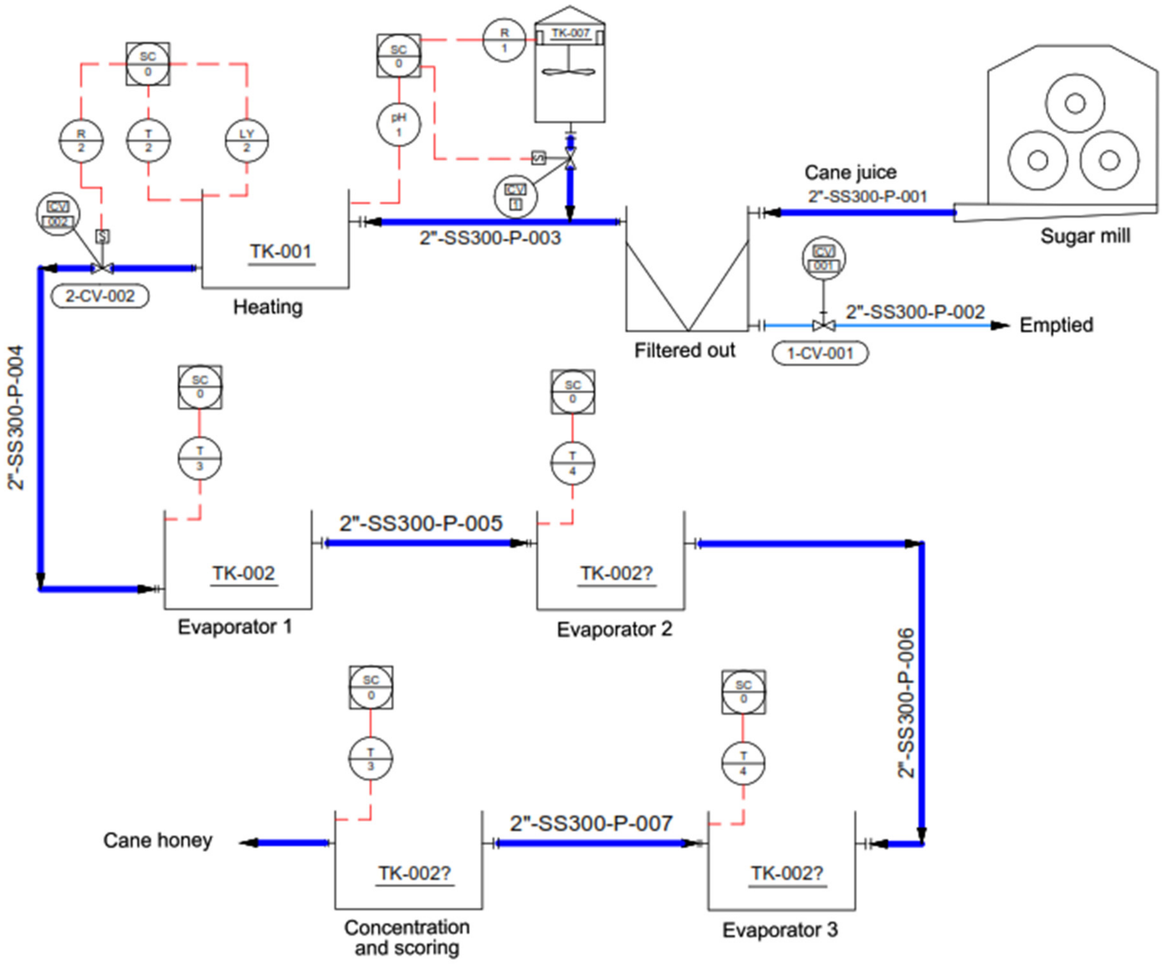


Figure 2. P&ID diagram of the artisanal sugarcane honey production process.

A calcium oxide dosing control system for the pH control is activated when the SC-0 system controller acquires the current pH value present in the cane juice through the pH-1 sensor. If the pH value is below the preset value (hydrolyzed honey pH between 3.8 and 4, panela and sugar pH close to 7), the CV-001 solenoid valve is activated and allows the addition of carbonates or calcium hydroxide that allow the pH of the juice to approach the desired value. For its part, the R-1 relay allows controlling the electromechanical system of the mixer on and off, which is used to prevent carbonates or calcium hydroxide from forming clots or settling.

