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Dynamics of a plastic aging chamber with PI temperature control

Dinámica de una cámara de envejecimiento de plástico con control de temperatura PI

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Abstract

Plastic pollution has become a global environmental problem, as rapidly increasing production of plastic products, increased international measures are being taken to reduce the problem. This paper aims to present the dynamics of a plastic aging chamber with PI temperature control, this study was conducted according to ASTM D-4329 standard. In this work, three transfer functions are obtained which represent the different times (morning, noon, and night), the results of the transfer functions parameters are analyzed using Matlab PID Tunner to show the effectiveness of the proposed method. Finally, the temperature-time graph for a cycle is shown in the results.

Transfer function, Digital control, Thermal systems, Aging chamber

Resumen

La contaminación plástica se ha convertido en un problema ambiental a nivel mundial, debido a que la producción de productos plásticos aumenta con rapidez actualmente se están tomando medidas internacionales para reducir el problema. Este artículo tiene como objetivo presentar la dinámica de una cámara de envejecimiento de plástico con control de temperatura PI, este estudio se realizó de acuerdo con la norma ASTM D-4329. En este trabajo, se obtienen tres funciones de transferencia que representan los diferentes horarios (mañana, medio día y tarde), los resultados de los parámetros de las funciones de transferencia se analizan utilizando Matlab PID Tunner para mostrar la efectividad del método propuesto. Finalmente, el gráfico de temperatura-tiempo para un ciclo se muestra en los resultados.

Función de transferencia, Control digital, Sistemas térmicos, Cámara de envejecimiento

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Introducción

Plastic is an indispensable raw material in human life due to the properties it possesses, it is used for the manufacture of automobile accessories, clothing, electronic equipment, construction, medicine, tools, etc., with an annual production in 2019 of 369 million tons worldwide. (Plastics Europe, 2021), but plastic also represents an environmental problem because the waste ends up in the sea or in landfills causing environmental pollution which produces greenhouse gases and toxins called dioxins that cause serious problems to human health (Bahl, Dolma, Jyot Singh, & Sehgal, 2020).

For this reason, the United Nations Environment Organization held its fourth assembly in 2019 seeking with other countries a sustainable consumer production using a "Circular Economy" for the search to create lightweight, versatile and durable plastics and to develop guidelines that inform the end consumer about the use, production, standards and labels of plastic. (International Institute for Sustainable Development, 2019) (PlasticsEurope, 2021).

In the creation of new polymers, laboratory tests are carried out to determine the useful life cycle, by means of an aging chamber which has a thermal system that causes an accelerated degradation of the plastic. In this work we propose the development and implementation of a PI controller obtaining the dynamics of the temperature system in a practical way.

The PID system is widely used in companies to control their industrial processes because it is reliable and intuitive to use. Some examples are:

- Water heating in a bathtub using a water heater, a valve that regulates the water inlet to the bathtub and a temperature sensor. (Kavita, Naga, Lavanya, & Arivalagan, 2015).

- Temperature control system using fuzzy PID of a mushroom culture, where temperature and humidity are controlled manually by means of an algorithm to determine the high, medium and low fuzzy function. (Kaewwiset & Yodkhad, 2017).

- Temperature control in an incubator (Yue, Fuqiang, Lifeng, Jun, & Benke, 2020).

- ON/OFF heating system (Sánchez, Dessì, Duffy, & Lens, 2020).

