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Comparative Study for a Conventional PID Controller Implemented with Three Different Component Sets

Estudio Comparativo para un Controlador PID Convencional Implementado Con Tres Conjuntos de Componentes Diferentes

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Abstract

In this work the ideal PID control structure was considered. This automatic controller was implemented by means of operational amplifiers using three different sets of values in its external components, but obtaining the same gains in each case. With each of these three sets of different components, three tests were carried out, adjusting the reference point to control an electric oven at a desired temperature of 140°C, 150°C and 160°C, the above was done experimentally to check if there is any change when varying the values of the components or if this does not affect the operation and performance of the PID controller. The plant in which the experiments were carried out is an electric muffle, which heats its interior using electrical resistances with a working voltage of 127 V and a power consumption of 12 A. It was found that the performance of the PID controller is not the same by using different sets of values in the components external to the operational amplifiers that make up the electronic PID controller, although these have the same gains K_p, K_i and K_d, one of the sets of components performs better than the other two, the above in two test cases considered.

Comparative Study, Control Systems, Performance Analysis, Energy Efficiency, Experimental Evaluation

Resumen

En este trabajo se consideró la estructura de control PID ideal. Se implementó este controlador automático mediante amplificadores operacionales usando tres conjuntos diferentes de valores en sus componentes externos, pero obteniendo en cada caso las mismas ganancias. Con cada uno de estos tres conjuntos de componentes diferentes se realizaron tres pruebas, ajustando el punto de referencia para controlar un horno eléctrico a una temperatura deseada de 140°C, 150°C y 160°C, lo anterior, se hizo de forma experimental para comprobar si existe algún cambio al variar los valores de los componentes o si esto no afecta al funcionamiento y desempeño del controlador PID. La planta en la que se realizaron los experimentos es una mufla eléctrica, que calienta su interior usando resistencias eléctricas con un voltaje de trabajo de 127 V y un consumo de energía de 12 A. Se comprobó que el desempeño del controlador PID no es el mismo al usar diferentes conjuntos de valores en los componentes externos a los amplificadores operacionales que conforman el controlador PID electrónico, aunque estos presentan las mismas ganancias K_p, K_i y K_d, Uno de los conjuntos de componentes tiene un mejor desempeño que los otros dos, lo anterior en dos casos de prueba considerados.

Estudio Comparativo, Sistemas de Control, Análisis de Desempeño, Eficiencia Energética, Evaluación Experimental

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Introduction

The implementation of automatic controllers is crucial for a wide range of applications in the field of electromechanical systems. With advances in digital technology, the science of automatic control now offers a wide spectrum of options for control schemes. However, more than 90% of industrial controllers are still implemented based on PID algorithms. [Ang, *et al.,* 2005] Among the different types of controllers, the proportional-integral-derivative (PID) controller is one of the most widely used controllers due to its simplicity and effectiveness in controlling both linear and nonlinear systems.

Currently, there are several control strategies, which, depending on their application and performance study, have determined the best strategy to implement in a process. Despite the existence of different types of control, 95% of the control loops used in industry are of the PID type [Bermeo, *et al*., 2021]. Despite the development of more intelligent control strategies and with better experimental results, PID control has not been displaced from the application in processes where it is desirable and at the same time sufficient for the operations to be performed, are simple and above all economic, especially when there are limitations in obtaining equipment to run more complex strategies or where there are no trained operators [Lozano-Valencia, et, al., 2012].

In this project, the PID control structure was adopted to implement an automatic controller with three different sets of values in its components, but achieving the same gain. Three tests were performed with the set point set at 140°C, 150°C and 160°C, in order to analyze if there is any change in the system response.

The selection of the PID controller component values is critical to obtain good performance of the controlled system. Therefore, several PID controller tuning techniques were investigated to find the optimal sets of component values. The controller is usually configured according to the experience of the designer. It is not only time-consuming and tedious, but also cannot be accurately controlled [Yanhong, et. al., 2015]. Despite being a widely used method, the PID controller may present some challenges.