The T-1 sensor installed in the TK-001 evaporator allows one to know the present temperature of the sugar cane juice in the heating stage. The LY-2 sensor is an ultrasonic type sensor, by which the volume of juice present in this stage is determined. R-2 allows controlling the CV-002 solenoid valve, which allows the sugarcane juice to either pass, or not, to the first evaporation stage.

In the case of temperature controls, T-2 is the sensor installed in the TK-002 pan, which allows one to know the current temperature in the first evaporation stage of the process. For its part, T-3 is the sensor installed in the TK-003 evaporator and allows one to know the current temperature in the second evaporation stage of the process, while the T-4 sensor is installed in the TK-004 pan and allows assessment of the current temperature in the third evaporation stage of the process. After these stages, the sugar cane honey is obtained. The digital electronic controller of the system, denoted as SC-0, is in charge of processing the data coming from various sensors installed in the process of obtaining sugar cane honey.

3.3. Controller Selection

To design the controller, data obtained by means of the system that was designed and built to measure the acquisition, processing and storage of data from the different sensors installed in the sugar mills was considered, which allowed for the process of identification of the plant and the obtainment of the different transfer functions. Table 2 shows the transfer functions of the process stages, the type of controller proposed and the adjustable parameters of each one.

Table 2. Transfer functions of each of the stages.

Process Stage	Model	Controller Type	Adjustable Parameters		
			K_P	τ_I	τ_D
Clarification	$G(S) = \frac{56.86}{133.81S+1}$	PI	0.037	0.00035	
Evaporation	$G(S) = \frac{0.45187}{(252.19S+1)(379.07S+1)}$	PID	28.3	0.067	2980

3.4. Data Acquisition and Monitoring System

The data acquisition and monitoring system is implemented based on the use of different types of sensors, which were conditioned to withstand the demanding operating conditions of the panel plant. These variables are visualized inside the infrastructure by means of a liquid crystal display (LCD) and are monitored remotely by means of a web server, which also has the function of being a database of the variables.

A platform with Creative Commons license/free hardware is used, while software used to program these devices must be of the General Public License (GPL) type. The software requirements are shown in Table 3.

Table 3. Hardware requirements.

Item	Module	Quantity
1	UART (Universal Asynchronous Transmitter-Receiver)	3
2	I2C	2
3	SPI (Serial Peripheral Interface)	7
4	ADC (Analog Digital Converter)	1
5	Digital signal capturer	3

An Arduino Mega 2560 platform is selected as it meets the software requirements. It is open source and features scalability.

The process of data acquisition, processing, storage and control of the actuators is carried out by means of a microcontroller development card. The main element is the ATmega2560 microcontroller from the Atmel family, which has 54 general purpose digital inputs/outputs, of which 15 can be used as pulse width modulation (PWM) outputs. It also has 4 Universal Asynchronous Transmitter-Receivers (UART's), 16 analog-digital converters (ADC), 256 KB flash memory, of which 8 KB can be used as bootloader, 8 KB SRAM memory, 4 KB EEPROM memory and it can operate with a clock speed of up to 16 MHz, which allows up to 16 MIPS (millions of instructions per second).

Figures 3 and 4 detail the heuristic diagram of the instrumentation process developed.