In order to understand the dynamics of the system in this work, it is proposed to perform the temperature control by means of the transfer function (TF):

$$\frac{\Theta(s)}{H_i(s)} = \frac{R}{RCs+1} \tag{1}$$

Where $\Theta(s)$ is the final temperature in ℃, $H_i(s)$ is the heat flow input in $\left(\frac{kcal}{seg}\right)$, R is the thermal resistance in $\left(\frac{℃ seg}{kcal,}\right)$, C is the thermal capacitance in $\left(\frac{kcal}{℃}\right)$ (Ogata, 2010). The laboratory application of FT is possible by means of the convection principle which states that, if the characteristics of the building materials are known, then the radiated energy and energy loss can be obtained by equation (2) and equation (3) respectively.

$$P=\delta A\epsilon T^4 \tag{2}$$

Where P is the radiated energy in Watts (W), δ is the Boltzmann constant in $\frac{W}{m^2 °K}$, A is the area of the inner wall material of the aging chamber (m^2), ϵ is the emissivity constant of the material and T is the surface temperature of the material °K.

$$P_{lost}=kA\Delta Tt \tag{3}$$

Where P_{lost} corresponds to the energy loss inside the aging chamber, k is the constant of the thermal conductivity of the material between the outer and inner wall of the aging chamber in (Wm°K), ΔT is the temperature difference between the inside and outside of the aging chamber in °K and t is the thickness of the material on the walls in m^2.

One drawback is that when controlling the temperature using equations (2) and (3), a temperature calibration process must be performed each time the temperature value is to be changed. (Ezike, Alabi, Ossai, & Aina, 2018).

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To obtain the dynamic behavior by characterizing the temperature inside the aging chamber, an input $u(t)$ is applied to the thermal system to obtain the temperature response until it reaches the steady state $c(t)$ as shown in Figure 1.

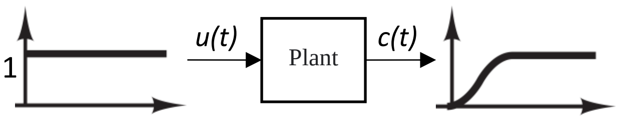

Figure 1 Response to a unit step of a plant
Source: Ogata, 2010

With the characterization of the thermal system, the transfer function can be obtained using the Ziegler-Nichols method or by means of a computational approximation (Fuentes, Castro, Medina, Moreno, & Sepúlveda, 2018) resulting in equation 4:

$$\frac{C(s)}{U(s)} = \frac{Ke^{-Ls}}{Ts+1} \qquad (4)$$

Where L is the delay, T is the time constant and K is the system gain. Once the FT of the thermal system is obtained, it is possible to design the PI controller. As described below.

Method

Algorithm of a complete cycle

The plastic aging chamber consists of a thermally insulated container of stainless steel sheets with two infrared luminaires at the ends of the specimens that perform the chamber heating function, as shown in Figure 2.

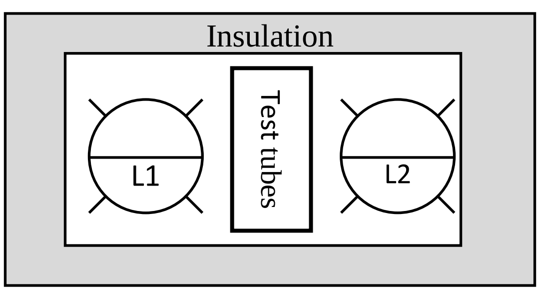

Figure 2 Plastic aging chamber with two infrared luminaires
Source: Own elaboration

ASTM D-4329 establishes a complete aging cycle which is divided into 4 sequences with different: lamp ignition cycles, temperatures and drive percentages, as shown in Table 1.

Sequence	Temperature	% aging cycle	L1	L2
Sunrise	60±3 °C	22.22	On	Off
Half day	60±3 °C	22.22	On	On
Sunset	60±3 °C	22.22	Off	On
Nightfall	50±3 °C.	33.33	Off	Off

Table 1 Characteristics of a chamber cycle.
Source: Own elaboration

In Figure 3, the control temperature is established by applying the ASTM D-4329 standard, then the response of the thermal system inside the chamber is obtained in a practical way, using an analog-to-digital converter and storing the information in a database to be processed through a computational numerical method (4) (MathWorks, 2021).

