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Design and implementation of a fuzzy control of temperature for a plastic aging chamber

Diseño e implementación de un control difuso de temperatura para una cámara de envejecimiento de plástico

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Abstract

Plastic is a versatile material found in virtually any type of product, however, due to its long-life cycle it has become an environmental problem. Therefore it is necessary to determine this cycle using an aging chamber, although previous research has already focused on this equipment, most implement ON-OFF or PID controllers, so it is proposed to design and implement a fuzzy controller using a microcontroller and Python, based on the ASTMD-4329 standard and simulating different sequences (sunrise, midday, sunset and night), In addition a preheating cycle is proposed, to verify the correct behavior the controller is compared with a simulation performed in Matlab giving a similarity of 96% for the sequence of half day to obtain this value is used the criterion of the Integral of time and Absolute Error (ITAE), finally all the sequences are implemented where the parameters established by the standard are met..

Fuzzy Control, Thermal Systems, ITAE criterion and Aging Chamber

Resumen

El plástico es un material versátil que se encuentra en prácticamente cualquier tipo de productos, sin embargo, por su amplio ciclo útil de vida se ha convertido en un problema ambiental. Por lo que es necesario determinar el este ciclo utilizando una cámara de envejecimiento, si bien investigaciones previas se han centrado ya en estos equipos, la mayoría implementan controladores ON-OFF o PID, por lo que se propone diseñar e implementar un controlador difuso utilizando un microcontrolador y Python, basado en la norma ASTMD-4329 y simulando diferentes secuencias (amanecer, medio día, atardecer y noche), además se propone un ciclo de precalentamiento, para verificar el correcto comportamiento se compara el controlador con una simulación realizada en Matlab dando una similitud del 96% para la secuencia del medio día para obtener este valor se utiliza el criterio de la Integral del tiempo y Error Absoluto (ITAE), finalmente se implementan todas las secuencias en donde se cumplen los parámetros establecidos por la norma.

Control difuso, Sistemas Térmicos, criterio ITAE y Cámara de Envejecimiento

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Introduction

Plastics are a set of materials artificially created from chemical reactions that use oil as the main raw material, this type of material is currently found in almost everything we occupy in our daily life, offering qualities and characteristics so competitive that they are suitable as essential components in clothing, technological components and food and beverage containers (Fernández & Jiménez, 2017). Due to this wide versatility, in 2019 according to data from the Plastics Europe association, the production of plastics reached 368 million tons, with the Asian continent being the main producer in the world (51%), in this region China is the country responsible for 31 % of world production, while in the American continent Canada, the United States and Mexico contribute 19% and the rest of Latin America only 4% (Plastics Europe, 2020). This production increases exponentially every year and given its long life cycle, most of the plastic can still be found in the environment, it is estimated that about 7.8 billion tons have been produced, which would mean the presence of one ton of plastic for each person in the world (Buteler, 2019).

Due to the great supply and demand of plastic, leaders of several countries have chosen to create agreements to correctly manage the life cycle of plastics worldwide, an example of this has been the fourth UN environmental assembly held in Nairobi Kenya, with the participation of more than 200 countries that have committed to reducing the use of plastics by 2030 (IISD, 2019).

However, agreements and laws are not enough, the development of new processes and technologies is a path that must be studied, for this reason, from the scientific and technological approach, various areas of science join in the search for new technologies for understanding of how certain environmental factors contribute to the degradation of plastic and not only that, today they focus on artificially simulating the environment in which the plastic will be exposed in order to accelerate its aging and guarantee the useful life of the material. To achieve a rapid degradation of the plastic material, aging chambers are commonly used where some of the physical variables such as temperature, humidity and ultraviolet radiation can be manipulated (Cai *et al.*, 2018; Celestine *et al.*, 2020; Chamas *et al.*, 2020; Vohlídal, 2021).

Currently, research seeks to adequately control physical variables to optimize aging processes, so this article shows the process to control and optimize temperature using fuzzy control, where it is not necessary to know how the temperature behaves within a aging chamber.

Fuzzy control is based on the concept of fuzzy sets which lays the foundations of fuzzy logic. This method was proposed by the mathematician Lofti Ali Asker Zade at the University of California in an attempt to formalize or mechanize two human capacities. It seeks in the first place to generalize the ability to converse, reason and make rational decisions about imprecision, uncertainty, incomplete information, contradictory information, partiality of truth and partiality of possibility in an environment of imperfect information, secondly, it seeks be able to perform a wide variety of physical and mental tasks without measurements or calculations (Siddique, 2014).