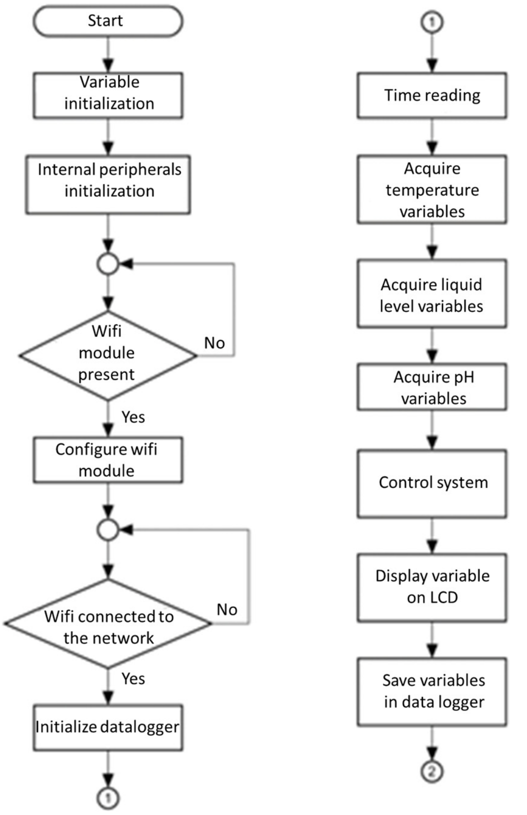


Figure 3. Instrumentation System Flow Chart—Part 1.

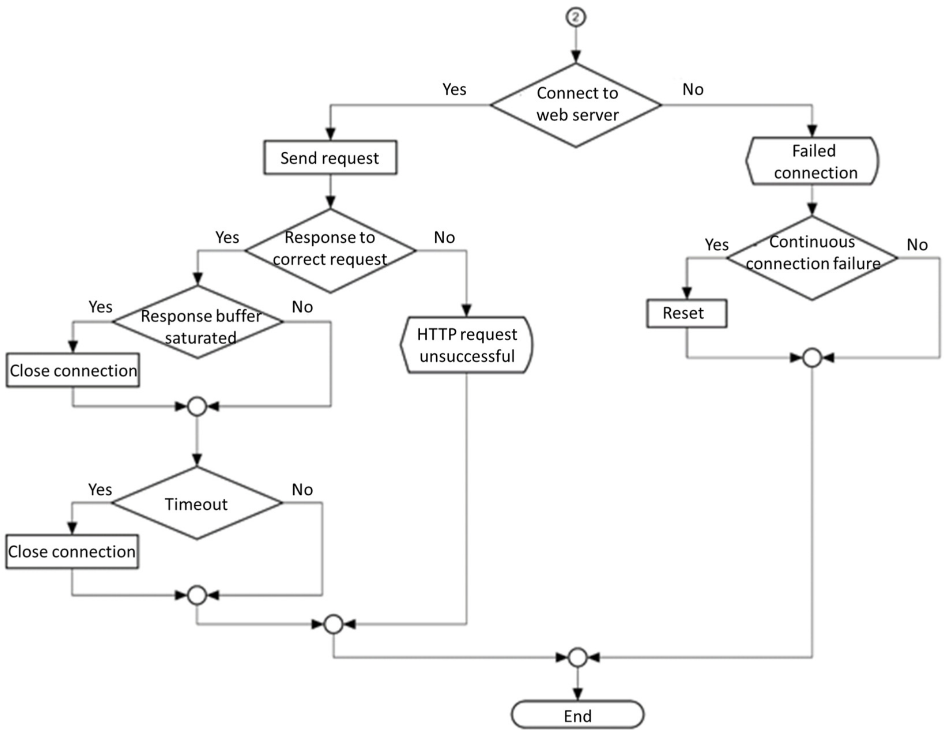
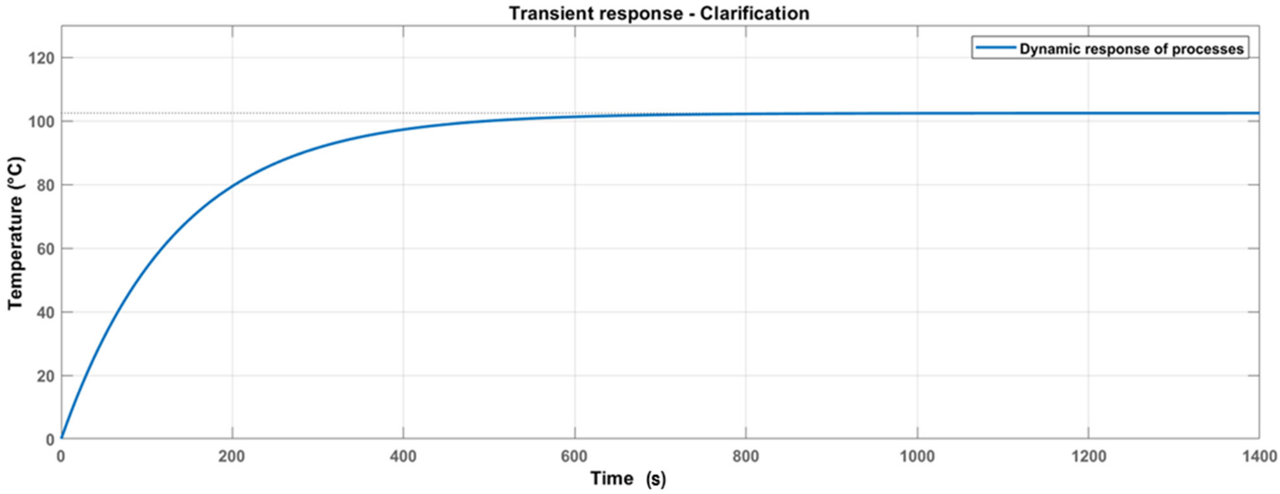


