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Development and Simulation of a Low Cost Closed Thermal System to Generate Thermal Cycles through PID Control and IoT Applications

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Abstract: ***The aim of this paper is to present the development of a multi-purpose device that enables the variation of temperature in a closed chamber with known volume. This system will allow students, researchers and engineers to acquire accurate data and process them in different applications where temperature control is relevant, for example bacterial growth, conservation of biological material, dry air sterilization and other laboratory process. The proposed approach applies proportional-integral-derivative (PID) control loop mechanism, which is widely used in laboratory equipment and industrial control systems. The difference with other systems is, that the one presented here, can be customized using inexpensive components including hybrid digital electronic and analogue actuators. These components can be arranged in different configurations according with a specific need or process. A thermal model was developed taking into account losses and disturbances, and the mathematical model was formulated by finding three different transfer functions for three temperature zones. The first zone covers the range from ambient temperature to 60° C with an actuator (Rb), another actuator for the range from 60°C to 200°C (Ra) and the third actuator (Rc) that covers the range from 0 to -13°C. The data is acquired using an Internet Of Things (IoT) platform.***

Keywords: PID controller, sensors, temperature, electronic instruments, environmental, IOT

1. Introduction

The need to design and build closed systems or systems with external disturbances in the study of temperature is very important in experimentation and present on a daily basis [1]. The effect of temperature is of great importance for human beings, oceans[2], flora and fauna, because every increase or lowering in temperature creates considerable fluctuations in their balance [3]. Closed chamber systems, with the ability to measure and control temperature, has become an indispensable research tool temperature dependent applications [4]. Its supervision allows the creation of models [5], experiments, applications and the development of devices and projects [6].

However, these systems should be inexpensive in order to be affordable by students, researchers, engineers or small experimentation groups. They also need to be scalable, with low energy consumption, versatile and customizable. To achieve this, several features need to be taken into account during the design phase, for instance, cost, accuracy, manufacturability, modularity (the capacity to add sensors and devices) and the type of experimentation (biological, chemical or physical). These technologies have a wide range of applications, for example experimentation in the drying process of agricultural products [7], fruit dehydration, agriculture in small-scale greenhouses [8] and aeroponics.

The total cost of the device is approximately one hundred euros in the case of a construction with brand new components. It is possible to use some reused or second-hand parts, decreasing the cost of the device. The main idea of this project is to generate a temperature gradient, between -10 ° C and 200 ° C, without affecting the integrity of the device [9], allowing to add different configurations of sensors and actuators depending on the temperature range, in order to ~~adapts~~ to different applications, such as cell cultures, tissue engineering or bacterial growth in biomedical applications. It is necessary to indicate that this system is equipped with devices not only to measure the internal chamber temperature but also with heating elements needed to raise the temperature up to 400°C if the container material allows it, and also with cooling elements that allows to lower the temperature to -13°C. Many industrial and productive processes use controlled temperature chambers, for example, food drying [10]. However, it is often not possible to study what is inside the drying chamber during the process, without samples.

The versatility of the equipment allows its use as a reflow oven for the construction of electronic circuits by means of the surface mount soldering technique (SMD), thanks to the fact that the high-power heating element can generate the temperature of 350°C necessary for this process. The system also has applications in the thermal treatment of small components or materials in electronics or nanotechnology applications [11]. However, the chamber material should be compatible with the maximum temperature needed in the specific process or heat treatment. For example, the tests carried out on the plastic container showed that that it is possible to reach a temperature of 200 °C without permanent deformation.

Steam generation at 110 ° C to clean and sterilize surgical instruments, is another possible application for the system presented [12]. It is achieved by adjusting the design and materials of the container, so that a pressure vessel is configured that would be very useful in small laboratories of veterinary or dental applications.

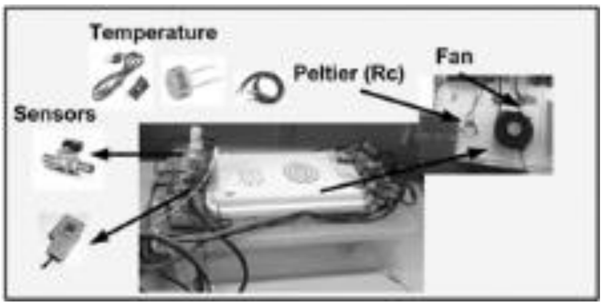
The camera is cooled using thermoelectric devices known as Peltier modules. The cooling capacity of the system will depend on the number of modules used and its electrical power [13]. For the volume of the selected container (see figure 1.2) and in order to reach a temperature of -13 ° C, six Peltier modules and a power supply of 20 Amps operating at 12 volts in direct current are required. To maintain the low-cost approach, an arrangement of three Peltier cells (two at the bottom and one at the top of the container) and a standard power supply was chosen. During the testing stage, it was possible to measure a difference of 15 ° C on average below the ambient temperature. In more specific tests, a gradient of 7 ° C in winter and 16 ° C in summer was measured.

