MULTIDIMENSIONAL HEAT CONDUCTION: A DIDACTIC EXPERIMENT

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Abstract. *The visualization and the understanding of the behavior and the physical phenomena related to the transient heat transfer are one of the great difficulties of mechanical and chemical engineering students. The experimental activities represent an opportunity to elucidate and clarify some theoretical concepts.*
Considering this, this work presents a didactic multi-dimensional transient heat transfer experiment in a plain plate. The experiment was constructed to have a good graphical interface. The student can see the experimental process and the evolution of the temperature (transient condition) throughout the plate during the heating. The plate is warmed up with electric resistances. The student can also choose the maximum temperature of work sampling time, as well as the amount of resistances of heating (from one to three). After the collection of data the results could be analyzed an discussed in class.
This experiment seems to be very appropriate to demonstrate the characteristics, the transfer mechanisms and boundary conditions involved on the transient heat transfer in a three-dimensional perspective. The authors also are sure that the lab experiments in the transport phenomena course (heat in this in case), will promote student's motivation as well as analyses and synthesis capacity, needed in the professional life.

Keywods: *Transport Phenomena, heat transfer, experimental activity, education of engineering.*

1. INTRODUCTION

One of the relevant aspects in the teaching of mechanical engineering and chemical engineering is the understanding of phenomena of heat transfer, in the stationary and in the transient regimes. This subject is developed in the discipline of Transport Phenomena in the courses of Mechanical, Chemical and Electronic Engineering of the institution where the authors work. The understanding of the transfer phenomena, in a general way, requests a solid mathematical and physical base. In the heat transfer, the future engineer should be able to differentiate and to understand the different mechanisms in which it is processed (Incropera and DeWitt, 2003; Kreith, and Bohn, 2003). It is also important in the both processes (transient and stationary) that the students perceive the behavior and the influence of the involved variables (time, temperature, thermal conductivity, boundary conditions).
With the objective of increasing the students´ motivation and provide them with an opportunity to investigate the heat transfer, the assembly described in this work was projected and built. The experimental character in the discipline of Transport Phenomena is this way enlarged. It is a quite versatile assembly, of multidimensional heat transfer in a plate, which allows different heating conditions, involving transport mechanisms such as conduction, convection and radiation simultaneously. Besides, it was also aimed to complement the two cylindrical bars previously assembled and presented (Espirito Santo et al., 2006). The initial tests of this experimental equipment will be shown in the present work.

2. EQUIPMENT DESCRIPTION

The experimentation assembly is constituted of the following equipments:

- Aluminum plate (0,3m x 0,3m x 0,05m).
- Thermocouples of the type " j " class 2 (standard)
- Construction according to the norm IEC 584-2 (Rev. 6/89)
- Electric resistances. .
- Keying block.
- Data acquisition system (A/D converter and data communication)
- Computer.
- Software for acquisition and control (E3 Studio).

Device construction details and thermocouples placement are presented in Fig. 1, Fig. 2, and Fig. 3. In Fig. 2 the disposition of the components is presented in a schematic way, also indicating the thermocouple (thermocp.) number relationship with the vertical position (PV) and horizontal position (PH).

A general diagram of the mounted group is presented in Fig. 1. In it, the computer has 2 functions: the first is the control of the connection and turning off of the electrical resistances. This is done through the "keying block". This block is a power interface capable to connect and disconnect the resistances from the electric net; the second is the temperature (temp.) data storage in a data file of Microsoft Visual Basic. The acquisition of the temperatures of each one of the thermocouples is accomplished in pre-programmed time intervals (now every 60 seconds). In the lateral face of the plate, in equidistant points, 25 sensors of temperature (thermocouples type J) are placed and are distributed in 5 lines and 5 columns equally spaced and in the same depth. Between the thermocouple and the plate, a conductive paste was put to minimize the contact resistance.

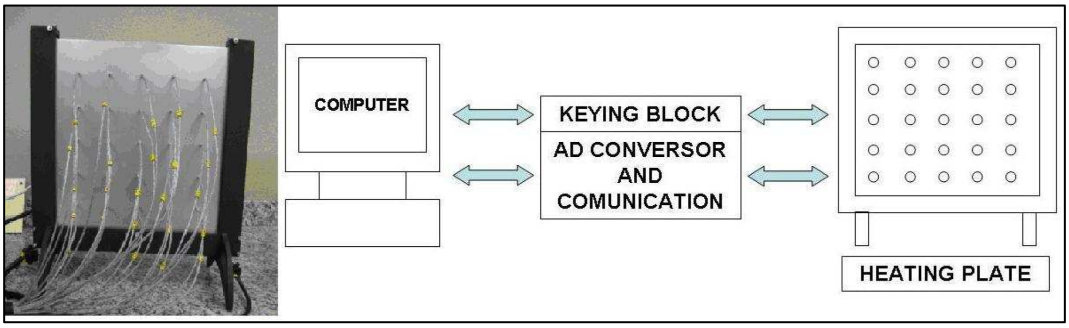

Figure 1. Mounted and assembly diagram of the complete experimental set.