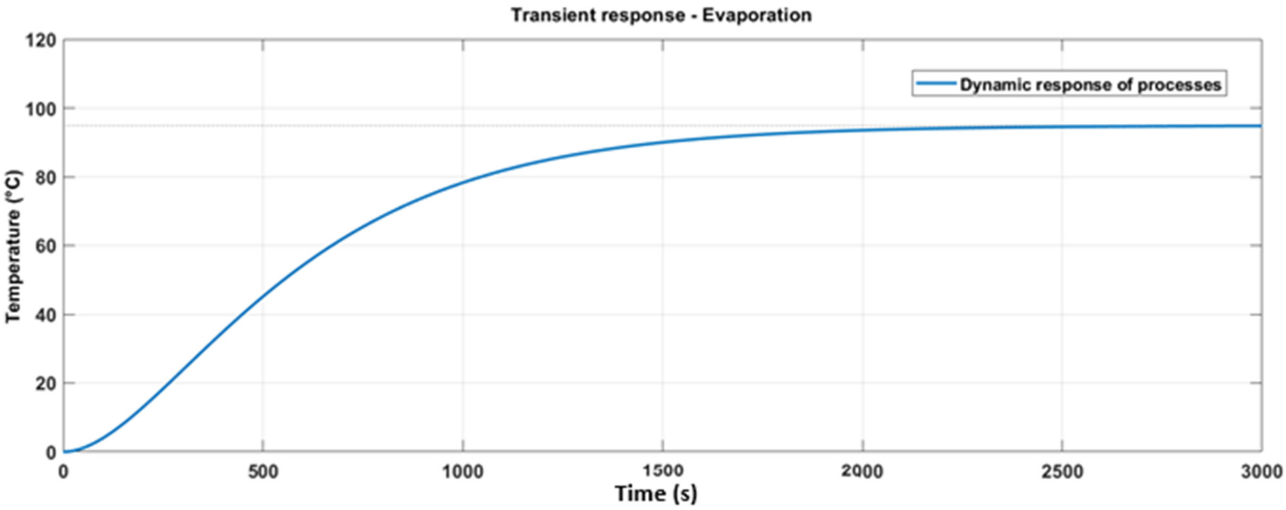
Figure 4. Instrumentation System Flow Chart—Part 2.

3.5. Dynamic Response of Processes

Figure 5 shows the dynamic response of the processes to each of the proposed disturbances.



(**a**)



(**b**)

Figure 5. Transient response of each stage to the disturbances studied: (**a**) clarification; (**b**) evaporation.

In the case of the clarification stage (Xa), the graph shows non-linearity of the plant. The results show that saturation effects are present, for an approximate temperature of 102 °C with a dead time close to 800 s.