For example, tuning the controller can be complicated and requires a thorough understanding of the control principles. In addition, fluctuations in ambient temperature and process variability can make it difficult to maintain a constant and accurate temperature.

In this project, the manual tuning method was used to select the three sets of values. The same gain was achieved with all three sets of values, suggesting that the system is robust to variations in the values of the PID controller components. The performance of PID controllers depends on the values taken by the gains Kp, Ki and Kd, which makes the process of choosing these gains crucial for the performance of the whole closed-loop control system [Berrones, et. al., 2019].

Therefore, the objective of this project is to design and implement a temperature control system using a PID controller in an electric furnace. It seeks to optimize the performance of the controller to guarantee a constant and accurate temperature, minimizing the variability of the process.

To achieve this objective, a detailed study of the system dynamics will be carried out and PID controller tuning techniques will be implemented. In addition, statistical data generated by the system will be analyzed to evaluate its performance and compared with the established objectives.

Theoretical Framework

The PID controller is a control algorithm widely used in industry and in various applications. The term "PID" refers to the three main components of the controller: proportional, integral and derivative. Its popularity is due to its simplicity, effectiveness and ability to control a wide range of processes. These components work together to maintain a process variable at a target value or setpoint, thus minimizing control errors [Astrom et. at, 2019].

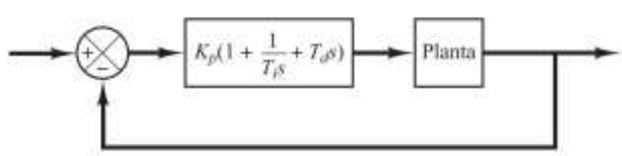

Figure 1 Block diagram of a PID controller
[Ogata, 2010]

Proper tuning of the PID controller parameters is critical to achieve optimum performance. Over the years, various tuning methods have been developed to adapt the PID controller to different types of processes. These methods include model-based approaches, heuristic methods, and optimization algorithms. [Chen *et, at* 2021].

Currently, more advanced techniques are being used to further improve the performance of the PID controller. Examples include the application of artificial intelligence algorithms, such as neural networks and genetic algorithms, for automatic tuning of PID controller parameters. In addition, hybrid approaches that combine PID control with other more advanced control techniques, such as model-based predictive control, are being explored [Li *et. at*. 2017].

In a comparative study of classical PID control algorithms for the angular control of an electromechanical arm [Astudillo et.at. 2020], it was concluded that the controller with the best performance is the parallel PID controller with a settling time of 7.1 seconds, followed by the PI-D controller that has a similar behavior, in third place, is located the PI-D controller that is just 0.14 seconds slower than those mentioned above. Figure 2 shows the results of this study.

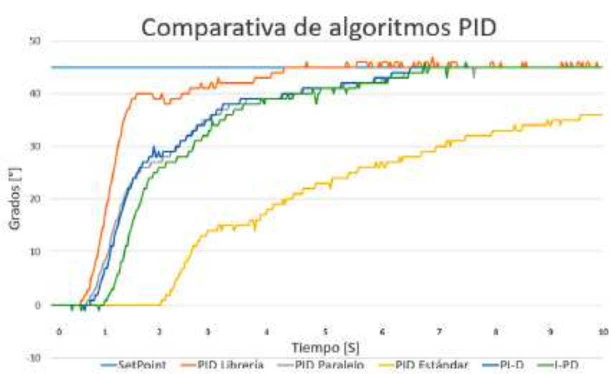

Figure 2 Comparison of PID algorithms
[Astudillo et.at., 2020]

Conventional PID controllers are widely used in temperature control in industrial furnaces. An example of their application is in the glass industry, where they are used to maintain a constant temperature during glass manufacturing [Guo.*et.at,* 2019].

Different techniques and approaches for the application of PID controllers in industrial furnaces have been proposed in the literature.

An adaptive PID controller based on neural networks has been proposed for temperature control in a heat treatment furnace. Their approach allowed more accurate control and better adaptation to process variations [Khan *et al*. 2017].