2. Materials and Methods

2.1. System Construction

In this work, a system composed of several sensors and actuators is presented, which allow generating and controlling the temperature conditions inside a container. The objective is to obtain stable thermal cycles (temperature versus time curves) so that it is possible to test conformance of sensor temperature ranges in respect to their data sheets, before performing an experiment. The system was designed to obtain data of real conditions within closed spaces, and then compare them with results obtained in larger spaces and thus establish their proportionality relationship. [14].

Top cover of the system [1.1]



Container and system elements [1.2]

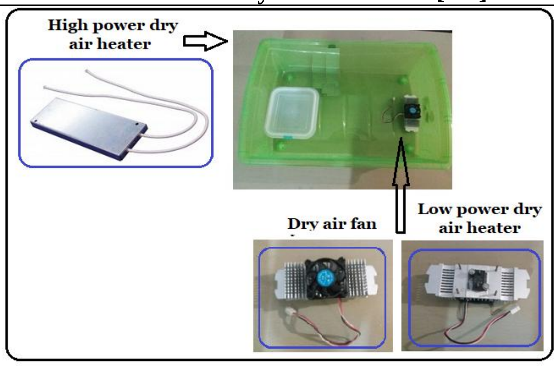


Figure 1: Container with some devices to modify the chamber temperature

Figure 1.1 shows the set of the devices and system elements located in the top cover. The most important components and their general use are described below:

- Air cooling system: it is composed of a Peltier cell and its respective heatsink with a fan to expel the heat.
- Recirculation fan: this device is responsible of generating disturbances in the study of the controller or maintaining a transient state from the inlet to the outlet using a solenoid valve.
- Current sensor: verifies the consumption electrical power of each actuator (Ra, Rb and Rc).
- Solenoid valve: Final actuator element to control the output of hot or cold air, or also to create steady state or transient conditions of the air.

Figure 1.2 shows the set of system elements attached to the plastic container:

- Air container: system designed for the study of air in closed environments through temperature control.
- Dry air heater (Ra): this device increases the air temperature and add kinetic energy allowing the air particles that are on the bottom surface to rise and mix by pressure, the temperature range can vary from 28 °C to 400 °C depending on the application.
- Sensors: The system has other sensors that verify variables and close the control loop on the flow, heating and cooling devices. These sensors are: dry temperature, cooling temperature, system temperature, atmospheric pressure inside and outside the system, external temperature and internal and external airflow from the environment [15].
- System cooler: Used to verify the responses of the data sheet sensors at low temperature, also to simulate environments where the temperature can be between 5 °C and 20 °C.
- Ambient air fan: used to introduce ambient air into the system, also to homogenize and monitor the internal air and change the state of the actuator Ra, Rb, Rc inside the container.

To model the system, experimental data were measured for the heat source in order to verify that the response times are compatible with the controller, the selected electronic components and to guarantee that the energy consumption is minimal to achieve thermodynamic equilibrium conditions. The container illustrated in Figure 2, has a known volume of 36.504 cm3 (0.036504 m3). With this data, it is possible to raise the equations of energy balance, making use of the first law of thermodynamics [16]. For this, it is assumed that the system can exchange energy with its surroundings through heat and work transfer (boundary work), which allows the increase of energy. However, in the control algorithm, the system disturbances represented in the entry of ambient airflow into the chamber, are also considered and this means non adiabatic conditions. (See figure 2).

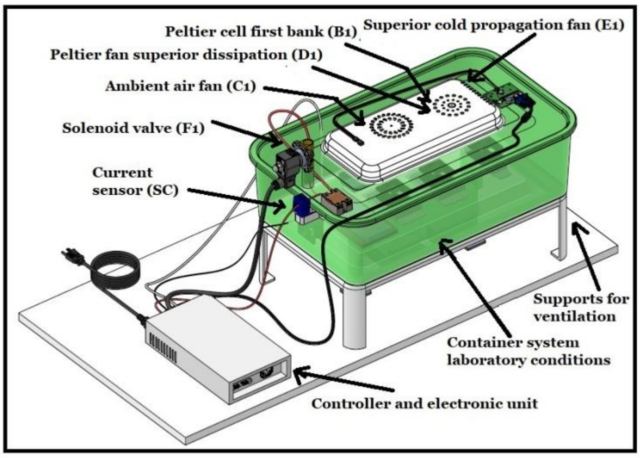


Figure 2: Top view of the generator system and temperature controller

For a closed system, the first law of thermodynamics states that during an interaction between a system and its surroundings, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings. Figure 3 illustrates a front view of the closed system to which the first law of thermodynamics is applied.