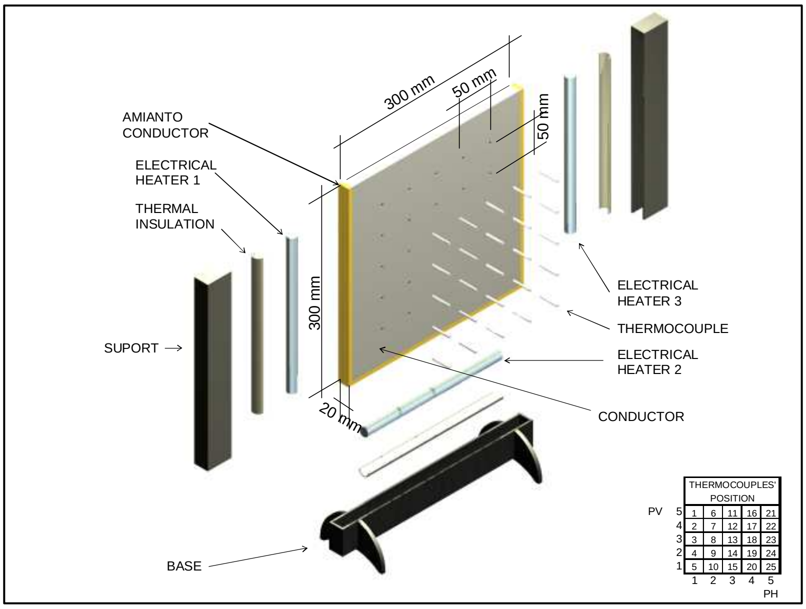

Figure 2. Plate and Thermocouples set.

The resistances, located in three of the four extremities of the plate (to see Fig. 1 and Fig. 2), are placed in an insulated support. Due to that fact, all generated heat is addressed to the aluminum plate. In these 3 extremities, because of the insulation, the heat exchange with the atmosphere can be considered null. When linked, they suffer heating for Joule effect and that heat is transferred for the aluminum plate (between the resistances and the aluminum plate, a fine foil of asbestos was placed to uniform the generated heat). The other extremity (superior) and the lateral faces of the Aluminum plate can exchange heat freely with the atmosphere (convection and radiation). The electric resistances power is of 150 W (nominal-effective value). It is possible to control them through the keying. For instance, a temperature can be stipulated by "software" and the "keying block" will act every time that it is necessary to maintain the value of the temperature arbitrated previously, turning on and turning off the resistances. Because of the function of the independent keying of the resistances, the experiment allows 7 possible situations of plate heating: each one of them separately linked, simultaneous connection of 2 resistances any or of all the 3 simultaneous. The block "converter A/D and communication" receives it amplifies and digitalizes the coming thermocouple analogical sign. Soon afterwards it sends to the computer according to the appropriate protocol to the door RS 232 (serial). The tasks of this block are carried out by a CLP. The typical resolution of the temperature is in the order of 1/10ºC. The administration of the experiment is done through the software "Elipse" with a routine dedicated to the experiment.

In Fig. 3 the visualized screens are shown in two different times of the experiment (in the chosen example: in the instants 0 and 35 min). For a demonstration purpose, it was chosen the situation of a heating ramp, with acquisition time of 2100 s (35 minutes) with the inferior resistance connected. All of the previously commented controls can be observed in Fig.3. The measured temperature (ºC) of the thermocouples, in any time of the experiment, can be seen in the rectangles. When starting the experiment the student should inform the program the room temperature for the thermocp. calibration that is done through software. Besides, the alteration of the temperature is accompanied by an alteration in the colors of the rectangle bottoms (indicators of temperature of each thermocouple). Varying between green (lower temperatures), to red (higher temperatures). This effect is very clear in the comparison of the Fig. 3 that shows the screen in 2 instants of the experiment. The student is able to have a good visualization of the temporary evolution of the temperatures during the experiment. These temperature data are also stored in a database that is available for subsequent investigations. In the experimental results section, some results obtained in the initial tests of the proposed experimentation will be shown.

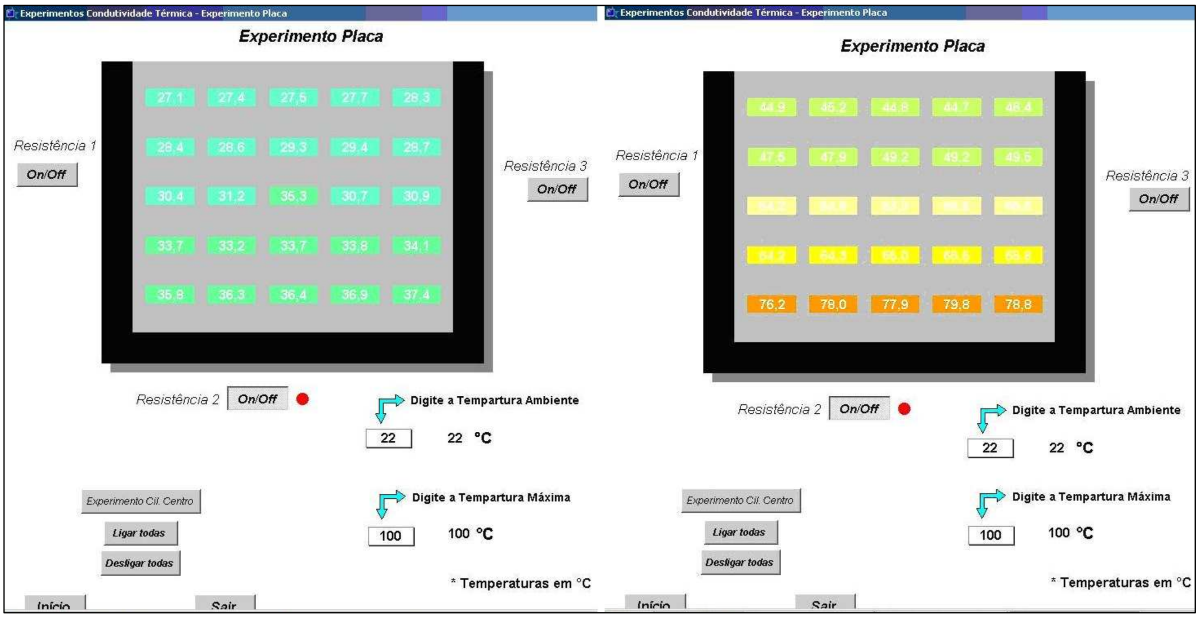

Figure 3. Computer screen of the experiment, time = 0 s and time = 2100 s.