For the part of the works related to aging chambers Orozco, (2010) carried out the design and construction of an aging chamber accelerated by temperature for polymers, this team worked in a temperature range of 100 to 50 ° C, additionally in the The design considered the interaction of construction materials with temperature and the ASTM E-95-1990 standard, five years later Uribe et al. (2015) made a design in which I modify the kp and ki values of a PI controller in an environment chamber by means of a fuzzy controller from the error and the derivative of the error that increases the robustness and efficiency of a control system of temperature to achieve this objective used MATLAB for the generation of the fuzzy control and the implementation was carried out with LabVIEW, while Ruiz (2016) implemented an ON-OFF controller in aging chambers from the construction materials, using LabVIEW and a data acquisition board.

Ezike *et al.* (2018) developed a low-cost controlled temperature chamber for testing materials where he used Arduino and an ON-OFF controller to control the temperature in the chamber.

In that same year Muñoz (2018) designed a climate-controlled chamber with the ability to recreate temperatures between 2 and 5°C and a relative humidity between 50% and 98% to perform quality and energy efficiency tests on refrigerators, in this design I use a programmable logic controller that is connected to the internet to be able to monitor the temperature behavior across the network, just one year later Bahena (2019) carries out the design and manufacture of an accelerated aging chamber for plastics using an Arduino microcontroller and an ON-OFF controller to control temperature, ultraviolet light and humidity all in accordance with the ASTM D-4329 standard.

According to the history of work on the development of aging chambers, it is observed that the temperature controller is designed based on the construction materials, and using an ON-OFF controller, even when designing the diffuse controller they are based on MATLAB and for its implementation in Labview, so it is proposed to design and implement a Mamdami fuzzy temperature controller that is capable of adapting to the temperature control of an aging chamber without the need to know the construction materials, using a microcontroller and Python.

Method

An accelerated aging chamber consists of a thermally insulated container of stainless steel sheets, in the central part are the test tubes that are the material to be aged and at the ends there are two infrared lights with the purpose of increasing the temperature in the container, In addition, there is a temperature sensor in order to monitor and control the temperature as shown in Figure 1. Therefore, the operating parameters of the aging chamber and the temperature to work in the fuzzy controller must be determined.

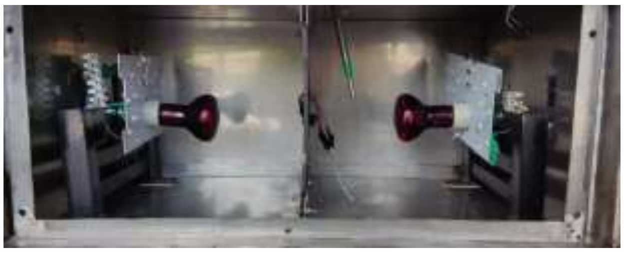

Figure 1 Plastic aging chamber with two infrared luminaires
Source: Self Made

To control the temperature, the ASTM D-4329 standard is used, which establishes a complete aging cycle consisting of 12 hours, on the other hand, Bahena proposes dividing a cycle into microcycles which is divided into 4 sequences with different: cycles of ignition of the lamps, temperatures and minutes of operation (Bahena, 2019), as shown in Table 1.

Sequence	Temperature	Weather	L1	L2
Dawn	60±3 ℃	20 min.	On	Off
Midday	60±3 ℃	20 min.	On	On
Sunset	60±3 ℃	20 min.	Off	On
To become night	50±3 ℃.	30 min.	Off	Off

Table 1 Characteristics of a chamber cycle
Source: Own Elaboration

In addition to the proposed microcycles, a preheating sequence is integrated into the first aging cycle, where the half-day sequence is activated, which lasts 40 minutes.

On the part of the fuzzy controller, it is divided into four main parts: fuzzification, knowledge base, decision logic (inferences) and defuzzification as shown in Figure 2.

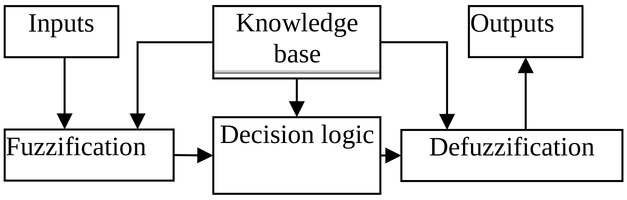

Figure 2 Structure of a fuzzy controller
Source: (Ponce, 2010)

Fuzzification converts the input data (numerical values) into linguistic variables in order to classify the input variable into fuzzy sets within the universe of discourse (Castaño et al., 2013), the input data correspond to the error and the derivative of the error, the linguistic variables determine the sets composed of each membership function defined by the expert for this investigation, the triangular function is used as shown in Figure 3, Eq. (1) (Singh & Lone, 2020) and they are used 7 linguistic variables as shown in Table 2.