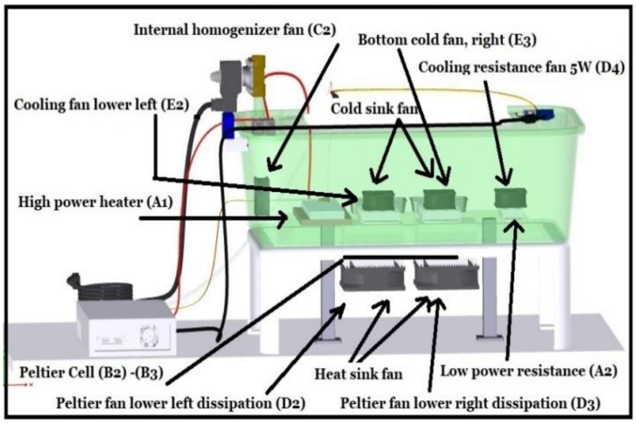


Figure 3: Front view of the temperature system with actuators

For the initial state, the constant volume of the container is considered as known, the medium will be air because variables such as density, temperature and humidity are equal inside and outside the chamber in the first interval from room temperature to 60 °C. The 5 watts electric heating element (Ra) is the actuator in this temperature zone, then the 150 watt electric heating element to heat the systems up to 200°C and finally the cooling effect (Rc). It is better to let the system start from rest at room temperature, using equation 1, **[17].**

$$\boldsymbol{Qcco = [(Qsap1 + Qsap2 + Qsap3) - Qstta - Qsicav - Qfm - Qpcon)] * (1 + F)} \quad \textbf{Eq-1}$$

Where ***Qcco*** is the thermal load of the container. ***Qsap1, Qsap2, Qsap3*** are the sensitive heat gain due to heating elements. ***Qstta*** is sensible heat loss through the top cover. **Qsicav** is the loss of sensible heat due to external infiltrations. ***Qfm*** is the thermal load of living biological material. **Qpcon** is the heat inside the container.

2.2. Electronic control system design

The electronic control system design included the use of the following actuators: (A1) 150-watt high power heating element 150-watt at 220 VAC, (A2) 5-watt low power heating element, (B1) top cooling Peltier module, (B2) bottom left cooling Peltier module, (B3) bottom right cooling Peltier module, (C1) ambient air fan, (D1) top Peltier dissipation fan, (D2) bottom left Peltier dissipation fan, (D3) bottom right Peltier dissipation fan, (D4) cooling fan in low power heating element, (E1) cold air top fan, (E2) bottom left cooling fan, (E3) bottom right cooling fan and (F1) solenoid valve. Different supply voltages are specified for each component (electrical power and digital control). To achieve this, two different power supplies are used. The first one feeds actuators B1, B2 and B3 at a voltage of 12 VDC. The second one feeds the actuators A2, D1, D2, D3, D4 and F1 at 12 VDC and the digital electronic components at 5 VDC [18].

Actuator (Ra): Circuit for high temperature from the middle zone to 200 ° C

It is possible to connect the actuator A1 directly to the power supply; however, it reaches its maximum temperature in a few minutes, forcing its disconnection to avoid damage. In order to exercise a control action on this element, an electronic circuit (see figure 4) was implemented that will regulate the supply current to the element through the switching of optocouplers DIAC DB32 and TRIAC BTA08400B, generating four different states of regulation at 115/220 VAC (rms). A solid-state relay (SSR) with appropriate switching times can replace the illustrated circuit.

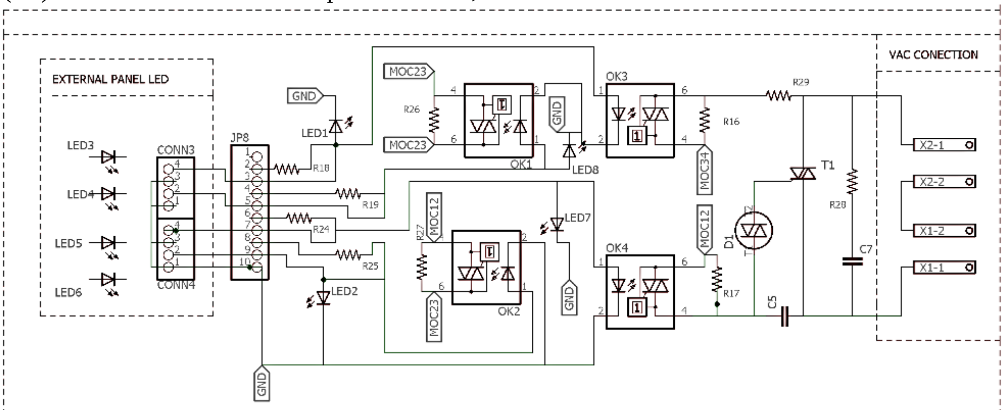


Figure 4: Circuit for the operation of the AC heater

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Figure 5.2 shows the main characteristics of the Triac, among which stand out an RMS current of 8 amps, a repetitive peak off-state voltage range from 600 to 800 volts and a triggering gate current in a range from 5 to 50 mA depending on the circuit and the supply voltage. Figure 5.1 show the Diac DB32 characteristics, which gas triggering of Triacs and Thyristors, AC switches and bidirectional switching.