3. EXPERIMENTAL RESULTS

As a follow up some results of the initial tests of the experiment are presented. The data refer to a ramp of heating of the aluminum plate, transient situation, with the inferior resistance turned on and time of acquisition of data of 2100 s (35 minutes), and with room temperature of 28ºC. It is convenient to observe that the times are expressed in minutes only for didactic visualization.

Figure 6 displays the temperature time evolution presented by all the 25 thermocouples, in the 35 minutes of data acquisition. Each one of them is represented by a color. Next to the graph, the thermocouple position in the aluminum plate, is shown, as well the inferior red strip indicating that the inferior resistance is on. This indication will be adopted in all the figures that will proceed. It is noticed that the heating behavior in all of them is similar and that the thermocouples which are more distant from the source take a larger time to begin their heating in relation to the nearest ones. Besides this the graph shows a "grouping" of curves that correspond to the thermocouples that belong to the same lines. As it can be seen, line 1, composed by the thermocouples 05, 10, 15, 20, 25, is the closest of the electric resistance (source of heat). As expected it reaches the highest temperatures (75 to 80ºC). It is followed by the line 2 (thermocp.: 04, 09, 14, 19, 24), line 3 (thermocouples: 04, 08, 13, 18, 23), line 4 (thermocp. : 02,07,12,17,22) respectively. The fifth line (thermocp.: 01,06,11,56,21) reaches the smaller temperature, in the range of 45 ºC. The transient situation is also very evident in this figure.

Worthy of note, that in the beginning of the data acquisition, the source closest lines are already in temperatures slightly superiors that the room temperature (28 ºC., in this case). This is due to the fact that in the first reading of the thermocouples the resistance is already connected. This should be corrected in the control software, so that the first temperature acquisition is done before the resistance to be turned on. The curves plotted in Fig. 4 represent the simple union of reading points, without any adjustment. In this figure, some fluctuations are noticed, particularly in the thermocouple 13. In few minutes this thermocouple was already able to keep up with the other measurement points on the same line. We believe this happens due to the initial adjustment of the thermocouples.

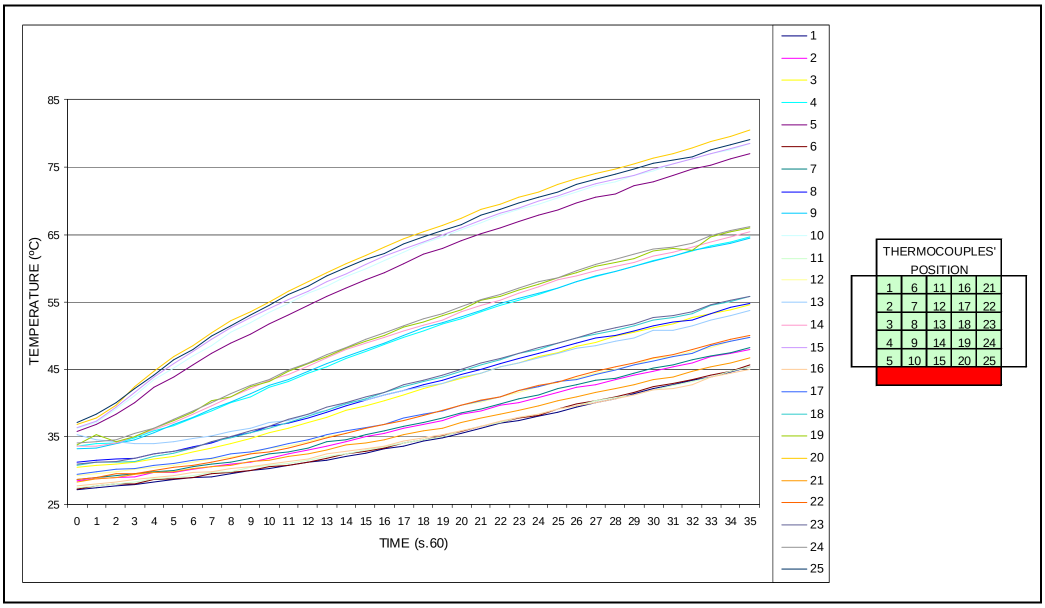

Figure 4. Temperature (ºC) distribution of all thermocouples as a function of time (s . 60); Inferior base heating.

The heating behavior described previously is also viewed in Figures 5 and 6 where the temperature time evolution is shown by the two external columns of thermocouples (thermocp. 01,02,03,04,05 and 21 22 23 24 25) and by the following internal columns (thermocp. 06,07,08,09,10 and 16,17,18,19,20). The symmetry effect already shown in Fig. 4 is also noticed there: the readings of the temperatures corresponding to the same lines are "contained" and show the same qualitative behavior. The difference in temperatures among points of a same line stays constant. The right column (thermocp. 21 to 25) reached temperatures slightly higher than the ones reached by the left line.

