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DESIGN AND APPLICATION OF A DIDACTIC PLATFORM FOR HEAT TRANSFER PRACTICE CLASSES

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Abstract. *This work describes the design and application of a didactic platform for temperature and analysis control in heat transfer practice classes. This control environment was equipped with five temperature sensors, a photo-coupler driver and an electric resistor, with heating function. A microcontroller receives the sensors signals and sends them to the computer interface programmed in Matlab, in which the monitoring and control of the system was implemented. This program sends a signal to the actuator to stabilize the thermal system. The platform can be used for modeling and controlling analysis of a heat pump, in addition to enabling the study of efficiency of controllers and thermal systems.*

Keywords: *Didactic platform, thermal system, control, heat transfer.*

1. INTRODUCTION

With the technological advances, the more precise industrial processes demand is increasing. For that, it is needed an evolution in the sensors, actuators, processors and control techniques. As entities that cooperate for that development, the universities aim to make qualified professionals with a solid theoretical and practical knowledge.

The didactic platforms are important tools that contribute in practice classes, because they are developed with the purpose of helping the students to understand the theory. The bigger the number of different platforms in a laboratory, the more engineering phenomena can be observed by the students along their graduation.

This work aims to develop a didactic platform to help students to apply the theory in practice classes in heat transfer and processes control areas. Besides this direct utility, the developed platform can be very useful to practice classes of control and instrumentation of mechanical systems from the Mechanical Engineering graduation course.

The main objective is to develop this platform for a heat transfer and processes control laboratory. The design has open source code and its hardware was made available to the academic community. Practical experiments were developed involving heat transfer conduction and convection, having a temperature control for heating of proof-bodies. It is believed that this information could be of great value to the academic community and serve as a basis for future related projects.

2. METHODOLOGY

The following are the components of the system that compose the platform, including the instrumentation used in the experimental evaluations and the methods used to determine parameters of performance analysis and system control.

2.1 System components

In order to choose the components of the platform, the literature was searched for the different types and the ones that best fit the specifications of the project were chosen. Here is a brief description of the components that were used.

2.1.1 Resistance temperature detectors (RTD's)

Resistive temperature detectors operate by varying the nominal value of their resistance under the influence of temperature. The voltage generated by the current flow is associated with a temperature value by means of the equation present in the sensor datasheet. (Texas Instrument, 2013).

2.1.2 Arduino development board

According to Al-Busaidi (2012), the Arduino development board is widely used by students because it is economically feasible, widely applicable and easy to program. It is based on C/ C++ language and contains functions of serial communication, A/D conversion, I2C communication, among others in its library.

The Arduino Uno is a development board based on the ATmega328 microcontroller. This microcontroller offers 14 digital inputs/outputs, 6 analog inputs, has a crystal generator clock of 16 Mhz, its ROM for recording programs is 32KB and has a 10-bit A/D converter. One of the differentials of the Arduino Uno development board is the presence of the ATmega16U2 chip, which is programmed for a USB to serial conversion, for greater ease of serial communication. (ATMEL, 2009).

2.1.3 MOSFET

Since 1970, various types of power semiconductor devices have been developed and have become commercially available. These can generally be divided into five types: power diodes, thyristors, bipolar junction transistors (BJTs), power MOSFETs and insulated gate bipolar transistors (IGBTs). (Rashid, 1999).

A power MOSFET is a voltage controlled device and requires only a small input current. The switching speed is very high and the switching times are of the order of nanoseconds. Their applications are increasing in high frequency and low power converters. MOSFETs do not have the problem of secondary breakdown phenomena like BJTs. However, MOSFETs have electrostatic discharge problems and require special care in handling. In addition, it is relatively difficult to protect them under short-circuit fault conditions.

2.1.4 Matlab

According to Chapman (2006), Matlab is a computer program of specific use, optimized to carry out scientific and engineering calculations. It implements the Matlab language, a high-level language in an interactive graphical environment, in which computational numerical computations, visualization and programming can be performed. Its extensive library of predefined functions makes programming much easier and more efficient.

Matlab has an extremely wide application, some examples are: digital signal processing, devices communication, systems control, tests, among others.

With the popularity and vast presence in universities around the world, this software is a good choice for projects developed by students of these institutions. And by simple language, one can easily understand the code, change it or even improve it. (Al-Busaidi, 2012).