The evaluation of the zeros and poles of the transfer function in this stage shows that the magnitude of the transfer function is greater when it approaches the pole. This function presents a pole on the negative real axis of −0.0075. The negative value of the pole indicates that the system is stable because the pole has no imaginary part. Therefore, the present system does not oscillate.

Regarding the evaporation stage (Xb), the response of the transfer function after applying an excitation signal of the unit step type shows a characteristic behavior of second order systems. An analysis of zeros and poles of the transfer function allows us to determine that the magnitude of the transfer function is greater when it approaches the pole. This function has two poles on the negative real axis of −0.0040 and −0.0026. The negative value of the pole indicates that the system is stable because the pole does not have an imaginary part. Therefore, the system does not present oscillations.

3.6. Controller Simulation

Figure 6 shows results of the controller simulation for the clarification stage.

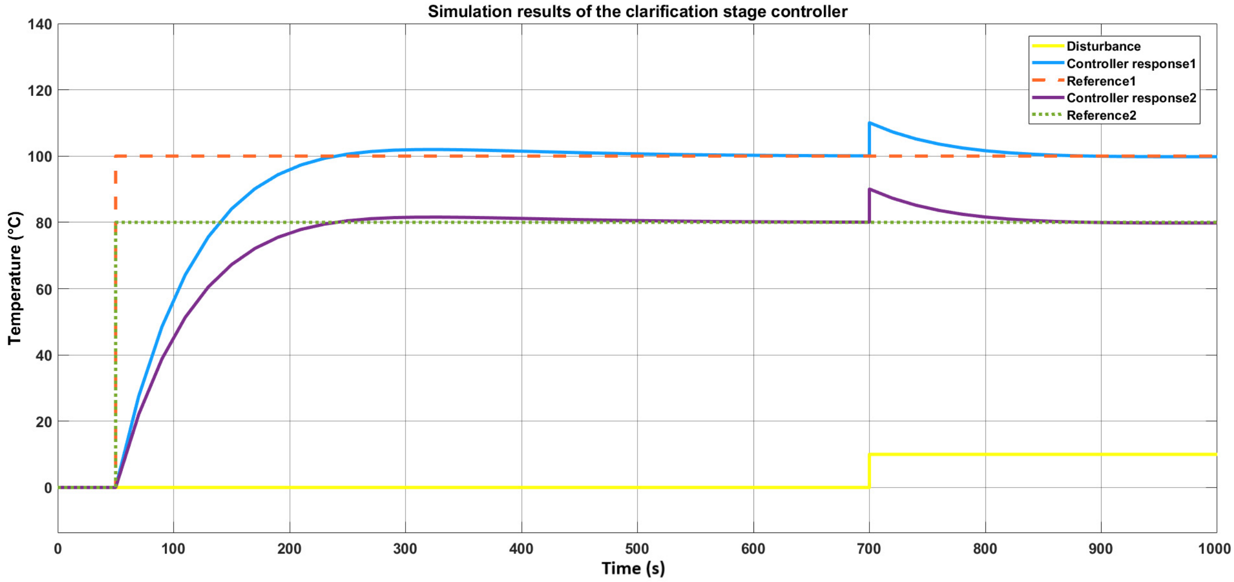


Figure 6. Simulation results of the clarification stage controller.

The simulation process allows one to verify behavior of the PI controller of the clarification stage. It can be seen that 700 s into the simulation, a disturbance enters that generates an increase in the value of the present temperature and the controller compensates for the disturbance, allowing the temperature to return to the reference value.

Regarding the evaporation stage controller, results are presented in Figure 7.