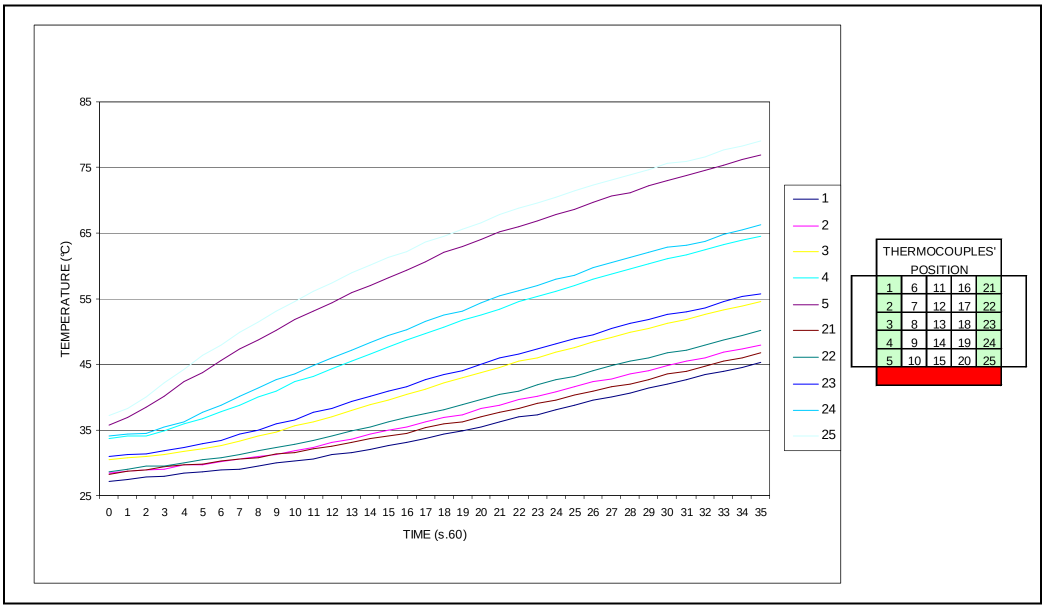

Figure 5. Temperature (ºC) distribution of thermocouples (1,2,3,4,5, 21,22,23,24,25) as a function of time (s . 60); Heating from the inferior base.

Figure 7 shows the temperature time evolution of the measurement points for different lines of thermocouples. That is, Fig. 7 shows the line 1(Fig. 7-A), line 2 (Fig. 7-B), line 4 (Fig. 7-C) and line 5 (Fig. 7-D). Once again, they showing the effect of symmetry of the temperature distribution, because the points in a same line have similar behavior. It is also visualized that the superior lines (more distant of the source) take a larger time to begin the heating and also present a slight difference of behavior. Some of them evidencing a logarithmic behavior (Fig. 7-A and B), and the others assuming an exponential behavior (Fig. 7-C and D).

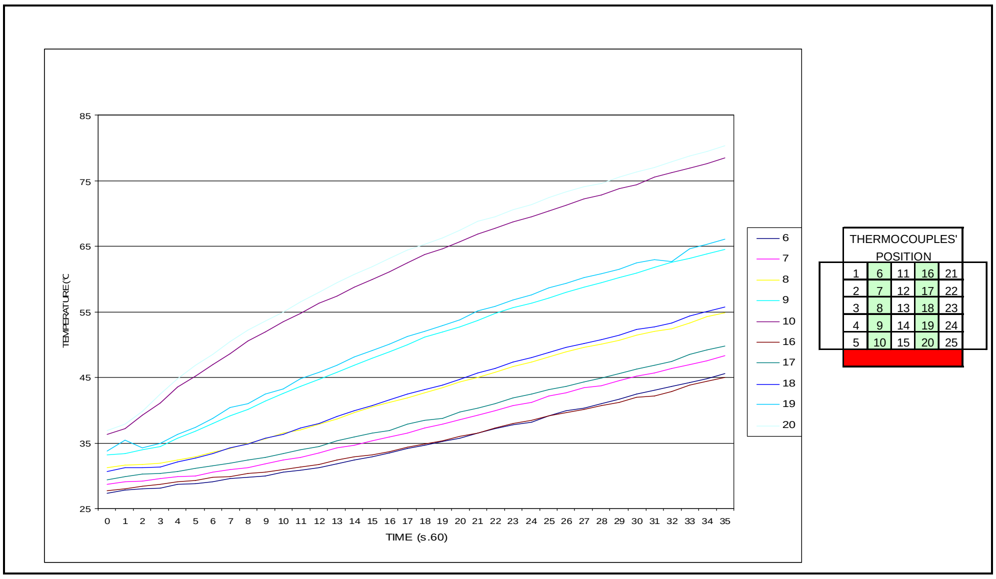

Figure 6. Temperature (ºC) distribution of thermocouples (6,7,8,9,10,16,17,18,19,20) as a function of time (s . 60); Heating from the inferior base.