2.2 Experimental procedures

The practical experiments carried out using the didactic platform are presented in this section, which can be seen in Fig. 1A. These experiments were done in order to generate data that allows to identify the mathematical models of the platform in different modes of operation. The obtained models were fundamental in the subsequent stage, that approaches the design of the dynamic controller of the system. In Fig. 1B, it is possible to see the internal part of the generating heat unit.

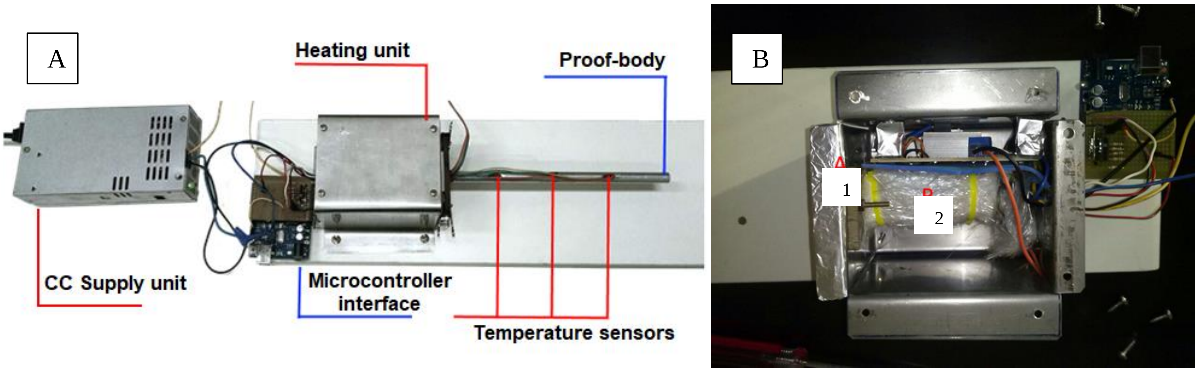

Figure 1. (A) Didactic platform overview. (B) Internal view of the heating unit, where (1) is the copper plate that transfers the heat from the electric resistor to the fins and (2) is the resistor enrolled in a thermal insulator

In Tab. 1, there are descriptions of the components used to build the platform.

Table 1. Components used to build the platform

Component - characteristic	Description
Platform base - material	Wood MDF
Platform base - dimensions	400 x 130 x 1.50 mm
Metal box - material	Stainless steel plate 0.7 mm
Metal box - dimensions	100 x 80 x 80 mm
Heater - power	60 watts
Heater - resistance	350 Ω
Heater - diameter	7 mm
Copper plate - dimensions	30 x 30 x 3 mm
Thermal insulation - material	Glass wool
Thermistors - quantity	5 units
Thermistors - resistance	10 kΩ
Power supply unit - voltage	85 V

In the development of the experiments it was necessary to use the supervision system developed so that the data acquisition could be performed.

When performing the test, the initial condition of the ambient temperature is verified, without having a coupled test body. The platform was configured so that the power dissipated in the heating resistance was 13.6% of the total power of 50 W. This value is maintained until the temperature of the base stabilizes. When the temperature reaches a stable point, the resistance is switched off, the ambient temperature is expected to be reached and then the data acquisition is finished.

2.3 Modeling procedures

In this section, it is presented the desctiption of the platform control and the mathematical modeling of two problems analysed with the appllication of the platform.

2.3.1 Platform control

The transfer function representing the system was determined by Eq. (1), where τ is the settling time divided by four, k is a constant and s is the time constant in the frequency domain. (Nise, 2002).

$$F.T.=\frac{k}{\tau.s+1} \qquad (1)$$

Using the transfer function obtained by the mathematical method to model first order systems, a routine was created in Matlab to obtain the open loop system response. A routine in Matlab was also implemented through the "sisotool" function to obtain the closed-loop system response for several controllers.

The routine implemented for the design of controllers for a closed-loop system allows to, adjusting the graph of the roots location, find a controller to achieve a desired behavior, considering the transfer function obtained for the first-order system. Adjustments were made for P (Proportional), PI (Proportional-Integral) and PID (Proportional-Integral-Derivative) controllers, aiming to obtain a lower stabilization time without overshoot, causing a great delay for stabilization because it is a thermal system.

2.3.2 Thermal conductivity practice

In this practice, an aluminum bar and a 1020 steel bar of the same length and diameter are used, in which the temperature profiles are measured in a steady state along their surface, as shown in Fig. 2. The bars are insulated to minimize the convection effects.