The concept of neural networks was taken as a principle for the learning and development of dynamic neural networks, which, due to the architecture and method used, and as it was proved, offered greater immunity to noise than static networks. The dynamic neural network served to determine the model of the plant to be controlled, in turn, delivered the calculation of the "Jacobian" to the neural architecture, which was called "neural tuner", which was in charge of developing the optimal parameters Kp, Ki and Kd that were then delivered to the PID controller [Cardozo, 2018].

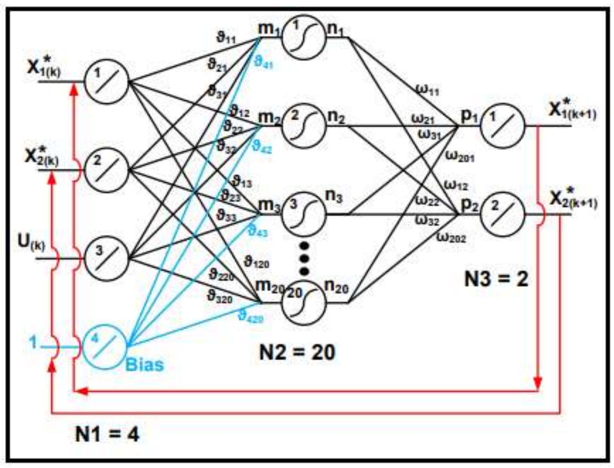

Figure 3 Architecture of Neural Network applied PID proposed
[Cardozo, 2018]

Another technique used in the application of PID control in industrial furnaces is automatic tuning, where an automatic tuning method based on genetic algorithms was proposed to tune the PID parameters optimally. This approach improved the control stability and reduced the response times of the furnace [Guo *et al.* 2018].

In the automatic control topic, the implementation of an intelligent algorithm based on the immune system response focused on the principle of clonal selection is proposed, in the algorithm a heuristic process is performed where various parameters are tested, their response is analyzed and the parameters are refined to obtain a set of solutions that satisfy the established criteria.

December, 2023 Vol.7 No.20 7-17

During the execution of the algorithm, the parameters whose results do not satisfy the criteria are discarded and those that reduce the error are replicated. At the end of its execution, the algorithm manages to significantly improve the result of the figures of merit compared to those obtained by the classical Ziegler Nichols tuning technique [Duque *et al*. 2017].

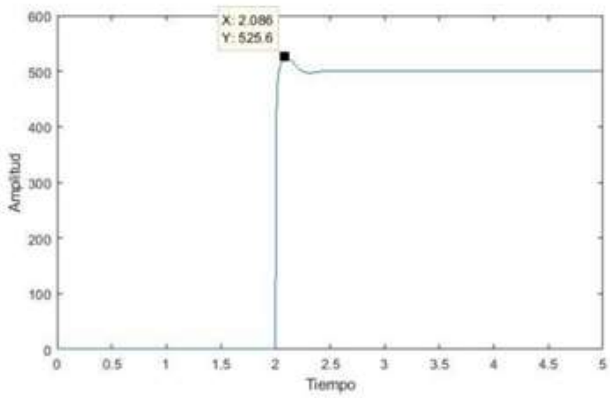

Figure 4 Automatic tuning after algorithm execution
[Duque et al. 2017]

In addition to temperature control, PID controllers are also used for protection and safety in industrial furnaces. Fathy *et al*., (2019) proposed a PID control system to monitor and protect the furnace pressure. In this work, the PID controller adjusted the output of the pressure control system to avoid dangerous situations and ensure safe operation of the furnace. These studies demonstrate the advances and practical applications of PID controllers in industrial furnaces. The use of adaptive and automatic tuning techniques improve furnace performance and efficiency while ensuring safety and process protection.

Materials and Methods

a) Experimental design

As a first resource, the PID control algorithm based on the proposal of K. Ogata (2003) was taken as a reference. In this research it was proposed to implement this structure using three different sets of values, but obtaining with these the same gains in K_p, K_i and K_d. For each of these sets of values, three different tests were performed, establishing as set points a desired temperature of 140°C, 150°C and 160°C, in order to see if there is any variation when changing the values of the components and to analyze the performance of the controller and how long it takes to reach the reference temperature in each case.