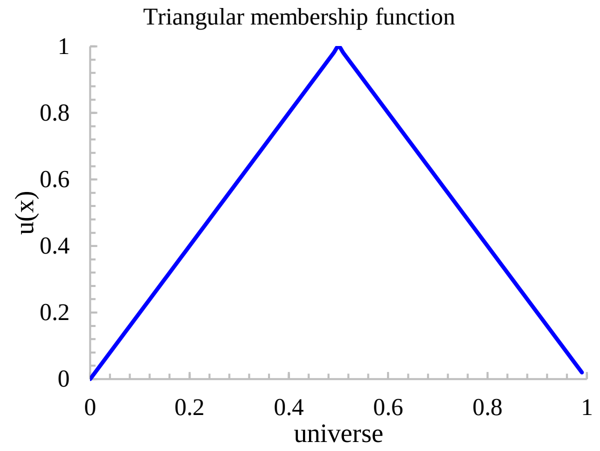

Figure 3 Triangular membership function
Source: Own Elaboration

$$f(x;a,b,c)=\max\left(\min\left(\frac{x-a}{b-a},\frac{c-x}{c-b}\right),0\right) \quad (1)$$

Where:
a is the lower limit
b is the center
c is the upper limit
x is the numeric value of the fuzzy controller input or output.

Error	Derived from the error	Output	Definition
eNG	deNG	uNG	Negative Large
eNM	deNM	uNM	Medium Negative
eNP	deNP	uNP	Small negative
eZ	deZ	uZ	Zero
ePP	dePP	uPP	Small Positive
ePM	dePM	uPM	Positive Medium
ePG	dePG	uPG	Positive Large

Table 2 Linguistic variables of the fuzzy controller
Source: (Castaño et al., 2013; Ponce, 2010)

The knowledge base contains all the information of the application to be controlled, as well as the goals of the controller, it consists of a database and a linguistic rule base to control the variable where the data provides the definitions for the establishment of rules and the manipulation of fuzzy data, on the part of the rules express the experience of the expert in a process of a combination of premises and consequents are carried out using prepositions for this case the prepositions “IF Input 1 and Input 2 Then Consequence ”. From the aforementioned, the inference matrix is generated as shown in Table 3 and using Eq. (2) for this case, Rule 1 (R1) is used as an example.

	deNG	deNM	deNP	deZ	dePP	dePM	dePG
eNG	R1	R2	R3	R4	R5	R6	R7
eNM	R8	R9	R10	R11	R12	R13	R14
eNP	R15	R16	R17	R18	R19	R20	R21
eZ	R22	R23	R24	R25	R26	R27	R28
ePP	R29	R30	R31	R32	R33	R34	R35
ePM	R36	R37	R38	R39	R40	R41	R42
ePG	R43	R44	R45	R46	R47	R48	R49

Table 3 Inference matrix
Source: Self Made

If Input 1 and Input 2 then
R1= min (Input 1, Input 2) (2)

The decision logic is in charge of determining which rules of the knowledge base have been activated in the operation of the control and in turn a membership value is assigned to the output, obtaining the degree of truth or weight of each of the rules It is being activated so it depends on the Fuzzy Association Matrix (FAM) rules as shown in Table 4.

	deNG	deNM	deNP	deZ	dePP	dePM	dePG
eNG	uNG	uNG	uNG	uNG	uNM	uNP	uZ
eNM	uNG	uNG	uNG	uNM	uNP	uZ	uPP
eNP	uNG	uNG	uNM	uNP	uZ	uPP	uPM
eZ	uNG	uNM	uNP	uZ	uPP	uPM	uPG
ePP	uNM	uNP	uZ	uPP	uPM	uPG	uPG
ePM	uNP	uZ	uPP	uPM	uPG	uPG	uPG
ePG	uZ	uPP	uPM	uPG	UPG	uPG	uPG

Table 4 Fuzzy Association Matrix (FAM)
Source: (Castaño et al., 2013; Ponce, 2010)

From Table 3 and 4 we proceed to obtain the aggregation stage that represents the union of the activated fuzzy rules, so the max implication is used. As shown in Eq. (3), this equation shows the implication process of the uNG output, this must be done for each of the fuzzy sets of the output.