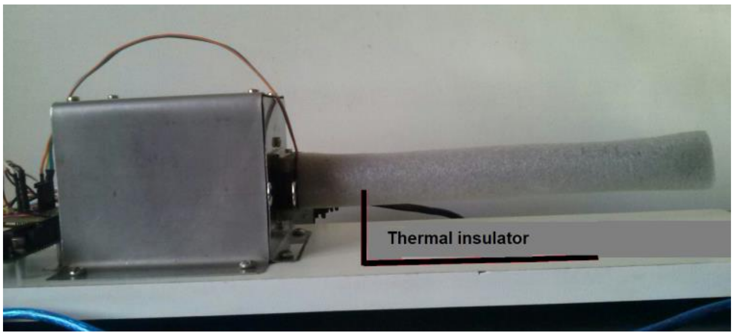

Figure 2. Proof-body with thermal insulator

With the data obtained, it is possible to obtain the values of the mean conduction coefficients. As the bars are removable, the platform can also be used to test different materials.

The didactic platform was adjusted in open loop to provide a constant heat flux, with a voltage of 23.5 volts. This voltage is applied to the heating 350-ohm platform resistor, where the heat flux obtained is of 1.58 Watts.

After the system reached equilibrium, measurements were taken for each " L " length distance of the bar. From these values, temperature lines as a function of the position along the fins were drawn.

Through the Fourier Law, given by Eq. (2) and Eq. (3), the thermal conductivities "k" of each material were calculated. Considering that part of the heat supplied by the thermal system is lost in the thermal insulation and in the heating resistor itself under a temperature variation ΔT, the heat flow q'' was used considering an efficiency of 80%.

$$q''=\frac{q}{A} \tag{2}$$

$$q''= k.\ \frac{\Delta T}{L} \tag{3}$$

2.3.3 Fins practice

The teaching platform was set to a base temperature of 80°C. After the system reached equilibrium, the ambient temperature measurements of 25.5°C and the fins temperature measurements were taken along its length. From these values, the temperature lines were plotted as a function of the position along the fins.

The theoretical model has the following characteristics: cylindrical aluminum or steel fin, with diameter D = 9.5 mm, length L = 200 mm, constant temperature stabilized at the base of 80 ºC, surface exposed to ambient air at T_a = 25.5°C with convection heat transfer coefficient of 20 W/(m²·K).

For the steel, it was considered k = 49 W/(m·K) and h = 20 W/(m²·K). For aluminum, k = 180 W/(m·K) and h = 20 W/(m²·K) (Incropera, 2008). The calculation of " m " was done through Eq. (4) to (6). It is assumed that "A" is the section area of the fin and "P" is the perimeter of this section.

$$A=\pi.D^2/4 \tag{4}$$

$$P=\pi\ .D \tag{5}$$

$$m=\sqrt{(hP/kA)} \tag{6}$$

For a fin insulated (adiabatic) at one end, the temperature can be calculated by Eq. (7), where T_b is the base temperature.

$$T=T_a+\left[\frac{(T_b-T_a).\cosh m(L-x)}{\cosh mL}\right] \tag{7}$$

3. RESULTS AND DISCUSSION

In this section, it is presented the results of the platform control and the suggested problems discussion.

3.1 Platform control

When the 15 V step was applied to the platform heat generating unit, the temperature behavior shown in Fig. 3 was obtained, with an increase of approximately 50°C.

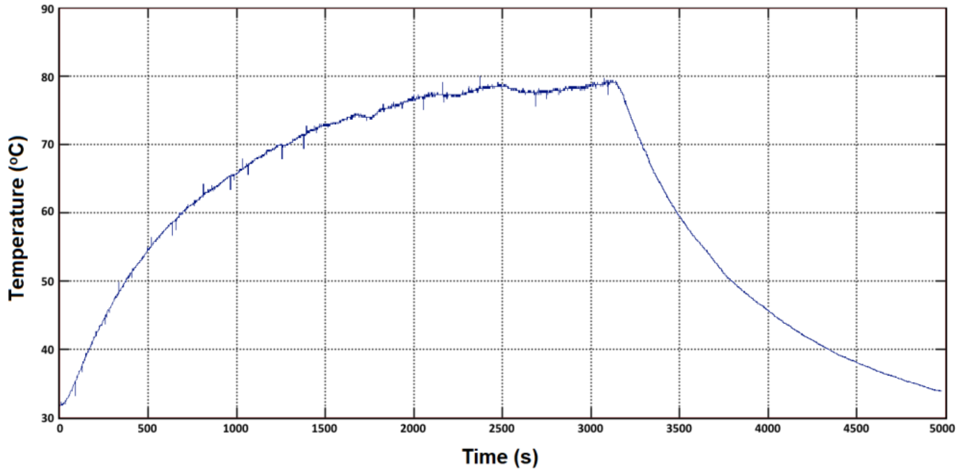

Figure 3. Platform temperature behaviour with a 15 V step

To evaluate the best controller for the system, P, PI and PID controllers were designed and their influence on the platform behaviour was analysed.