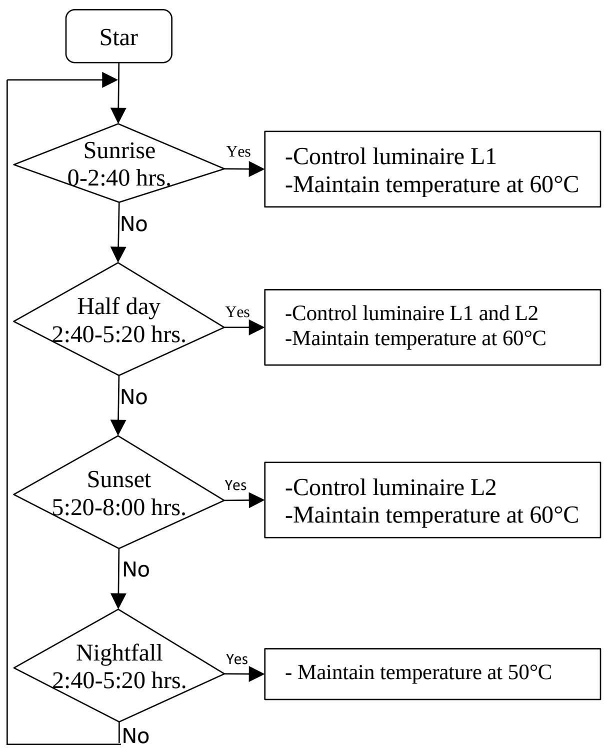

Figure 3 Flow diagram of a complete cycle
Source: Own elaboration

Development of the PI control

With the transfer function of equation (4) the PID Tuner tool of Matlab is used which will result in a continuous time parallel PI as shown in figure 4.

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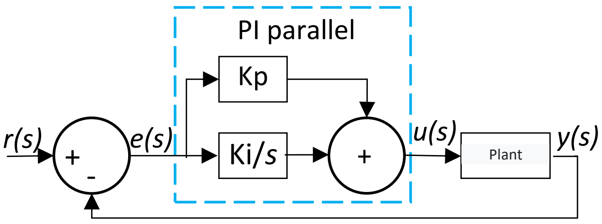

Figure 4 Parallel PI control
Source: Own elaboration

Where r(s) is the setpoint, y(s) is the output of the plant to be controlled, u(s) is the controller output, e(s) is the difference between u(s) and y(s), with the PI equation defined by equation (5). with the PI equation defined by the relation of equation (5).

$$\frac{u(t)}{e(t)} = K_p + \frac{K_i}{s} \tag{5}$$

K_p is the proportional gain, K_i is the integral gain. Once the continuous time controller is obtained, it can be converted to digital using Tustin's method to be able to program it in the microcontroller, which consists of substituting $s = \frac{2}{T_s}\frac{z-1}{z+1}$ in equation 5 resulting in a discrete controller of the following form:

$$\frac{u(z)}{e(z)} = K_p + \frac{K_i T_s}{2}\frac{z+1}{z-1} \tag{6}$$

Where T_s is the sampling time and z is the discrete function. The discrete controller of equation 6 by itself cannot be input to a microcontroller so it needs to be converted to a difference equation by applying the inverse z-transform to obtain equation (7).

$$u_k = u_{k-1} + k_p(e_k - e_{k-1}) + \frac{K_i T_s}{2}(e_k + e_{k-1}) \tag{7}$$

Where u_k is the result of the current controller, $u_{k-1}$the result of the previous controller, e_k the current error, e_{k-1} the previous error. By entering the difference equation into a microcontroller, the thermal system of the aging chamber can be controlled.

The implementation of the PI controller is shown in Figure 5 where the microcontroller is in charge of obtaining the temperature information inside the aging chamber and by means of the cycle assignment the difference equation is implemented in the PI controller resulting in a PWM signal that controls the system.

As can be seen in Figure 5, the prototype is divided into the following three phases:

1. **Storage**: where a history of the chamber temperatures is stored.