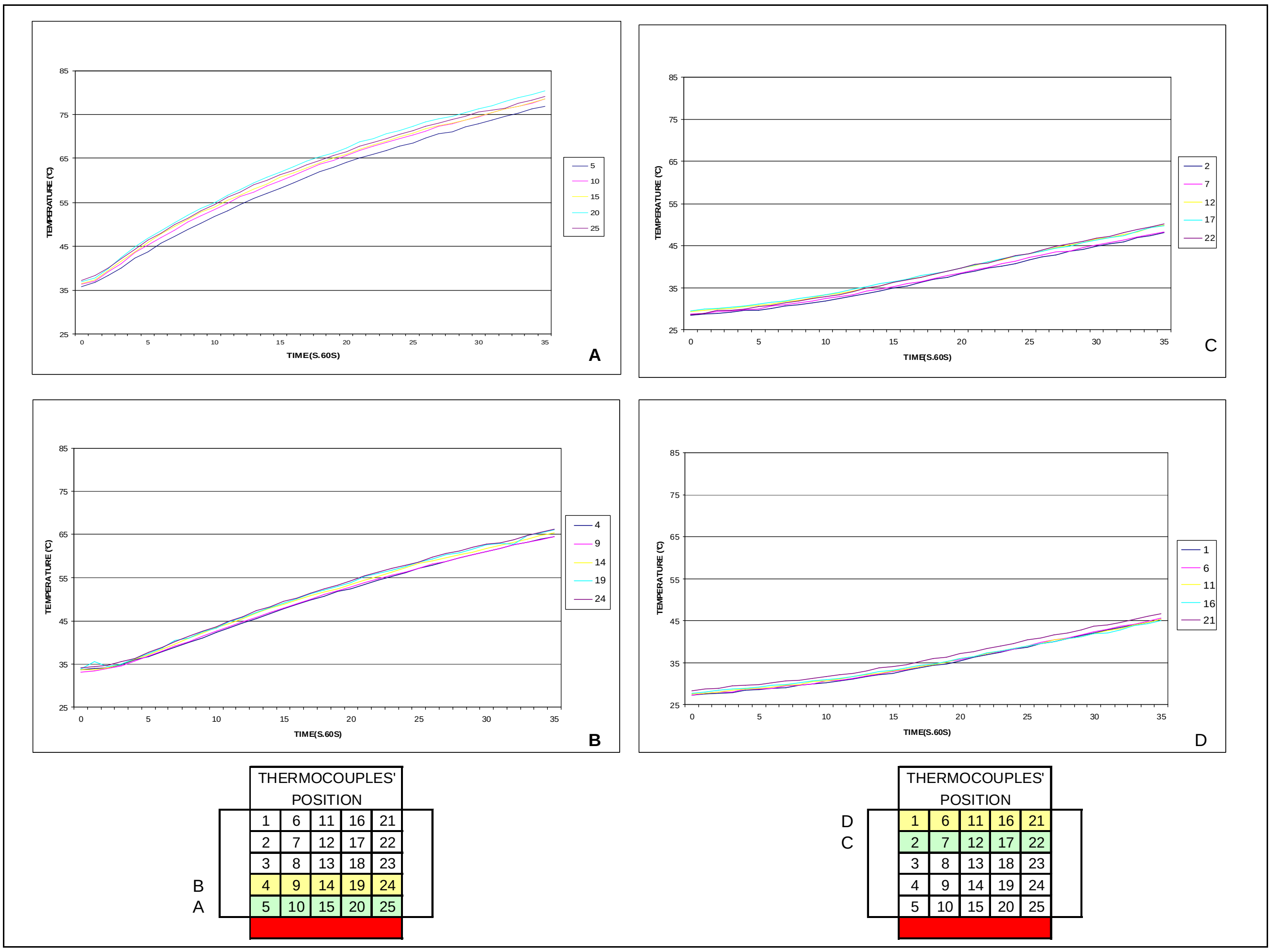

Figure 7. Temperature (ºC) distribution of thermocouples (5,10,15,20,25,4,9,14,24,2,7,12,17,22,1,6,11,16,21) as a function of time (s . 60); Heating the inferior base.

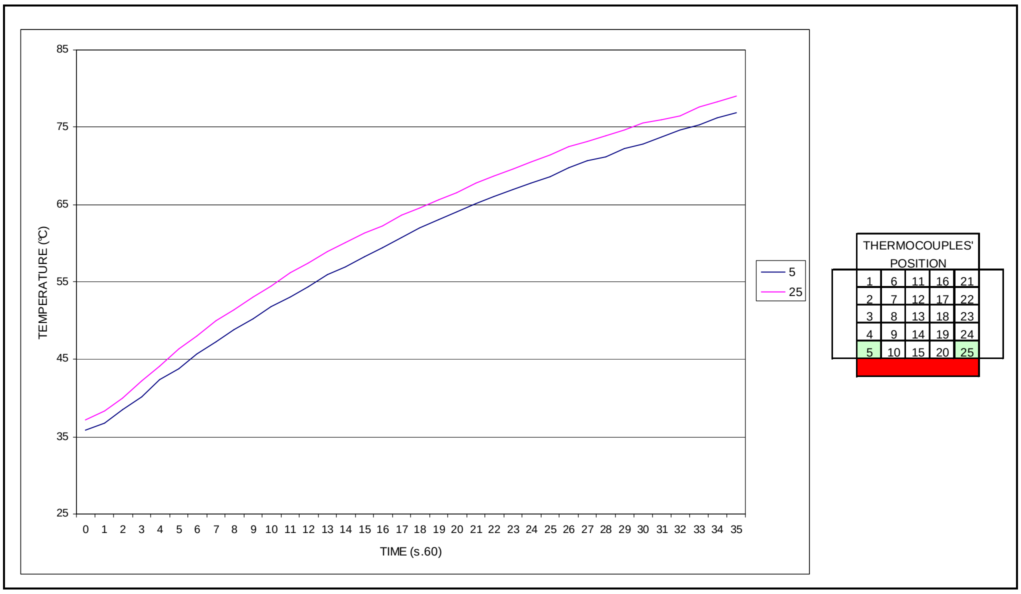

Figure 8. Temperature (ºC) distribution of thermocouples (5,25) as a function of time (s . 60); Heating from the inferior base.