By observing the curves of the controllers P, PI and PID it is possible to conclude that, in terms of settling time, all of them are faster when compared to the open loop system. The controlled systems take from 320 to 366 seconds to stabilize, against the 2540 seconds taken by the open loop system. The P controller did not reach the desired temperature value because it did not have an integrative part that could correct the system error signal. The PI and PID controller had satisfactory responses, but the PID controller presented a bigger difficulty in obtaining the control coefficients. Therefore, the use of the PI controller was implemented.

3.1.1 Thermal conductivity practice

After the system reached equilibrium, the measurements were performed, as in Tab. 2 and Tab. 3

Table 2. Temperature in the aluminum bar (D = 9.5 mm, L = 0.2 m)

Spatial coordinate x (mm)	Temperature T (°C)
0	61.94
50	52.86
100	49.83
150	47.21

Table 3. Temperature in the iron bar (D = 9.5 mm, L = 0.2 m)

Spatial coordinate	Temperature

x (mm)	T (^oC)
0	81.7
50	44.6
100	38.6
150	34.9

From these values, temperature curves were drawn as a function of the position along the fins, shown in Fig. 4 and 5.

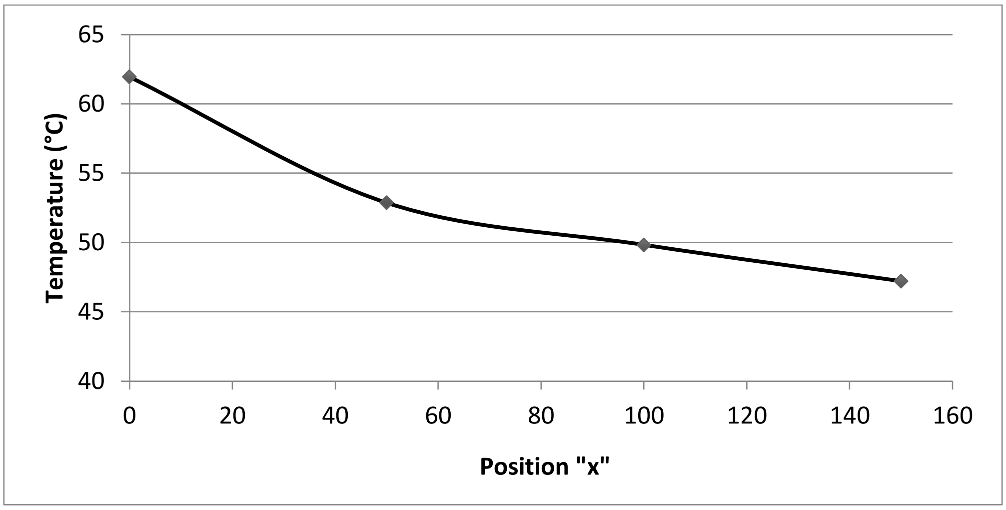

Figure 4. Temperature versus aluminum fin position

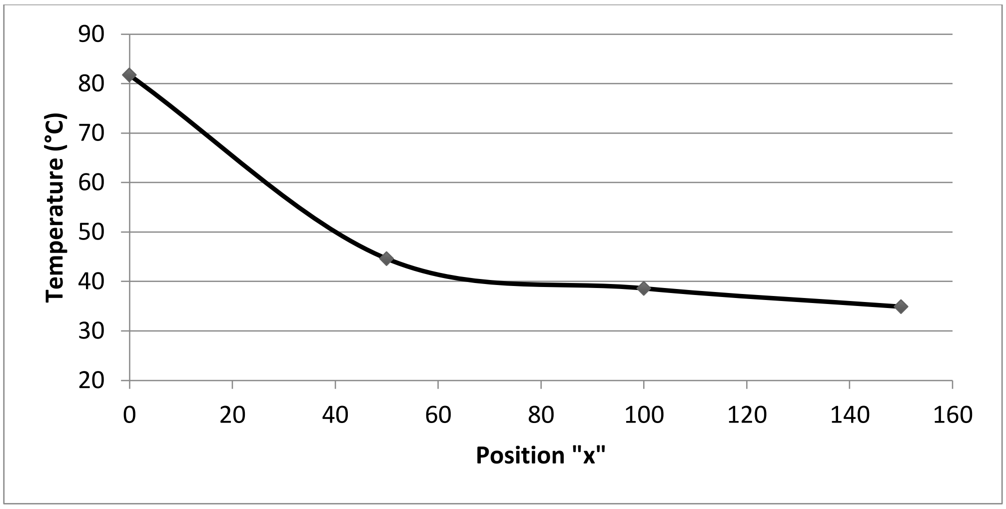

Figure 5. Temperature versus iron fin position

The heat flux was calculated as in Eq. (8). Through Fourier Law it was calculated the thermal conductivities of each material, shown in in Eq. (9) and (10).