2. **Control**: integrated by the microcontroller

3. **Drive stage:** consists of the plastic aging chamber

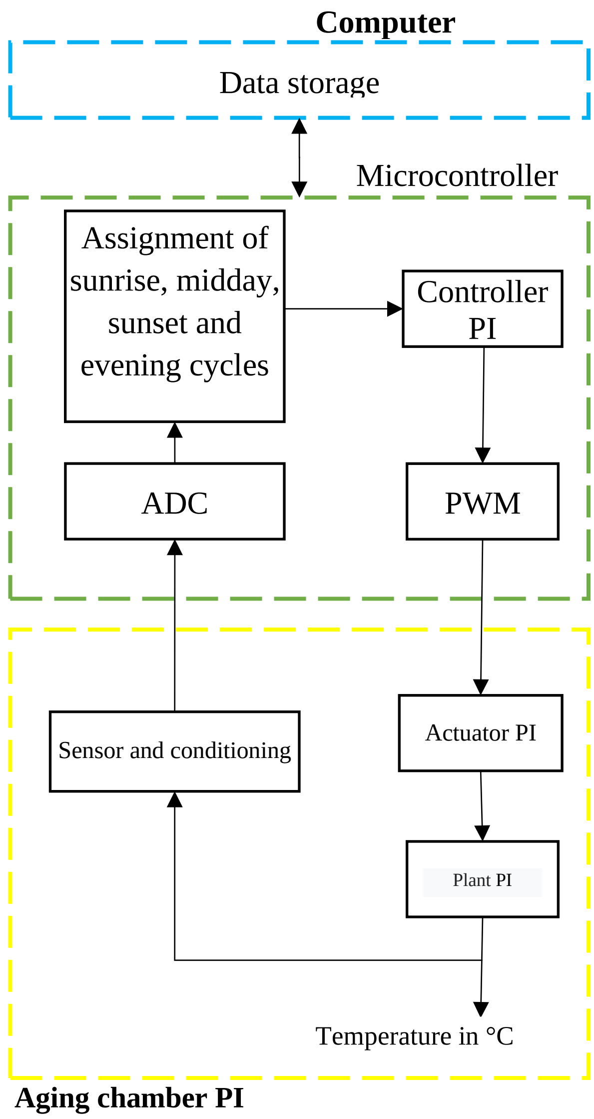

Figure 5 Block diagram of the PI controller implementation
Source: Own elaboration

The characterization of the sunrise and sunset sequence is obtained by applying 50% of the PWM signal, for the case of the half-day sequence a 24% signal is applied to the aging chamber in an approximate time of 890 seconds, the results obtained are shown in Table 2 and Figure 6.

The results obtained are shown in Table 2 and Figure 6.

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Time	Sunrise Sequence °C	Sequence Half day °C	Sunset Sequence °C
2.5	22.97	21.51	21.99
3	22.97	21.51	22.48
3.5	22.97	23.46	23.46
4	24.44	21.51	21.99
4.5	24.44	21.51	21.99
5	23.95	21.51	21.99
5.5	23.95	21.51	21.99
6	23.46	21.51	21.99

Table 2 Stored data for the characterization of the thermal system in the aging chamber
Source: Own elaboration

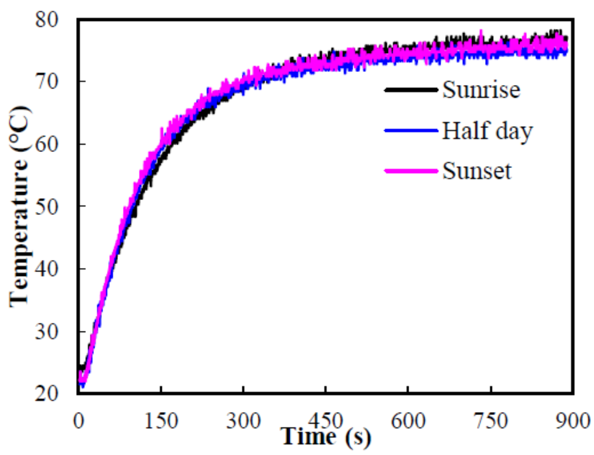

Figure 6 Characterization of the thermal system
Source: Own elaboration

With the practical characterization of the thermal system and using the Matlab System Identification Toolbox, the FT parameters described in equation (4) can be obtained as shown in Table 3.