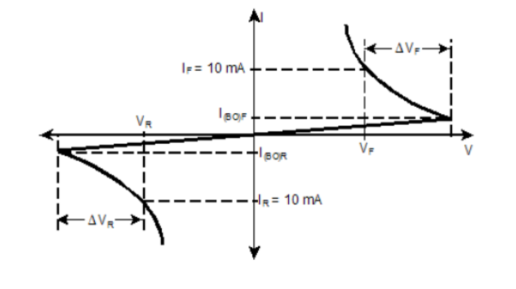
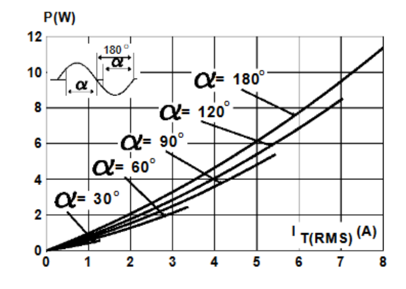
Diac DB32 [5.1]	Triac BTA08400B [5.2]
	

Figure 5: Main characteristics of the triac and the diac section of cut

Actuator (Rb): temperature control from room temperature up to 60 °C

This circuit carries out the control action on actuator A2 (5-watt low power resistor). This actuator is governed by the IRF540 MOSFET, which allows to control the current and thus choose a specific thermal cycle (temperature ramp). Figure 6 illustrates how the other components of the system interact, including last generation air fans activated through the element TIP122 and that allow reading of its rotation speed in revolutions per minute (RPM).

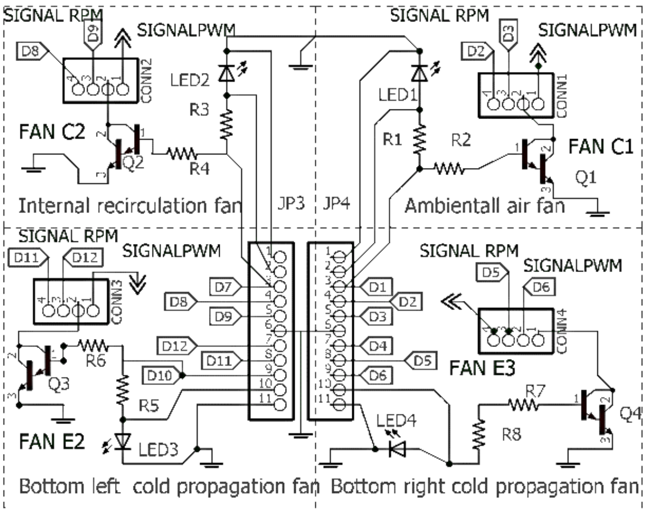


Figure 6: Switching circuit for fans and rpm reading

Actuator (Rc): temperature control from -10 °C to room temperature

To cool the system, a set of Peltier modules were installed, whose proper operation was guaranteed by a 20-amp power supply. The circuit illustrated in Figure 7 uses a 4N35 optocoupler for the handling of transistors and the drive of the MOSFET IRF540. A set of three circuits is used for cooling through Peltier modules. The cooling stage always starts when the system reaches room temperature [19].

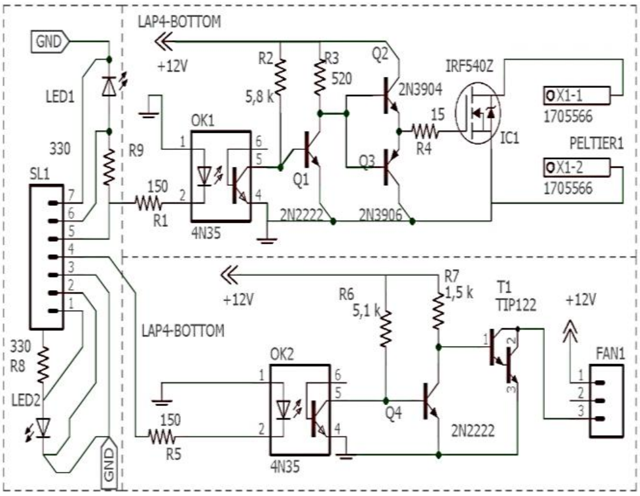


Figure 7: Circuit for the handling of the peltier cell and fan

2.3. Methodology and procedures

The first step was the integration, inside a polyurethane enclosure, of two different power sources. The first one, with a capacity of 20 amps and a supply voltage of 12 VDC, and the second one with a capacity of 2 amps and multiple leads to 220 VAC, 12 VDC, 5VDC and 3.3 VDC. Next, the circuit boards were assembled to control components such as fans, heating elements and the solenoid valve. Then, the connection of the system sensors (temperature, humidity, electrical current) and that were installed to monitor different system components. For the data acquisition process, an Arduino Mega 2560 development card was initially implemented, however, a new main card was developed that integrated all the components using the AtMega 2560 microcontroller, a Wi-Fi module ESP8266 and a real time clock M41T11 for the management of time.

2.4. Analytical expressions for dynamic modeling

In order to observe the dynamic behavior and inertia of the system, data was captured in different scenarios. The first scenario consisted in heating the air with the low-power resistance (5 watts). The second in heating the air with the high-power resistance (150 watts). The third was to cool naturally by disconnecting the heaters until reaching ambient temperature (the slope of the temperature versus time curve is moderate and governed by the heat losses through the walls of the container). Finally, the fourth scenario consisted of the cooling process through the Peltier modules. It can inferred that the internal fan was able to homogenize the internal temperature by mixing the hot air around the heaters. The (β), (α), (Ж), (ŧ), (T), (Y), values were determined and recorded in table 1. Then the system was simulated, obtaining a transfer function (Eq2,Eq4,Eq6) for each scenario or segment of the process (the actuators and some thermal parameters change in each scenario).