uNG=max(R1,R2,R3,R4,R8,R9,
R10, R15, R16,R22) (3)

Defuzzification is the process that converts the results obtained through the inference mechanism to a signal that can be interpreted by an actuator. To calculate this output, the centroid method for discrete values is used, which is defined in Eq. (4).

$$z^{*}=\frac{\sum_{i=1}^{n} A_i * x_i}{\sum_{i=1}^{n} A_i} \quad (4)$$

Where Ai represents the subareas of the centroid and xi represents the centroid (Singh & Lone, 2020). Finally, the fuzzy controller is shown in Figure 4 where the setpoint is the desired temperature r (t), the error is the difference from the reference and the process output y (t), the controller output must be integrated to enter the process u (t), finally the system must be in closed loop.

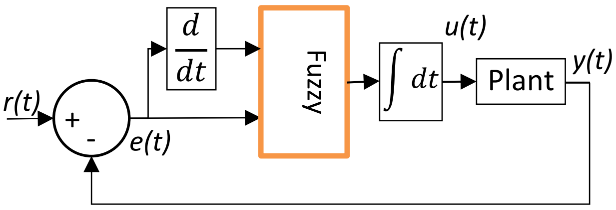

Figure 3 Fuzzy controller in block diagram
Source: Self Made

To obtain the error that is going to enter the controller, it must be considered when the controller reference is 60 ° C and the temperature inside the aging chamber is ambient temperature, for this case 0 ° C is taken as ambient temperature, therefore that the error is 60 ° C, otherwise the error is -60 ° C. Regarding the derivative of the error, it is necessary to know how the temperature behaves inside the aging chamber.

For this case, the noon sequence is used as shown in Fig. 5 where the microcontroller is in charge of sending a signal to the actuator that transforms electrical energy into heat by means of the luminaires, the change in temperature inside the aging chamber is measured by a temperature sensor that is connected to a 16-bit resolution analog-digital converter with a time of 4-second sampling, which is in charge of discretizing the analog to digital signal, the result obtained is sent to the microcontroller by I2C communication and finally the data is stored in the computer to determine the derivative of the error.

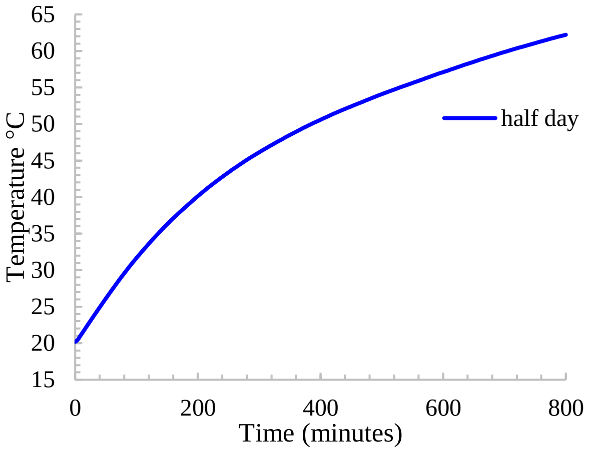

Figure 4 Temperature response in the aging chamber
Source: Self Made

The data obtained is shown in Table 5 and the temperature behavior is shown in Figure 6 where the derivative of the error is the difference between the current error and the previous error between the sampling time, so the maximum value of the derived from the error is 0.1277 from this value it is determined to work in a range of -0.2 to 0.2, for the output part u (t) is the resolution of the PWM controller that goes from 0 to 255 bits where the value of The integral can be defined as u (t) + u (t) above, so u (t) has to be a proportional part of the PWM for this work, the range of -35 to 35 was chosen (Castaño et al., 2013).

Weather	Temperature ° C
0	20.185
4	20.4453
8	20.9481
12	21.4441
….	…..
796	62.1191
800	62.2125

Table 5 Obtaining the data of the derivative of the error
Source: self made

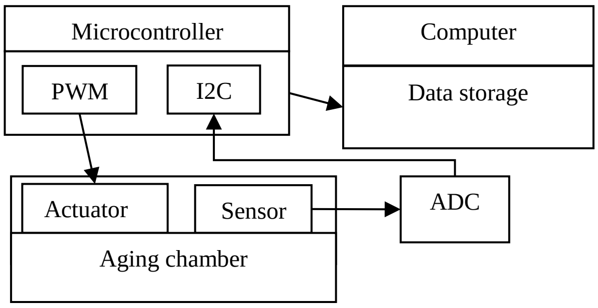

Figure 5 Block diagram to obtain the derivative of the error
Source: Self Made

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With the data obtained, the transfer function of the aging chamber can be obtained using Matlab in order to compare the result obtained from the fuzzy controller with a simulation carried out in Simulink, the result obtained is shown in Eq. (5).

$$\frac{0.2625}{379.12s+1} \qquad (5)$$

For the part of the simulation in Matlab, the Fuzzy toolbox is executed where the fuzzy controller is designed, where the first step is to add the control signals and the output as shown in Figure 7.