A muffle was used as a plant that heats its interior by means of an electrical resistance, operates at 127 V and consumes 12 A, has two heating resistors inside embedded in refractory brick, which is supported by an iron casing that forms the outer structure. Figure 5 shows the muffle used.

Figure 5 Electric muffle
Photograph on site

The PID controller circuit that was used to perform these tests is implemented in a didactic module that has all the appropriate components so that it can control the set temperature. A photograph of the module is shown in Figure 6.

Figure 6 PID controller training module
Photograph on site

Two multimeters were used to set the desired temperature (set point), one was used to measure the actual temperature and the other to measure the desired temperature.

By using the multimeter software, all the readings taken by the multimeter could be saved in real time and thus the results of each test performed could be obtained.

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The first set of values of the components that externally configure the PID controller are shown in Figure 7. With this first set of values, 3 tests were performed at 140°C, 150°C and 160°C.

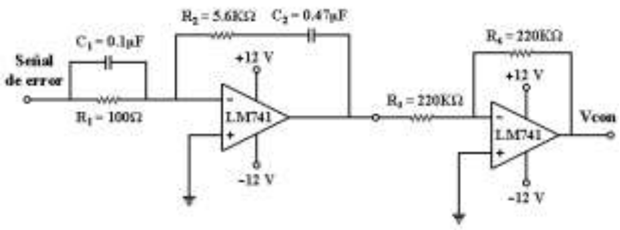

Figure 7 Values determined for the PID structure
Own Elaboration based on the proposal of K. Ogata (2010)

The first test was carried out with a desired temperature of 140°C, with which the corresponding measurements were taken to record the time it took for the muffle to reach this temperature, its maximum overshoot and its establishment time.

The next day the test was performed by changing the desired temperature to 150°C, the rise time was recorded, as well as the time it takes to reach the maximum point and settle at the desired temperature.

One day after the second test, the test was performed with the reference temperature set at 160°C, and the corresponding measurements were recorded. To know the exact temperature of the muffle, a thermocouple is connected to the same plate where the PID control is located, and from there it is connected to the muffle as shown in Figure 8.

Figure 8 Thermocouple
On-site photograph

To test the second set of values of the external configuration components, the same PID control structure is used, in which the gains are the same. The final circuit is shown in Figure 9.

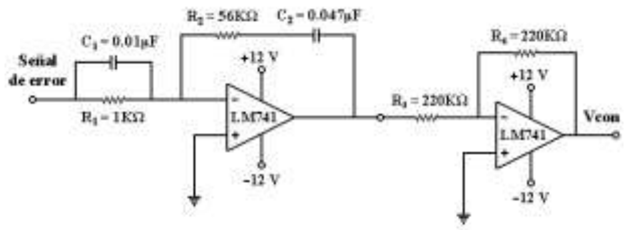

Figure 9 Second set of values retaining the same gains
Own Elaboration

As in the first procedure, the temperature was changed every day, starting with 140°C, followed by 150°C, and finally, the test was carried out at 160°C, recording the corresponding measurements.

Finally, the tests were performed with the third set of values of external configuration components, always keeping the same gains. The circuit obtained is shown in Figure 10.

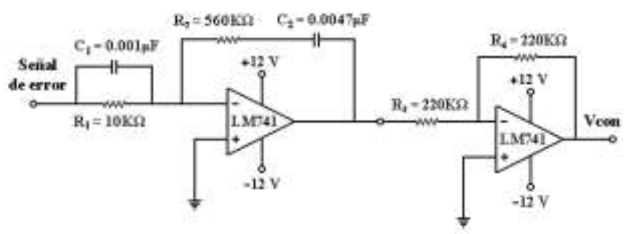

Figure 10 Third set of values conserving the same gains
Own Elaboration

As in the previous procedures, three different tests were also carried out on three days at the same time; in the first one the desired temperature was 140°C, the second one 150°C and the third one 160°C; recording the corresponding measurements.

b) Statistical design and analysis of experiments

A completely randomized design was used, where the factors were the temperature treatments. An analysis of variance (ANDEVA) was performed on the data of all treatments at a 99% significance level. To see differences between specific means, Tukey's test was used ($P<0.05$). The ANDEVA was performed using SAS software (SAS 2012).