$$q''=\frac{q}{A}=\frac{1.58*0.80}{\frac{\pi*0.0095^2}{4}}=17832\ W/m^2 \quad (8)$$

For the aluminum, L = 0.15 m and ΔT = 14.7 ^oC.

$$k=q''\cdot\frac{L}{\Delta T}=17832\cdot\frac{0.15}{14.7}=182\ W/(m\cdot K) \quad (9)$$

For the iron, L = 0.15 m and ΔT = 46.8 ^oC.

$$k=q''\cdot\frac{L}{\Delta T}=17832\cdot\frac{0.15}{46.8}=57\ W/(m\cdot K) \quad (10)$$

The values calculated by the data provided by the didactic platform were higher than the tabulated values. The differences were from 182 to 180 W/m.k for aluminum and from 57 to 49 W/m.K for steel. The thermal conductivities presented values close to the tables, but the difference can be caused due to the inability to predict how much of the heat provided by the resistor is delivered to the system.

3.2 Fins practice

The teaching platform was set to a base temperature of 80°C. After the system reached equilibrium, the ambient temperature was recorded as 25.5°C and fins temperatures along their lengths were recorded and organized in Tab. 4 and Tab. 5.

Table 4. Temperature in the aluminum bar (D = 9.5 mm, L = 0.2 m)

Spatial coordinate x (mm)	Temperature T (x) (^oC)	Temperature excess θ (x) = T (x) - T_∞ (^oC)
0	80.9	55.4
50	65.1	39.6
100	60.0	34.5
150	56.3	30.8

Table 5. Temperature in the iron bar (D = 9.5 mm, L = 0.2 m)

Spatial coordinate x (mm)	Temperature T(x) (^oC)	Temperature excess θ(x) = T(x) - T_∞ (^oC)
0	81.0	55.5
50	51.5	26.0
100	41.8	16.3
150	37.1	11.6

From these values, the temperature curves were plotted as a function of the position along the fins, and the result is shown in Fig. 6 and Fig. 7.