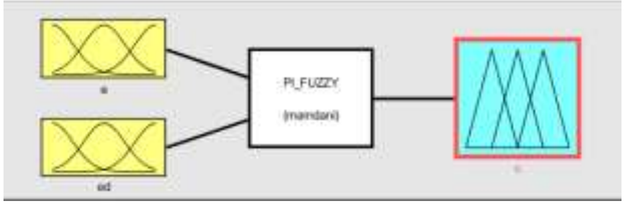
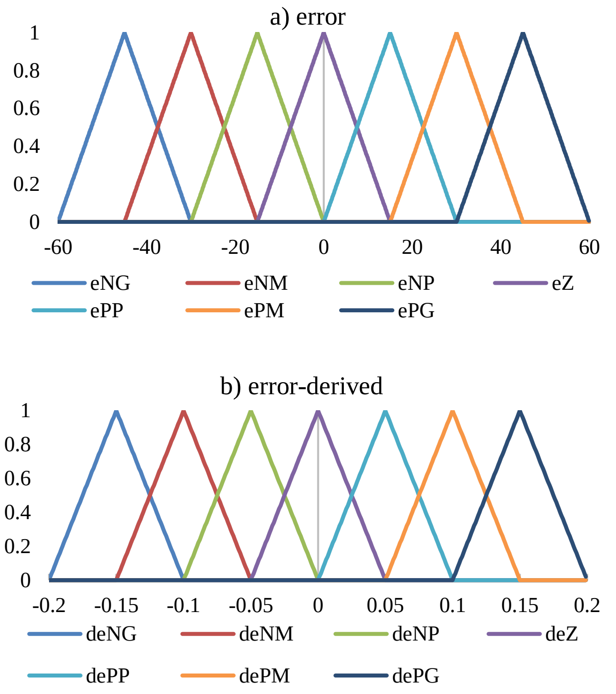


Figure 6 Fuzzy controller in Matlab
Source: Self Made

Subsequently, the linguistic variables are added to the inputs and the output shown in Table 2. In the case of all the input and output variables, a triangular membership function is used that have the same spacing depending on the domain established for the case of the error is from -60 to 60, for the derivative of the error is from -0.2 to 0.2 and u is from -35 to 35, as shown in Figure 8.



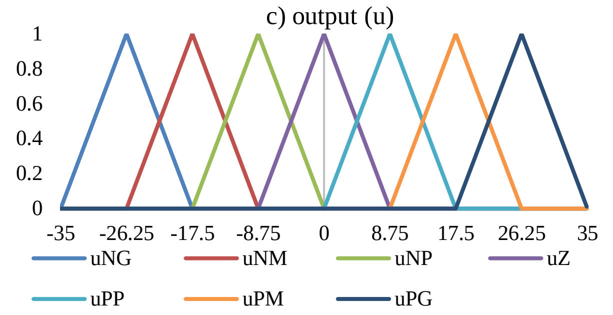


Figure 7 Integration of membership functions a) error, b) derived from error, c) u with their respective linguistic variables
Source: Self Made

The rules governing the fuzzy controller are added (Table 3 and 4). Finally, the series of steps that must be developed for the implementation of the fuzzy controller in Python is added.

1. Fuzzify the input by applying Eq. 1.
2. Obtain the value of each of the rules by means of Eq. 2, Table 3 and 4
3. Apply the aggregation method applying Eq. 3
4. Defuzzify by applying Eq. 4

Once the fuzzy control implementation steps have been completed, we proceed to obtain the controller results.

Results

To check the operation of the fuzzy controller, a simulation is performed using Matlab's Simulink, in which the fuzzy controller is exported as shown in Figure 9, where the fuzzy controller is simulated for the preheating cycle by the process part is The transfer function obtained by Eq. 5, in the case of the fuzzy controller implemented in the aging chamber is shown in Figure 9.