Development

a) Mathematical model of the PID controller

A PID controller is a type of controller used to control dynamic systems. It is composed of three terms: proportional, integral and derivative. The proportional term is proportional to the current error, the integral term is proportional to the sum of past errors, and the derivative term is proportional to the rate of change of the error. Together, these terms help keep the system in a steady state. The mathematical model of the PID control algorithm can be expressed by the transfer function shown in equation (1).

$$\frac{E_0(s)}{E_i(s)} = K_p + \frac{K_i}{s} + K_d \quad (1)$$

To obtain the proportional gain K_p, the integral gain Ki and the derivative gain K_d, the following equations are available:

$$K_P = \frac{R_4(R_1C_1 + R_2C_2)}{R_3R_1C_2} \quad (2)$$

$$K_i = \frac{R_4}{R_3R_1C_2} \quad (3)$$

$$K_d = \frac{R_4R_2C_1}{R_3} \quad (4)$$

The results obtained for the gains, substituting the component values in the three test cases, are:

$K_p = 56.21$ $Segun$ (2)

$K_i = 21276.5921$ $Segun$ (3)

$K_d = 5.6 \times 10{-}4$ $Segun$ (4)

Sustituyendo los resultados de las ganancias en (1) se tiene:

$$\frac{E_0(s)}{E_i(s)} = 56.21 + \frac{21276.59}{s} + 0.00056s$$

Simplifying the above equation yields the final transfer function:

$$\frac{E_0(s)}{E_i(s)} = \frac{0.00056s^2 + 56.21s + 21276.59}{s}$$

b) Mathematical model of the plant

An electric muffle is a furnace used to heat materials to high temperatures. It operates through the use of an electric heating element that converts electrical energy into heat. The electric muffle has an insulating lining that helps maintain the temperature in the furnace. It is used in a variety of applications including ceramics production, metal melting and heat treatment of materials. To obtain the transfer function of the plant (electric muffle) we have (5):

$$G_c(s) = \frac{K * e^{t_0 s}}{t * s + 1} \quad (5)$$

Figure 10 shows the experimentally achieved response curve, and plots temperature versus time, with open-loop control; in which the temperature reaches a maximum value in about 2 000 seconds.

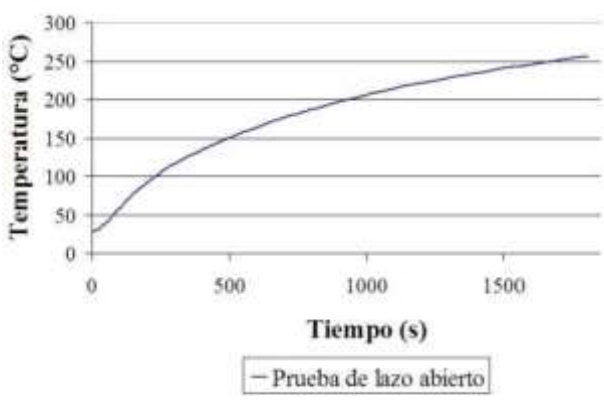

Figure 10 Reaction curve characteristic of the plant operating in open loop
Own Elaboration using Excel software

Figure 10 shows the results for K, t_0 and t.

$$K = \frac{100°C - 50°C}{232.48s - 76.43s} = 0.3204°C/s$$

$t_0 = 28.6s$

$t = 257 * 0.632 = 162.42$

Equation (6) is given to replace in (5).

$$e^{t_0 s} = \frac{1}{t_0 s + 1} \quad (6)$$

Replacing, we obtain (7):

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$$G_c(s) = \frac{K}{t*s+1} * \frac{1}{t_0 s+1} \quad (7)$$