Another aspect which was observed is the difference in temperature between the two extremities (left and right) for points of a same line. Fig. 8 was designed to show this difference better. The left extremity presents a temperature slightly smaller than the right extremity. This can also be verified in all the shown graphs, repeating for points of the same line. This situation can be associated to a slight difference in the heat flow of the electric resistance that being of tubular type, presents in its characteristics a colder area in the entrance region. It is known that the area of energy entrance of a resistance corresponds to a colder area of the electrical resistance. Another assumption is that the left side can have a larger escape of heat that the right side, as well the non-homogeneous conditions of the material of the plate (aluminum).

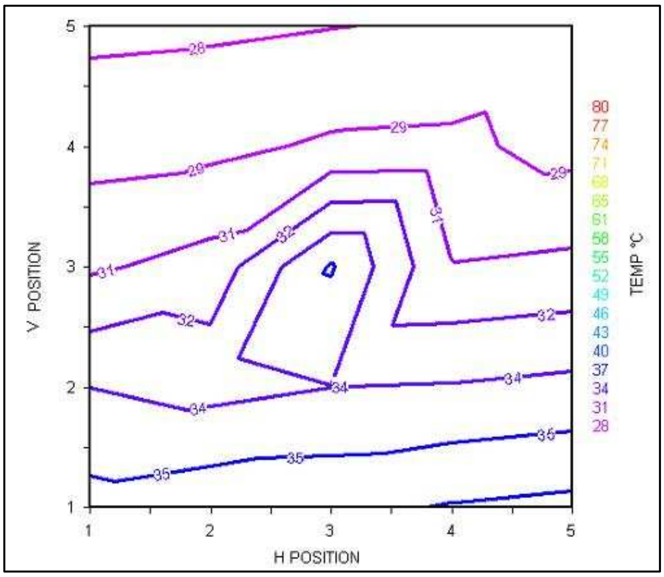

Figure 9. Temperature Isolines of plate in time=0s; Heating from the inferior base.

Figure 9 and Fig. 10 show the temperature distribution of the aluminum plate (temperature isolines), for the time zero and 35 min respectively. (see the Fig. 2 the horizontal H dispositions and the vertical V dispositions of the thermocouples in the aluminum plate). In the time zero (Fig. 9) once again it is evident the small temperature alteration shown by the thermocouple 13 already commented in the Fig. 5. In the time 35 min (Fig. 10) the isolines show a behavior of heat transfer that seems to be one-dimensional. This effect could happen due to the symmetry of the experimental set. Small fluctuations of temperature are visualized in the superior extremity of the plate at the 35th minute. It is believed that is the influence of the convection heat losses that happens in the lateral and superior surfaces of the aluminum plate. It seems to indicate that the multi-dimensional effects of heat transfer, expected for this set, are in balance due to the experimental set symmetry. It still shows a slight difference between the left and the right side of the experiment, already commented on previously.

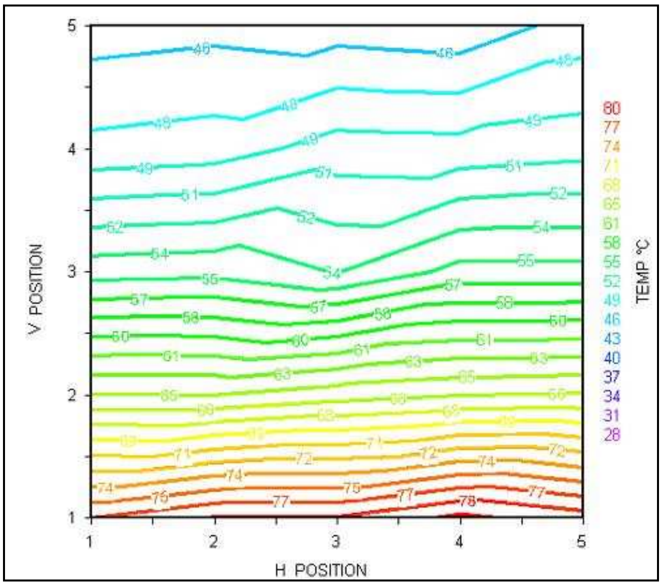

Figure 10. Temperature isolines of plate in time=2100 s; Heating from the inferior base.

Something interesting is shown at Fig. 11 and Fig. 12. They refer to the time evolution of the first thermocouples line (thermocouples 5, 10, 15, 20, 25) and of to last thermocouples line (thermocouples 1, 6, 11, 16, 21) The temperature difference between the left and right side of the plate in a same line stays in the range of 2,2 ºC to 3,1 ºC (for the first line) and in the range of 1,1 ºC to 1,6 ºC (for the last line).