$G(s) = \frac{Z}{NS+M}$ **Eq- 2** using the resistance Ra: 48 ***Ω*** to 220 Vac

$G(s) = \frac{4{,}94}{2{,}78S+1{,}72}$ **Eq- 3**

$G(s) = \frac{C}{As+B}$ **Eq- 4** using the resistance Rb: 220 ***Ω*** to 12 Vdc

$G(s) = \frac{4{,}94}{4{,}826S+0{,}583}$ **Eq- 5**

$G(s) = \frac{F}{Ds+E}$ **Eq- 6** using the resistance Rc: 1,98 ***Ω*** to 12 Vdc

$G(s) = \frac{36}{12{,}42s+7{,}27}$ **Eq- 7**

To tune each transfer function, we used the Simulink software developed by MahtWorks®, in order to see the behavior of each plant. This tuning is used to find the constants P (proportional), I (integral) and D (derivative) that will give stability to the plant. This means that the plant must operate in manual mode, also known as open loop mode [20], identifying the system as first order. For each scenario, a different temperature (set point) was established, a step was applied and it was maintained. The signals were observed in each sensor and changes in amplitude were recorded until stability of the same signal was found.

The design of the controller was based on the method proposed by [21] using Simulink again with the closed-loop system, which for synchronization purposes with the written code for the microcontroller was decided to use only the PID control , whose variables are recorded in table 1.

3. Results and Discussion

The same method described before was used for each actuator, using the mathematical model proposed, which was then applied, carrying out a balance of energy and heat over the process, to get the results recorded in Table 1. In this balance, the functions of each sensor, the final control elements and the system variables were taken into account to obtain three different transfer functions, (Eq2), (Eq4) and (Eq6). According to several authors, it is confirmed that the corresponding thermal model is classified as first order and that it describes the behavior of the system showing a monotonous increasing response without oscillations.

Table 1: Variables, results and data obtained through the equations

Container		Unit	Material	PVC	Air	Unit
Lengt	58,5	cm	Thermal conductivity (K)	0,17	0,02735	W/m°K
Width	39	cm	Specific heat (Cp) at 50°C	900	1007	J/Kg°K
Height	16	cm	Density (d) at 50°C	1390	1,092	Kg/m3
Area	7683	cm2	Thermal conductivity (K)	0,17	0,02735	W/m°K
Volume	36504	cm3	Specific heat (Cp) at 70°C	900	1007	J/Kg°K
Weigth	900	g	Density (d) at 70°C	1390	1,092	Kg/m3
Vac (area)	56,74	cm2	Ventilation duct	0,005675		m2

C_{rhp}	C_{con}	C_{cmv}	Ra	Rb	Rc	Rpe	Rph
0,00902	0,1934	0,00023	48	220	1,98	0,000294	0,009

Type	Mass (g)	Cp(Cal/g°C)
Skin	1	3,77
Blood	1	3,8
Bone	1	2,39
Muscle	1	3,94

Actuator	Ж	β1	T_6	ŧ	T_1
Peltier (Rc)	7	6,277	1,98	15,8600	0,38
Actuator	**α**	**β2**	**T_3**	**T_2**	**Y1**
Resistance(Ra)	7	333,378	1,835	9,438	46,62
Actuator	**α**	**β3**	**T_4**	**T_1**	**Y2**
Resistance(Rb)	7	7,002	8,27	0,000049	46,62

Data type	Vmax	Imax	Qmax	Atmax	Th		
Measured value	13,5	7	50	15	25	α(m)	0,42747253
Theoric value	12,5	5	50	12	27	α(T)	0,49242424

F.T Ra=ON, Rb=OFF, Rc=OFF			F.T Ra=OFF, Rb=ON, Rc=OFF			F.T Ra=OFF, Rb=OFF, Rc=ON		
Z	N	M	C	A	B	F	D	E
4,94	2,78	1,72	4,94	4,826	0,583	36	12,42	7,27

Controller		P	I	D	F(CoTi)
TUNE (Ra)	PID	0,4590	0,4805	-0,1539	2,982
TUNE (Rb)	PID	0,1556	0,0318	-0,2672	0,5823
TUNE (Rc)	PID	0,2662	0,2637	-0,0943	2,821

Physical system		H	F	T (°C)	V(vo)
(Ra)	PID	0,000041	0,00002391	70	220 Vac
(Rb)	PID	0,01	0,04166	50	12 Vdc
(Rc)	PID	0,01	0,0125	15	12 Vdc

As shown in the Table 1, each actuator has different constant times (T) and this changes the transfer function, also influences the value of the resistance and the temperature range, however the model remained stable, which will be useful in the calibration process of other sensors.