Substituting in (7) the real values obtained above, we have:

$$G_c(s) = \frac{0.3204}{162.42s+1} * \frac{1}{28.6s+1}$$

Simplifying the mathematical model used for the plant is obtained:

$$G_c(s) = \frac{0.3204}{4645.2s^2+191s+1}$$

Results

The results of the investigation show that the PID controller is very effective in maintaining the desired temperature in the muffle, even when different sets of values are used. However, it was found that the performance of the controller varies according to the set of values used. Each procedure was performed in triplicate, where, the tests performed at 140°C, are numbered 1401, 1402 and 1403. Code 01 means the treatment with the first set of values, "02" the treatment with the second set of values and "03" the treatment used in the third set of values. The same methodology was applied for the tests at temperatures at 150°C (1501, 1502 and 1502) and 160°C (1601, 1602, 1603).

Figure 11 shows the performance of the PID controller at the 140°C temperature. Treatment 1402 took less time to reach the set point, unlike the other two sets (1401 and 1403).

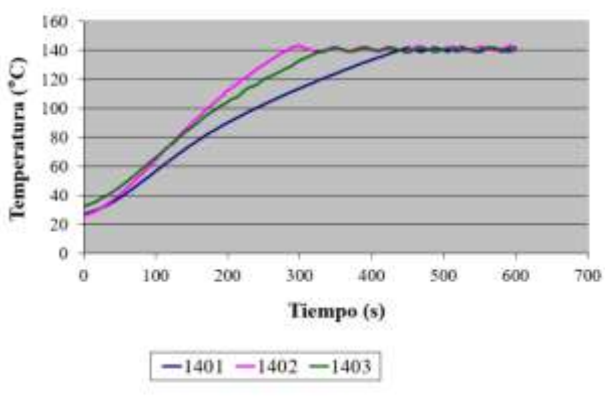

Figure 11 Results with the reference temperature set at 140°C
Own Elaboration using Excel Software

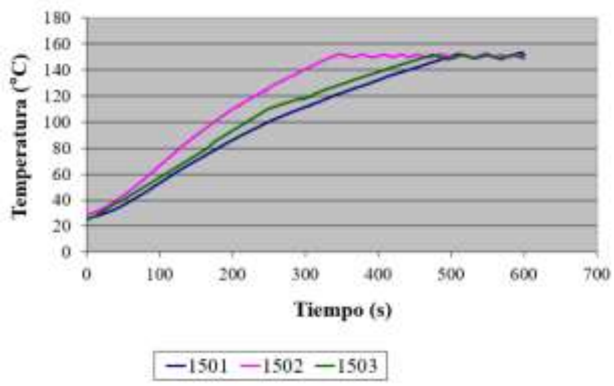

Figure 12 Results with the set point temperature set at 150°C
Own Elaboration using Excel Software

Figure 12 shows the performance of the PID controller at the 150°C temperature. The temperature took less time to reach the set point using treatment 1502, unlike 1501 and 1503, where the performance was similar.

Similarly, Figure 13 shows the performance of the PID controller at the 160°C temperature. The behavior was similar to that observed at 150°C, since 1602 reached the reference temperature or set point faster than the other two methods.

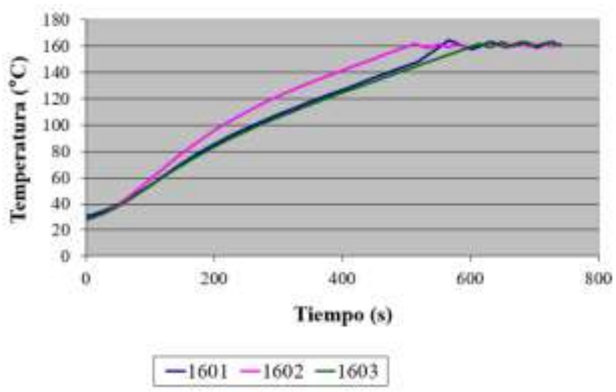

Figure 13 Results with the desired temperature set at 160°C
Own Elaboration using Excel Software

Discussion of results

The PID controller allows obtaining reliable performances in different applications, such as temperature, flow or pressure control. In this particular case, SAS software (SAS Institute 2012) was used to perform a statistical analysis of variance (ANDEVA). Figure 14 shows the temperature distribution for the 140°C tests.