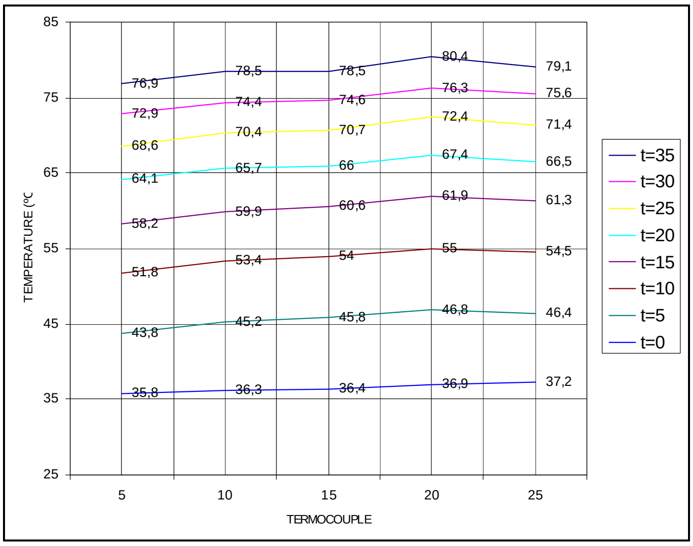

Figure 11. Temperatures (ºC) of thermocouple line (5, 10, 15, 20, 25) as a function of time (s . 60); Heating from the inferior base.

In a comparison between the two figures (Fig. 11 and Fig. 12) a lesser time variation of the temperatures of the last line is evident (average temperature difference is 17,98 ºC for 35 min) when compared with those of the first line (average temperature difference is 42,16 ºC for 35 min). Thus it is evident that a heat loss occurs throughout the plate. This loss is mainly due to the natural convection (It would be interesting to be able to measure involved speeds in the natural convection).

Figure12 shows that the warming up is higher in the initial instants than in the final ones. It sees there is a tendency of balance among the several transfer mechanisms that act in the plate (convection and conduction). This was also evidenced already in the Fig. 6.

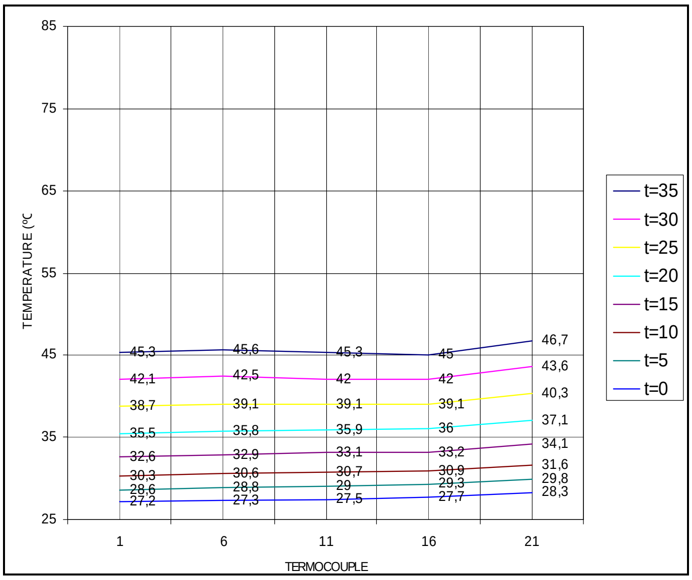

Figure 12. Temperatures (ºC) of thermocouple line (1, 6, 11, 16, 21) as a function of time (s . 60); Heating from the inferior base.

Figures 13 and 14 already show the temperature time evolution of the first and second column of the experiment. The difference in temperature between the thermocouples is clearly seen. Thermocouples 05 and 25 (next to the source) present greater temperature rise for the considered time interval. From them the temperatures decaying exponentially with the increase of the source distance. The difference in temperatures between the near source points and distant source points is in the interval of 8,6 ºC the 8,9 ºC (between thermocp. 05 and 01, and between thermocp. 25 and 21, respectively) in instant zero and grows logarithmical until the range of 31,6 ºC the 32,4 ºC for the 35 minutes. In the comparison between the two figures: a smaller temperature time variation of the last line is evidenced (mean temperature difference is 17,98 ºC in the 35 minutes) and those of the first line (mean temperature difference is of 42,16 ºC in the 35 minutes). As this plate is not insulated it is subjected to the natural convection on both sides. It is evident that the heat loss occurs due to convection along the height of the plate. In this way we can see that not all the heat transmitted by the source to the plate is transferred throughout the same one.

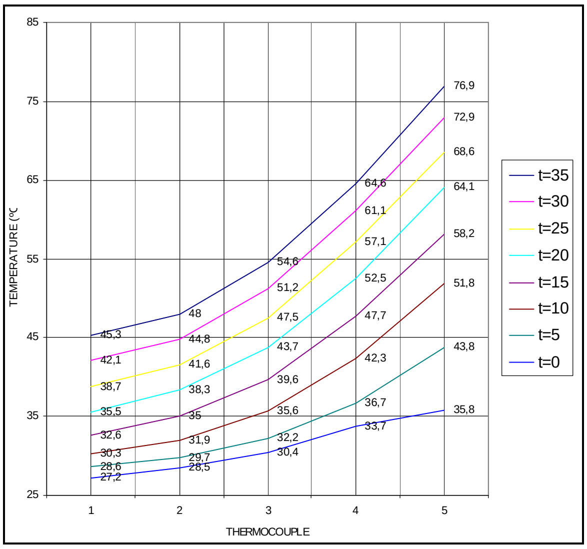

Figure 13. . Temperatures (ºC) of thermocouple column (1, 2, 3, 4, 5) as a function of time (s . 60); Heating from the inferior base.

In the process, the transversal heat exit can occurs due to convection and radiation and this exit increases with the increase of the plate temperature. This can be verified as we observe the difference between the points that are nearer and those that are more distant from the source.