3.1. Response curve of the Ra actuator

In order to model the behavior of a system, it is necessary to collect theoretical information and experimental data of the actuator (Ra). To collect experimental data, the procedure was to connect the heating element directly to a 220 VAC power supply. Figure 8.1 illustrates how fast the actuator reaches a temperature of 270°C. Even though this element is able to heat up to 600°C, during the experimentation stage, it will only get 130 °C, and to prevent deformation caused by overheating of the plastic container due direct contact, a common ceramic tile between the resistor and the plastic floor, configures a way of thermal insulation.

Accelerated damage due to thermal expansion must be prevented trough the implementation of an electric power control system. The circuit described in figure 4, generates different current control stages according with each application or case study. The response illustrated in figure 8.2, shows the effect of the control action over the actuator, represented in heating time of 600 seconds to reach a temperature of 200°C (ten minutes), which is more suitable in comparison with the 50 second period illustrated in figure 8.1.

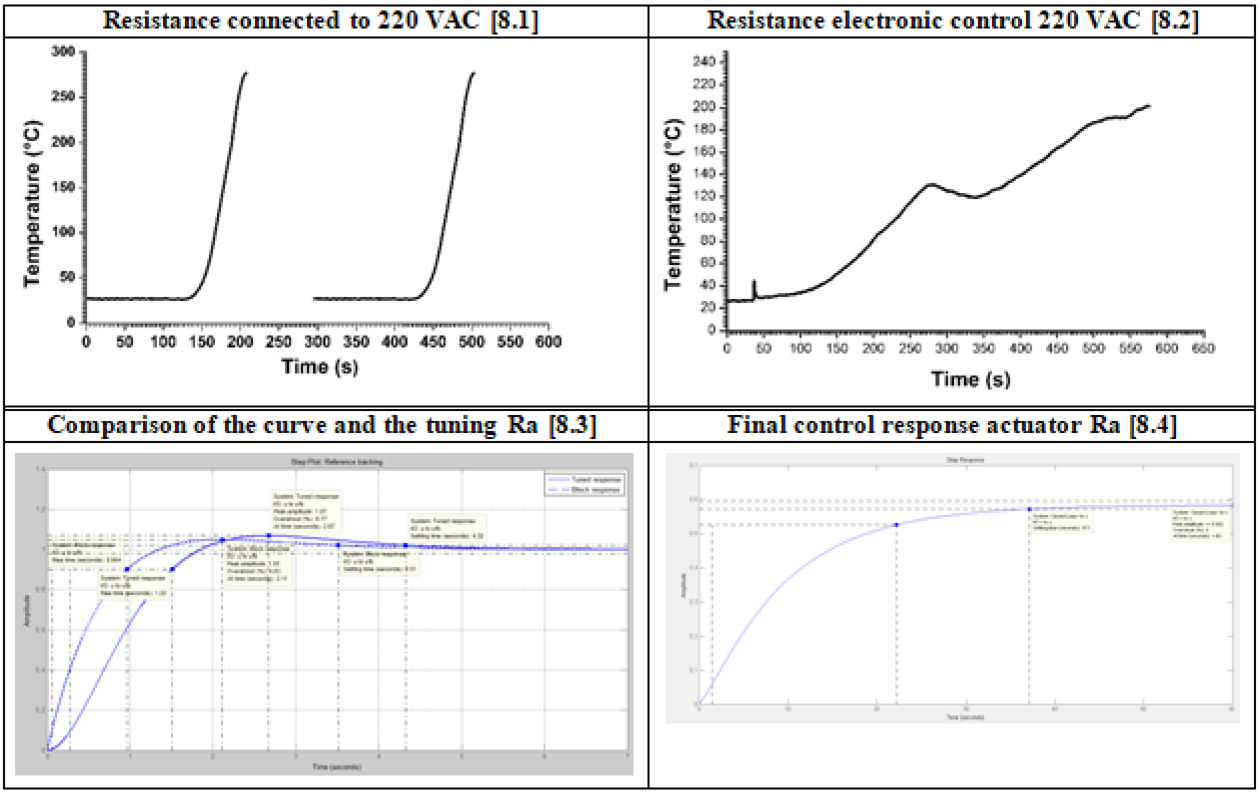


Figure 8: Actual response of the actuator, Ra of 160 W, using the electronic circuit and simulation

Figure 8.3 presents the presents the curve before the tuning process and the specific correction points. After the tuning process, the overshoot is 6.43% with a stabilization time of 3.68 seconds.

Figure 8.4 illustrates the result of the simulation of the PID control implemented with the parameters listed in Table 1, specifically for the actuator (Ra) at a reference temperature of 70 ° C, taking into account the thermal capacity of the air to said temperature. The result is a stabilization time of 60 seconds and an overshoot of 0%.

3.2. Response curve of the actuator Rb

In Figure 9.1 the behavior of the heating element Rb is shown, which unlike the Ra element, operates at 12 VDC. The curves in Figure 9.2 illustrate an apparent stability after the third minute, which is achieved through the control action of the circuit of Figure 6 (use TIP122 to regulate the output) and even without using the control algorithm PID.

Figure 9.1 shows the response of the heating element until reaching the limit proposed by the 60 ° C model, including the current delivery time of the electronic circuit extending the values in time up to almost four times with respect to figure 9.2.