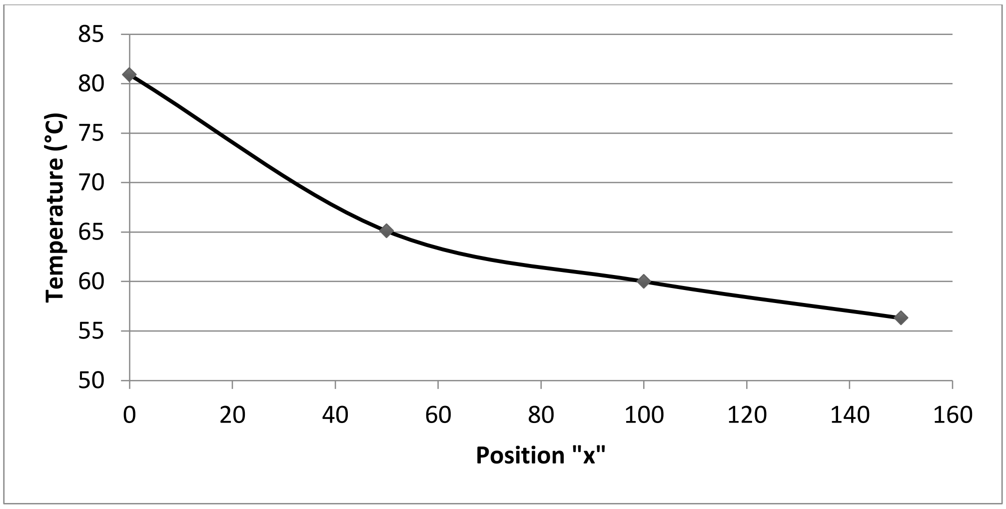

Figure 6. Temperature versus aluminum fin position

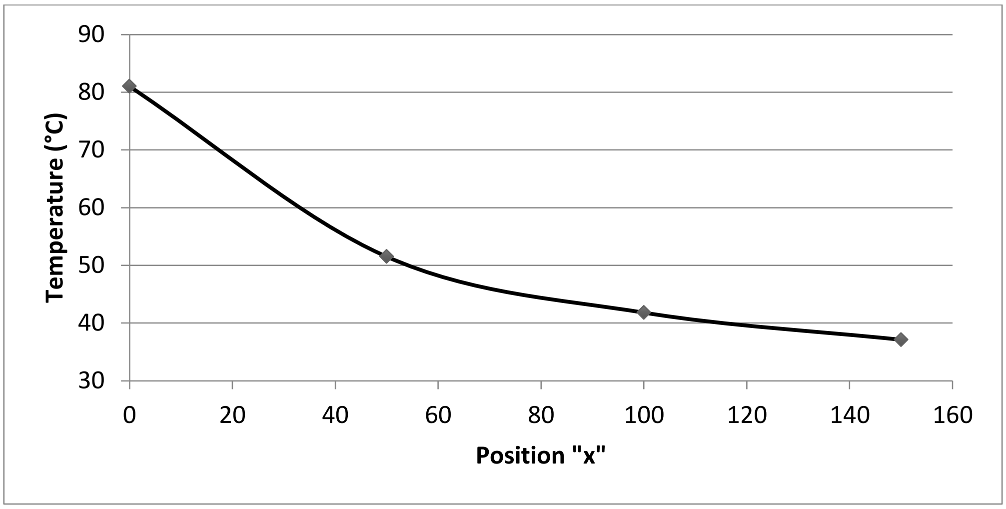

Figure 7. Temperature versus iron fin position

The calculation procedures were organized in Tab. 6 for the theoretical solution (analytical) case.

Table 6. Analytical solution for the fin problem

Aluminum fin	Iron fin
$A=\pi D^2/4=0.00007088$ m²	$A=\pi D^2/4=0.00007088$ m²
$P=\pi D=0.0298$ m	$P=\pi D=0.0298$ m
$m=\sqrt{(hP/kA)}=6.84$	$m=\sqrt{(hP/kA)}=13.12$

Temperatures were calculated for different positions in both materials fins, as in Tab. 7.

Table 7. Theoretical model values for the aluminum fin

Material	T_b (°C)	x = 50 mm	x = 100 mm	x = 150 mm
Aluminum	80.0	66.5	57.9	53.8
Iron	80.0	54.1	41.2	35.1

When comparing the temperature values obtained by the practical experiment and the theoretical model, it can be observed that they were relatively close. The errors presented can be due to imprecision of the natural convection coefficient adopted for the air, imprecision of the aluminum alloy thermal conductivity because of the lack of knowledge of its exact chemical composition or due to the non-perfect contact of the temperature sensors with the surface of the fin.

A good repeatability of the tests performed was observed, showing very close values in all measurements.

4. CONCLUSION

This work presented the development of a didactic platform for teaching in the areas of heat transfer and control systems. The use of this platform allows an analysis of the thermal behavior of specimens of different materials, besides the temperature control of the system.

In the thermal conductivity tests, the values obtained by the platform were close to the tabulated values, and this difference may have been caused by the uncertainty of the sensors and thermal losses in the supply of heat from the electrical resistor to the metal test body. And in the fin tests, the values obtained were also close to the theoretical ones, and the errors could have been caused by imprecision of the natural convection coefficient adopted for the air; variation of the chemical composition of the aluminum alloy that influences its thermal conductivity coefficient; non-perfect contact of the sensors with the fin surface.

Regarding the proposed objectives, the didactic platform developed provides the academic community with a tool that contributes to the practice of lessons learned in the areas of heat transfer and control system analysis.

It can be concluded that the Didactic Platform project fulfilled the main objective of leaving the academic community a portable and flexible tool to use in the laboratories, or even in the classroom, in the disciplines of heat transfer and control systems.

5. REFERENCES

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