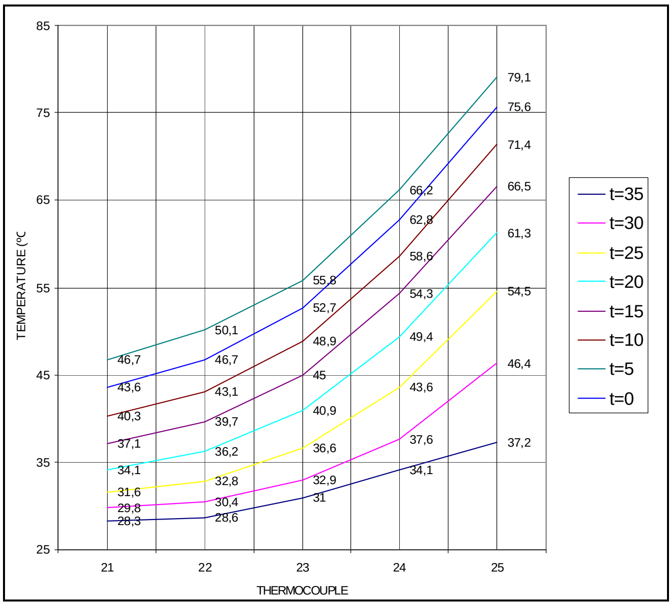

Figure 14. . Temperatures (ºC) of thermocouple column (21, 22, 23, 24, 25) as a function of time (s . 60); Heating from the inferior base.

We can also see that this heat exit increases with the increase of experimentation time. The temperature difference between the right and left sides is shown one more time. Even so we can't say much because this difference is in the range of uncertainty of the thermocouple. What happens is that type J thermocouples present an uncertainty associated to the sensor of ± 2,2ºC. This means that for the work range (between 10ºC and 100ºC) the uncertainty, in terms of percentile varies about 20% in the beginning of the heating up to 2 % in the end. These figures also show a bigger heating in the final instants and lesser in the initial instants.

4. RESULTS ANALYSES

The experiment involved a conducting aluminum plate, with a heat source located in the inferior extremity (heat entrance). The heat received in this extremity propagates throughout the plate. Two faces are insulated to restrict the heat exit. The other three faces have freedom to exchange heat with the environment (heat exit). This exchange occurs mainly through the convection mechanism, however a small parcel also can be lost for radiation.
The presented figures show a transient behavior. According to the heat transfer theory, the temperatures in distant points of the source are lower than the temperatures in the closest points. The beginning of the heating occurs later than the measure that occurs when the source becomes far.

It was also observed that for equidistant source points (in one same line of thermocouples), the temperature difference remains constant throughout the time. The average difference between the extremities left and right varies from 1,3 ºC in the first thermocouple line up to 2,7 ºC in the last line. The highest temperatures are reached the right side probably because of the existence of a cold zone in the entrance of electric energy. This entrance is situated exactly in this extremity of the conduct plate.

Small temperature fluctuations are seen in the superior extremity of the plate in the 35th min. It can be assumed that this is due to a not homogeneous heat loss in the region. But nothing can be appointed, because the fluctuation values are in the band of thermocouple uncertainty. J thermocouples present an uncertainty associated to the sensor of ± 2,2ºC in the work temperature range.

The heat exit to the environment is verified in the process. The intensity of this exit increases with the increase of the plate temperature. This can be seen by the difference in temperature between close and far points and by the fact that the difference was increased with the time. In relation to the difference between the left and right side, attention can be called to the fact that it is the near of the range of thermocouple uncertainty. Even so there is a coldest zone in one of the heated extremities of the plate. Finally another observed important fact was the influence of the symmetry of the set. This symmetry is not expected for other possible configurations of the experimental set.

5. CONCLUSIONS

The present work shows the construction of an experimental didactic set that seeks to show the processes of multidimensional and transient heat transfer. The equipment is quite versatile allowing several configurations with the possibility of alterations of boundary conditions. It still makes possible an interface that allows the students' attention during the whole experimental process, as well as the acquisition of data for subsequent analyses. It's necessary to emphasize that the initial tests were presented in this work. These tests were done with a continuous heat source located in the inferior part of the aluminum plate.

The results of these initial tests were quite good, although there are still some points to correct as the first temperature acquisition (that should be done before the resistance starting), and the situation of alteration of the initial readings of temperature of the central thermocouple (13), whose causes are being already investigated.

In the results was shown the behavior of the experiment for the transient condition with a heat source. The experiments are subject to multiples heat transfer mechanisms simultaneously (conduction, convection and radiation).

In this configuration there was showed a strong influence of the set symmetry making the heat transfer behavior to look as being one-dimensional. This situation is not expected for other possible configurations, for instance when the sources transfer heat for two contiguous sides of the plate.

This configuration was already tested in the classroom and the students were more motivated and involved. The students were asked about the behavior of the transient conduction, the heat transfer type involved, and estimated the radiation and convection involved. This was very productive. They can verify the influence of each type of heat transfer process involved. These experiments generated quite useful discussions in classroom increasing the student's perception in relation to the processes and phenomena involved in the heat transfer. In that way the objectives of this work have been reached. Very still it can explore, as the determination of the characteristic parameters, as the creation of mathematical models for the possible situations and consequent interaction with other disciplines of the engineering course (Özisik, M.N., 1980; Maliska, C.R., 2004). This fact rewards the authors and the students and the teaching-learning process happens in a natural way.

6. ACKNOWLEDGEMENTS

The authors thanks the apport of the C. Universitário Feevale without which this work could not have been carried out.

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