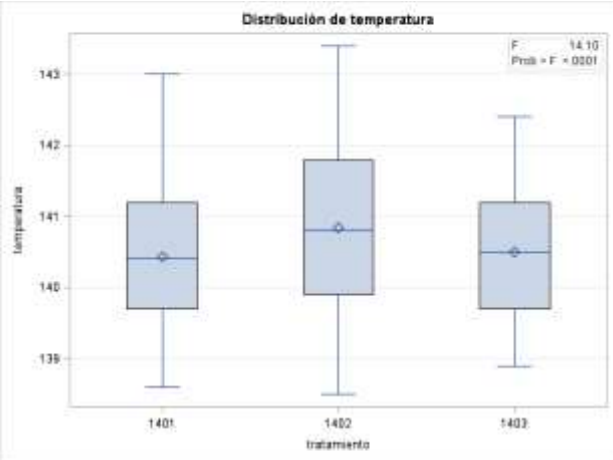

Figure 14 Temperature distribution for the 140°C treatment
Own Elaboration using SAS Software

Tables 1, 2 and 3, respectively, show the mean values of each temperature evaluated. Likewise, it can be seen that, for each process, three treatments were carried out.

Grouping	Media	N	Treatment
A	140.80	299	1402
B	140.05	299	1403
B	140.97	299	1401

Table 1 Test averages at 140°C
Own Elaboration using SAS Software

From Table 1, it can be seen that the second set of values (treatment 1402) shows a higher performance than the other two (1401 and 1403). It is observed that, when changing the external configuration values, although the same gains are preserved numerically speaking, the performance experiences a decrease. The software is conclusive in determining that there is a difference between treatments, assigning a letter "A" to the set of values 1402 and a letter "B" to the other two. Likewise, in the performance of the controller, the time it takes to reach the set point is different for treatments 1401 and 1403. According to the study done by Souran *et al*. (2013), using PID controllers to control the flow of water in a reservoir, variations in the inflow and outflow can be observed; this is because the components are adjusted according to the nature of each system, as the response obtained is different in each treatment.

Figure 15 shows the temperature distribution for the tests at the 150°C temperature. The behavior of 1502 was similar to that observed in 1402, since the mean temperature (150.95) was the highest.

This is very significant, since the arrangement established for this treatment allowed obtaining the set-point in a shorter time, having a faster response, as shown in Figure 12.

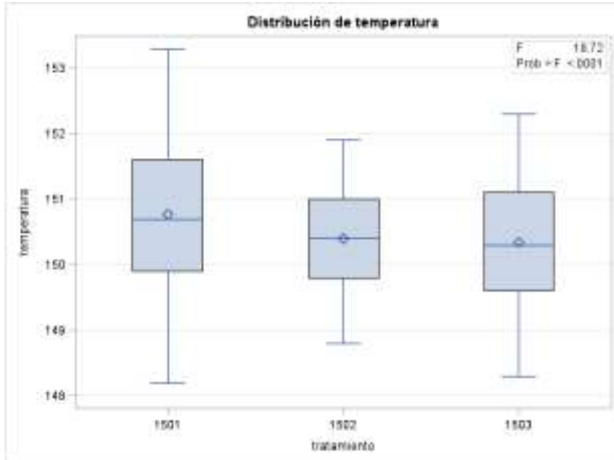

Figure 15 Temperature distribution for the 150°C treatment
Own Elaboration using SAS Software

Grouping	Media	N	Treatment
A	150.95	299	1502
B	150.5	299	1503
B	149.8	299	1501

Table 2 Test averages at 150°C
Own Elaboration using SAS Software

Figure 16 shows the temperature distribution for the 160°C tests. From this it can be concluded that the temperature in each treatment shows significant differences according to Tukey's grouping, which is most likely due to the fact that the higher the temperature, the greater the change required in the controlled variable, which implies installing a higher power actuator.