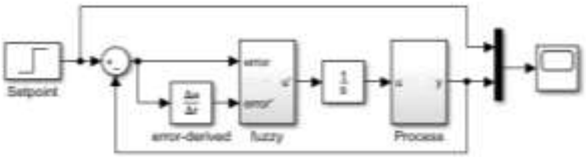


Figure 8 Simulator of a fuzzy controller in Matlab
Source: Self Made

The simulation is compared in a time of 0 to 30 minutes for the noon sequence with a setpoint of 60 ° C and the fuzzy controller with a sampling time of 4 seconds.

The results obtained are shown in Figure 10 where it presents a similarity of 96% this result was obtained by the Integral of Time and Absolute Error (ITAE) (Arrieta & Alfaro, 2011) which is described in Eq. 6.

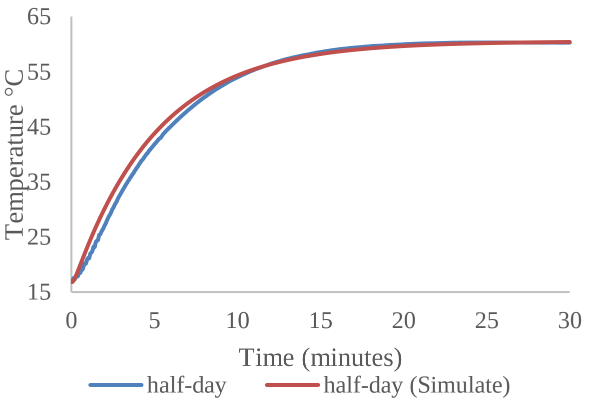


Figure 9 comparison of real and simulated fuzzy controller
Source: Self Made

$$\text{ITAE}=\int_0^{\infty} t|e(t)|dt=\sum_{k=0}^{n} t_k * |e_k| * \Delta x \qquad (5)$$

$$Similarity = \frac{ITAE\ simulated}{ITAE\ real} * 100\%$$

Where:

- tk is the time occurred at the sampling instant
- | e_k | is the absolute value of the error.
- Δx is the sampling time.
  - ITAE simulated is the error obtained in the Matlab simulation
  - ITAE real is the error obtained in the aging chamber

Finally, a microcycle described in Table 1 is carried out plus the preheating time as shown in Figure 11, for the preheating part (0 to 40 minutes) the temperature is set at approximately 15 minutes with a maximum value from 60.33 ° C, the sunrise sequence (40 to 60 minutes) the temperature decreases to a minimum value of 57.22 ° C, the half-day sequence (60 to 80 minutes) reaches a maximum peak of 62.83 ° C, the sunset sequence (80 at 100 minutes) has a minimum value of 59.29 ° C, lastly the nightfall sequence (100-130 minutes) maintains the temperature at 49.78 ° C, so it can be observed that the microcycles meet the parameters established by the ASTMD-4329 standard.

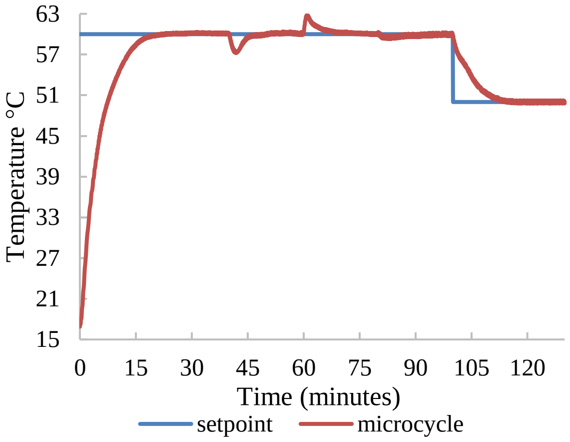


Figure 10 Result of preheating and microcycles of the aging chamber with diffuse control
Source: Self Made

Conclusions and future work

This research work shows that it is feasible to control the temperature using a fuzzy controller without knowing the mathematical model of how the temperature behaves internally in the aging chamber. However, it is important to bear in mind that to obtain satisfactory results it depends entirely on the expert and his knowledge in the process, for example, it is necessary to know how the temperature changes during the process, the input signals that will be input to the controller and their respective outputs, the membership function that best adapts to the process, the number of linguistic variables that will be used, the more linguistic variables are handled in the fuzzy controller, the rules in the knowledge base will increase, finally once the This controller can be implemented in other processes that need to control the temperature or another physical variable. For future work, the fuzzy controller will be optimized using genetic algorithms.

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