Sequence	K	L	T
Sunrise	1.5	10.5	172.6
Half day	3.15	6.4	137.68
Sunset	1.5	12	172.6

Table 3 FT parameters of the required temperature time sequence
Source: Own elaboration

Using the Matlab PID Tunner tool and the results in Table 3, the parameters for the PI controller of equation (5) are obtained as shown in Table 4.

Sequence	K_p	K_i
Sunrise	3.76	0.0737
Half day	1.52	0.0159
Sunset	4.42	0.0350

Table 4 PI controller parameters of the sunrise, sunset and midday sequence
Source: Own elaboration

Once the PI control of Table 4 is obtained for each of the cases of interest, they are changed to discrete time using equation (6) as shown in Table 5.

Sequence	K_p	$\frac{K_i T_s}{2}$
Sunrise	3.76	0.1837
Half day	1.52	0.03975
Sunset	4.42	0.0875

Table 5 Discrete-time PI controller
Source: Own elaboration

Finally, from the results in Table 5 and using Equation 7, a discrete PI controller capable of being implemented on a microcontroller as in Table 6 results.

Sequence	Difference equation
Sunrise	$u_k = u_{k-1} + 3.76(e_k - e_{k-1}) + 0.1837(e_k + e_{k-1})$
Half day	$u_k = u_{k-1} + 1.52(e_k - e_{k-1}) + 0.0397(e_k + e_{k-1})$
Sunset	$u_k = u_{k-1} + 4.42(e_k - e_{k-1}) + 0.0875(e_k + e_{k-1})$

Table 6 Difference equation of the PI controller
Source: Own elaboration

Results

To verify the effectiveness of the implemented method, the results of the aging chamber control are compared individually with respect to the simulation, the equations in Table 3 are implemented. For the case of the sunrise, midday and sunset cycle, the equations in Table 6 are programmed in a microcontroller according to the aging cycle shown in Table 1, following the ASTM D-4329 standard, where it can be observed that they have a similar behavior with respect to the simulation and reaching a temperature of 60 °C in an approximate time of 250 seconds for the dawn sequence the temperature in the establishment time has an error of less than 1% as shown in figure 7, similarly happens in the half day cycle as shown in figure 8 in the case of the sunset sequence has an establishment time of 400 seconds as shown in figure 9 with an establishment error similar to the previous cases.

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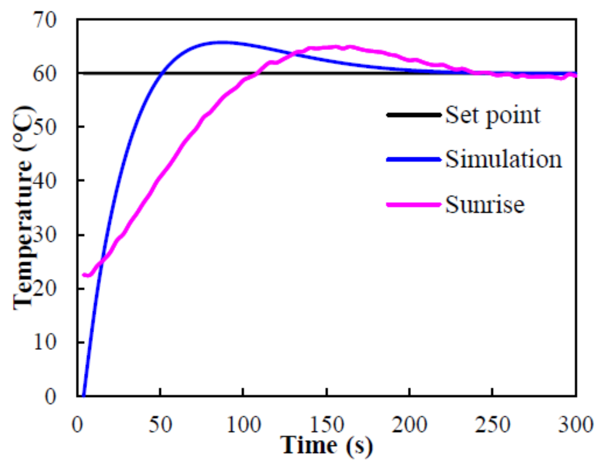