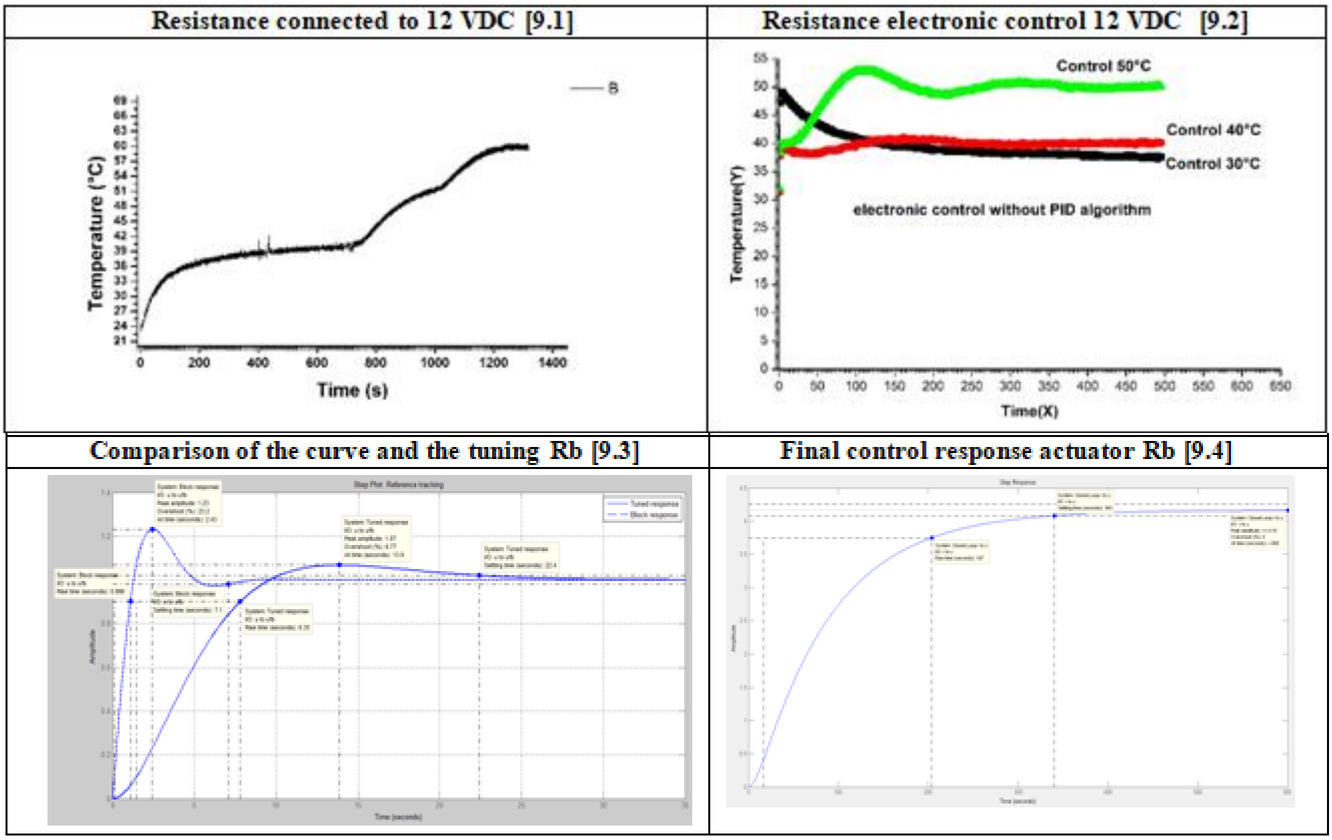


Figure 9: Actual response of the actuator, Rb of 25W, using the electronic circuit and simulation

Figure 9.3 illustrates the response curve at 50 ° C in dotted line and the continuous line curve because of the optimization process with the suggested PID parameters. To perform the tuning procedure, a set point is chosen to then apply a step to the plant and observe the signal from the sensors. The change in amplitude as a function of time is recorded and the values reported in Table 1. The overshoot in the signal is optimized from 23.2% to 6.77%, however the stabilization time increases from 1 to 6.35 seconds.

Figure 9.4 shows the correction of the stabilization time after tuning by means of the Matlab Sisotool tool, in which it is possible to have an overshoot of 0% upon reaching the second 600.

3.3. Response curve of the actuator Rc - Peltier

The response of the Peltier cell without electronic control is shown in figure 10.1. It can be seen that the gradient is about 10 °C/s going from 28 °C to 14 °C in a 14 minutes period, temperature as a function of time, response of the system without control, for 1 Peltier module. Because the container has a large volume, two Peltier modules were added to have three modules in total. The response of one single Peltier module with electronic control allows to have the same gradient of about 10 °C going from 28 °C to 13.5 °C with the advantage of extending the time up to 30 minutes to make measurements over time at certain temperatures as shown in figure 10.2.