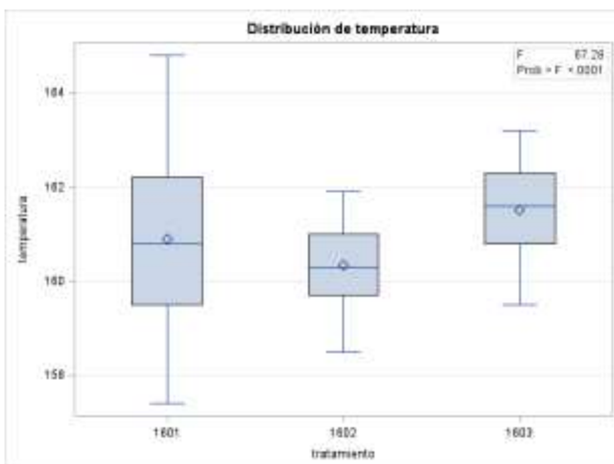

Figure 16 Temperature distribution for the 160°C treatment
Own Elaboration using SAS Software

Grouping	Media	N	Treatment
A	161.35	299	1602
B	160.77	299	1601
C	161.74	299	1603

Table 3 Test averages at 160°C
Own Elaboration using SAS Software

The capacity of a controller to maintain the temperature in a desired or preset range can vary according to the desired temperature range. The results show that the behavior for temperature measurement at 140°C and 150°C is similar, but not so for 160°C; where each procedure shows truly significant differences (DVS) in their measurements.

Table 4 shows the ANDEVA performed for each treatment. It shows the DVS between treatments. The behavior for the temperature control at 140°C and 150°C is similar, but not for the 160°C control.

Treatment	Temperature (°C)
1401	$140.97^1 \pm 1.2469$b
1402	$140.80 \pm 1.7678a^2$
1403	140.05 ± 0.6354b
1501	$149.8 \pm 0.4243b$
1502	$150.95 \pm 2.0506a^2$
1503	150.5 ± 1.2021b
1601	160.77 ± 0.8507b
1602	$161.35 \pm 1.3628a$
1603	$161.74 \pm 1.0648c$
[1]Mean ± standard deviation. [2]Means with the same letter are not significantly different ($p > 0.05$).	

Table 4 Temperature measurement for the 140, 150 and 160°C treatments
Own Elaboration

It is likely that, at higher temperatures, (higher powers) regardless of the set of values used, this no longer impacts the performance of the controller as much, and a different response is obtained for each reference scale tested; the above is an issue to be addressed in future work. The study by Al-Dhaffallah *et al.* (2018), showed that using PID to control the pressure in a measurement system at an experimental level, allows shortening the response time to achieve a stable pressure, giving good results, compared to other controllers such as FOPID and FFOPID. Recall that in a PID controller the proportional gain (K_p), integral gain (K_i) and derivative gain (K_d) are three tuning parameters that determine the controller response to error signals.

These gains are used to adjust the controller output as a function of the current error, the sum of the previous errors and the rate of change of the error, respectively. That is why, as "THE PLANT" is exposed to different operating conditions, we obtain higher DVS as the temperature increases inside the muffle.

It is proposed for future research to test other systems with different combinations of K_p, K_i and K_d to optimize performance.

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Conclusions

In this work, an ideal PID controller was implemented and experimentally tested by implementing three different sets of values in its external configuration components but maintaining the same theoretical gains in an electric muffle furnace, performing on-site tests at temperatures of 140°C, 150°C and 160°C. The results obtained clearly show that in all cases the PID controller is able to regulate the temperature accurately and stably. It was demonstrated that the performance of a PID controller implemented with operational amplifiers is affected by the value of the external components with which it is configured. The scientific community is invited to replicate the experiment in their laboratories to verify these results. Likewise, the subject remains open for future work to investigate and get to know why the treatments with the second set of values achieved the best performance in the tests performed. In this regard, we already have some hypotheses that will be verified in future work.

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