Figure 7 Simulation vs. real system of the sunrise cycle
Source: Own elaboration

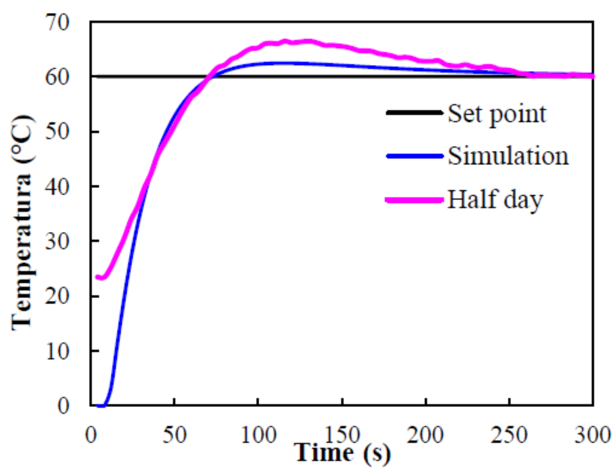

Figure 8 Simulation vs. real system of the half-day cycle
Source: Own elaboration

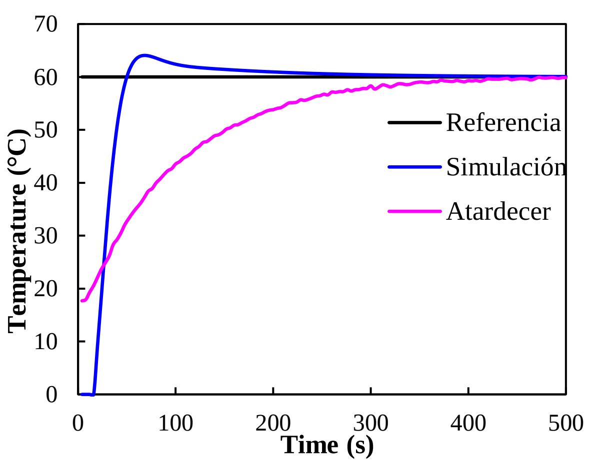

Figure 9 Simulation vs. real system of the sunset cycle
Source: Own elaboration

Finally, the control is implemented in the plastic aging chamber as shown in Figure 10, which shows the effectiveness of the method.

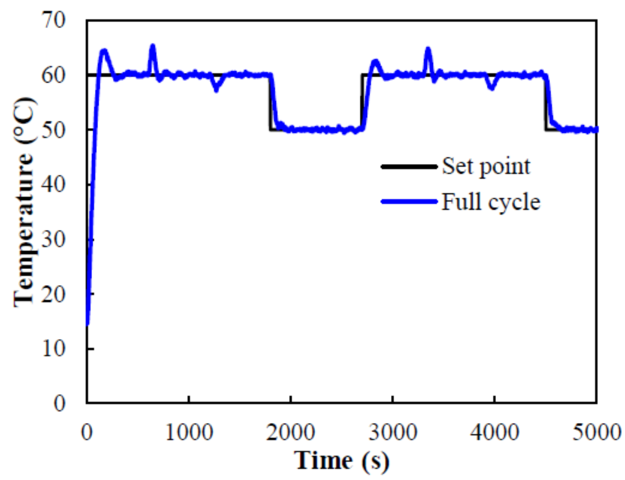

Figure 10 Cycle inside the aging chamber
Source: Own elaboration

Figure 10 shows two operating cycles of the chamber where the operating ranges were maintained within the parameters of the ASTM D-4329 standard, the algorithm used takes into account the different lighting sequences for the luminaires (see Table 1).

Conclusions

In this work a PI control is developed for a plastic aging chamber under the ASTM D-4329 standard, which consists of the development of three transfer functions that are used as the work cycle develops.

Having a different system dynamics for each half duty cycle (dawn, midday and dusk) it is necessary to implement in the microcontroller three actions or duty controls, this is possible by converting the PI controller in discrete time (z) and by a difference expression that can be interpreted by the microcontroller as a PWM value of the luminaires drive.

Temperature plays an important role in plastic aging, but it is not the only factor affecting degradation, other elements contributing to plastic degradation are humidity and UV rays, which will be considered and included in the control routine in future work.

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