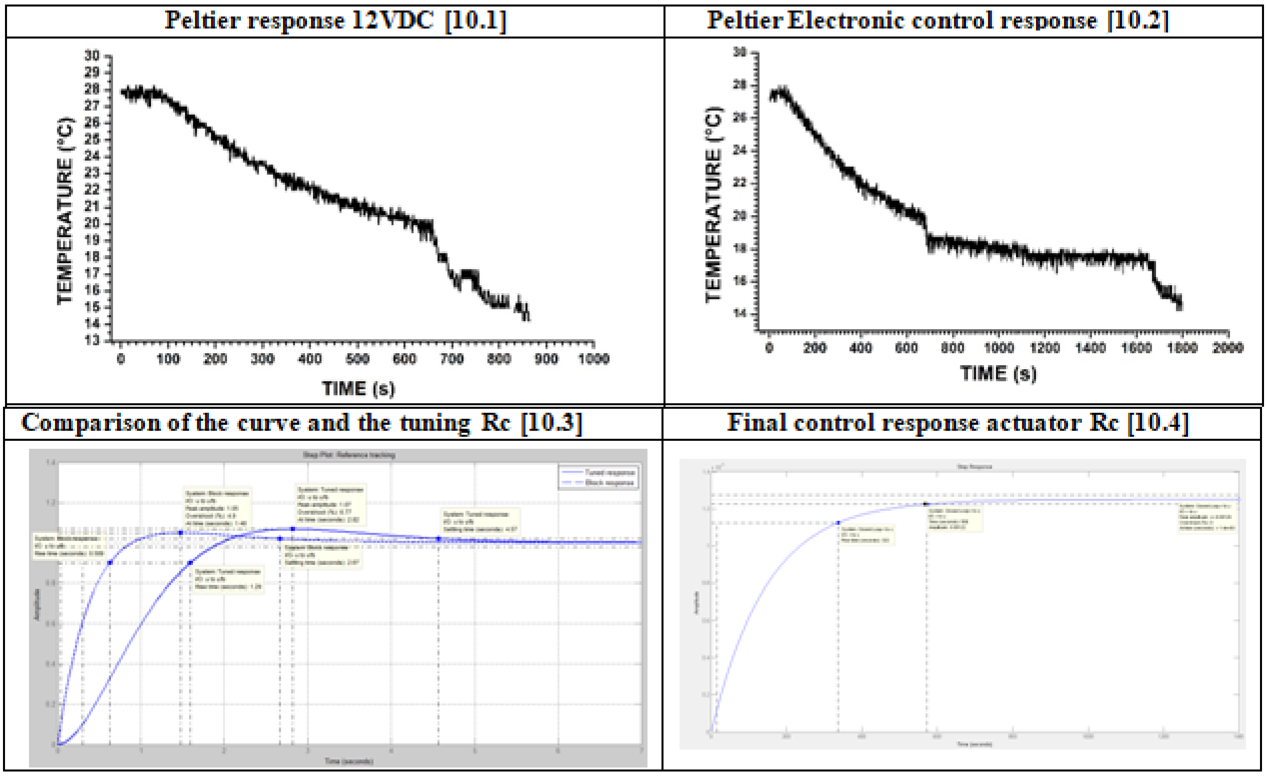


Figure 10: Actual response of the actuator, Rc peltier to 12V dc, electronic circuit and simulation

Figure 10.3 shows the curve temperature versus time for a set point of 15 ° C in dotted line, and in continuous line the curve tuned to the suggested P, I, D parameters (see Table 1). The same tuning method explained above was used. In this case, the overshoot goes from 4.9% to 6.77% and the stabilization time goes up from 2.67 seconds to 4.57 seconds. Figure 10.4 shows the correction of the stabilization time after the tuning process using the Matlab's Sisotool tool, in which an overshoot of 0% is achieved upon reaching 600 seconds.

$$\alpha = \frac{V_{max} * I_{max} * 2Q_{max}}{I_{max}} \qquad \text{Eq-8}$$

With the equation 8, the parameters (α), (Kt), (R) were obtained for the calculation of the heat using the voltages and theoretical currents and measured according to the temperature differential and that are reported in table 1.

4. Conclusions

- This work shows that it is possible to use the same mathematical and thermodynamic model in different scenarios. In this way the actuators Ra, Rb, Rc operating with sensors ST1, ST2 and ST3, which being of similar characteristics, act on the same system without changing its general configuration, obtaining three transfer functions in three different temperature ranges .
- The system was initially developed empirically, and although it worked satisfactorily through electronic control, the improvements introduced through the simulation and optimization of the PID parameters allowed a better response that is evidenced in greater stability and accuracy of the system. . The optimized strategy of PID control over the actuators, with its three different transfer functions, allowed reducing the transient response and sending the stationary error to zero. This helps to dampen the signal and brings considerable benefits when selecting the control action.
- It is difficult to maintain a low cost approach with easy-to-buy components for this prototype. Even though an inexpensive container was selected, it may not be the most convenient option, since when the temperature approaches 120 ° C (the heat transferred by contact of the heating elements with the walls of the container), it is damaged. Therefore, it is necessary to include a ceramic support that separates these components and allows the systems to reach a temperature of 190 ° C.

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GICEI: Scientific and Industrial Instrumentation Group, Department of Physics, National University of Colombia, at Medellin –Colombia.

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