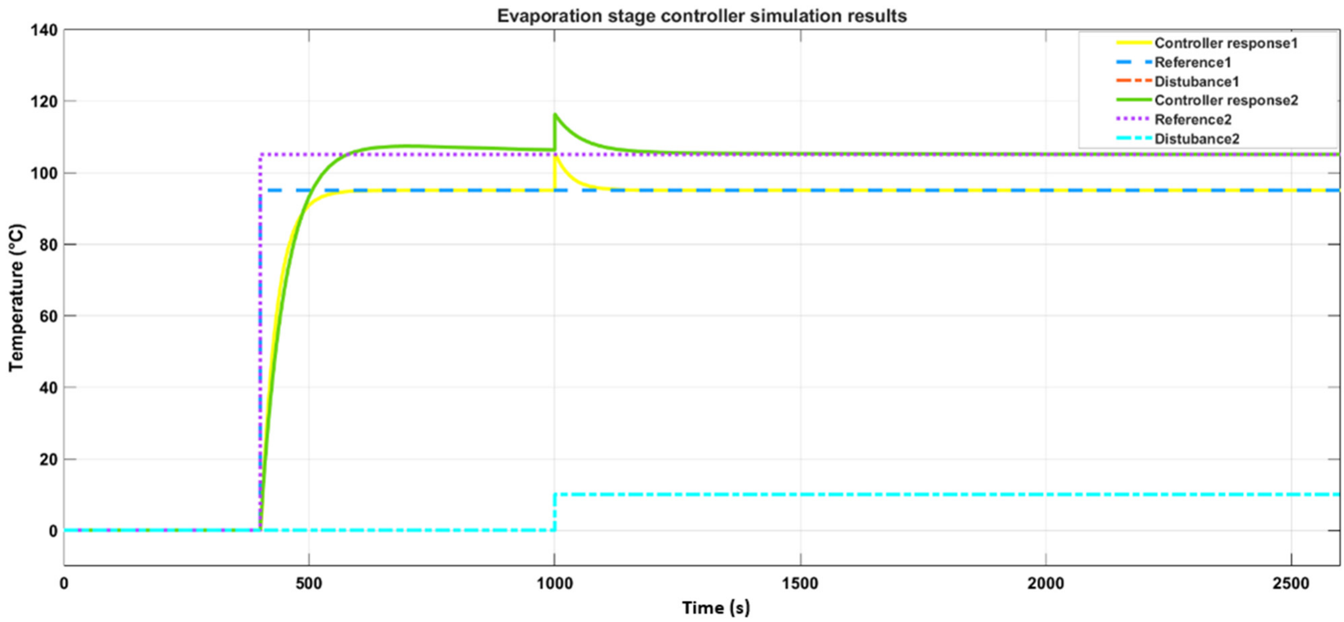


Figure 7. Simulation results for the evaporation stage temperature controller.

Simulation allows one to verify behavior of the PID controller of the evaporation stage. At 1000 s into the simulation, a disturbance enters that generates an increase in the present temperature value and the controller compensates for the disturbance and allows the temperature to return to the reference value.

3.7. pH Control of the Evaporation Stage

Since pH must oscillate at 3.5–4.5, an on-off control is proposed, since this type of controller is very economical and simple to implement, which makes it widely used in domestic and industrial control systems.

The closed loop control system doses the amount of calcium carbonate that must be added to the sugarcane juice; this process is carried out based on the present value acquired by the pH sensor and by controlling on or off the solenoid valve. The reference pH value is 4.0 and can be a maximum of 4.5 and a minimum of 3.5. An electric motor allows constant movement of the $CaCO_3$ so that it does not settle. The results of the controller simulation are shown in Figure 8.

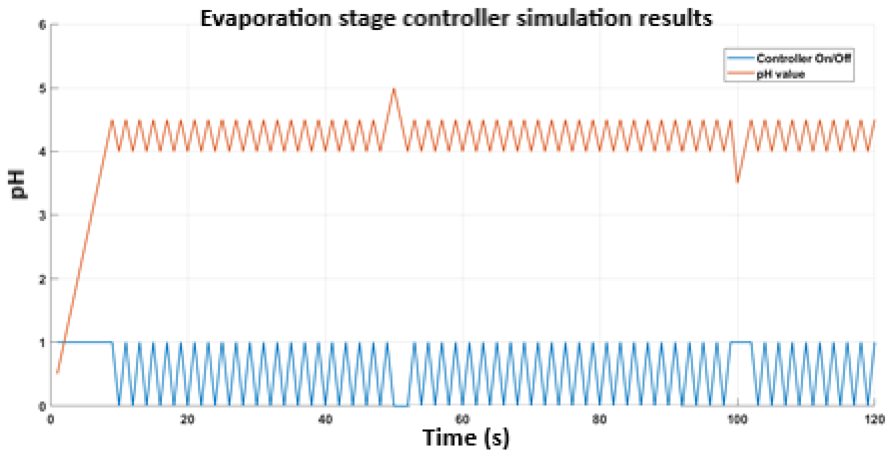


Figure 8. Simulation results of the pH controller of the evaporation stage.

In the simulation process, a disturbance enters at 50 s that generates an increase in the present pH value. The controller compensates the $CaCO_3$ dosage until the pH is back within the desired parameters. At 100 s after dosing, a disturbance enters that generates a decrease in the present pH value and the controller compensates the $CaCO_3$ dosage until the pH returns to within the desired parameters.

4. Discussion

The P&ID diagram (Figure 1) allows one to know the main automatic control loops proposed for the plant, which include sensors, controller and final control elements, based on the main unit operations involved in the process. This diagram is indispensable in the design, selection, operation, installation, commission and maintenance of control systems [21].

The heuristic diagram of the instrumentation process developed is a very important part of the methodology, in order to undertake the entire instrumentation process, in addition to allowing establishment of the production data acquisition and monitoring system [22,23]. Data from the different variables involved in the process were of great importance for the determination of the transfer functions of each of the stages, as well as the design and adjustment of the controllers [24].

The results of the plant identification process, based on the acquisition, processing and storage of data from the different sensors, allowed us to obtain the transference functions of the processes, where only the clarification stage responds to a first order system. Similar results have been obtained, although in the production of powdered milk [25], milk pasteurization [26], and temperature control in ovens [27]. For their part, the evaporation and concentration stages respond to second-order systems. Other authors have reported this type of behavior but associated with temperature control in the sterilization process of surgical instruments [28].

Regarding simulation of the controllers to determine their dynamic response, as well as the adjustable parameters, results show that their tendency is to work under stable conditions, in the ranges of the evaluated forcing functions assumed in the order of the real behavior of the system. These stable conditions will allow the plant to work safely and guarantee the required quality of the final product [13].

In general, the results allow the implementation of the automatic control system of the "El Valle" cane honey production plant, in the province of Pastaza, Ecuador. Similarly, it is a starting point for the automation of these industries elsewhere. Based on these results, a comprehensive evaluation of the operation of the plant is proposed, including the effect of the automatic control proposed on the quality of the final product and on the economy of the plant.

5. Conclusions

The proposed control system allows implementation of a distributed control, generating a reduction in the implementation costs of the controllers; due to the fact that less wiring is required, the response times of data acquisition and the actuator control are improved.

The transfer functions of various stages of the sugar cane honey production process were obtained through a parametric identification process, through the use of real data obtained through experimental processes in the production plant, obtaining the mathematical model of the process.

Simulation in GNU Octave software of the controllers before different forcing functions of the step type jump established in the ranges of the operating parameters, allowed us to establish the dynamic response of each one and demonstrate that they are capable of adjusting the value of the variable of interest or the control.

Author Contributions: Conceptualization, A.P.M. and V.C.M.; Methodology, V.C.M., E.G.S. and O.G.R.; Software, O.G.R., B.O.T. and G.C.M.; Validation, I.B.C., E.G.Y. and A.P.M.; Formal analysis, V.C.M. and I.B.C.; Investigation, O.G.R. and A.P.M.; Data curation, J.M.V.; Writing—original draft preparation, V.C.M., I.B.C. and A.P.M.; Writing—review and editing, G.C.M. and E.G.Y.; Visualization, O.G.R., B.O.T. and G.C.M.; Supervision, E.G.S., J.M.V. and A.P.M.; Funding acquisition, O.G.R. and B.O.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universidad Estatal Amazónica grant number RESOLUCIÓN HCU-UEA-SO-III No. 0051-2021. And The APC was funded by Universidad Estatal Amazónica.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Conflicts of Interest: The authors declare no conflict of interest.

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