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Development of a theoretical-practical guide to study the radial heat conduction in steady state condition

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Abstract : This article presents the development of a theoretical-practical guide with purpose of improve the process of learning radial heat conduction in steady-state condition for undergraduate engineering students. With the construction of the radial heat conduction module, the procedure described in the guide was performed in such way that it was possible to verify that the proposed objectives were feasible; a comparison of these results were made with SolidWorks software, which gave a positive feedback. For that reason, is possible to affirm that the experience is a great educational tool, due to it facilitatesin the process of consolidation of the concepts in heat transfer, self-learning and improvement in critical thinking.
Key words : Heat conduction, engineering education, learning guide.

Introduction

Conventional laboratories has been traditionally the only place to develop practices and experimentations [1]because the practical training is relevant for the performance of the profession as for the personal and academic development [2], however, the Center of Laboratories and Workshops of Engineering (CELTI, acronym in Spanish) located at the Universidad del Atlántico (Barranquilla, Colombia) does not have the optimal conditions to provide a learning environments to engineering's students.

According to a study carried out with students of Engineering of the National Faculty of La Plata showed that 45% of them have an inclination toward kinesthetic, an expected result, since the engineering programs are geared towards making, to work and the experimentation [3], for this reason is confirmed that praxis is transcendental for the consolidation of theoretical knowledge. Likewise, people have been carried out works based in the design of competency learning methodologies in areas of thermal sciences, where students become familiar with the fundamental concepts of heat transfer, general theory of open and closed thermodynamic systems and the application of mass and energy balances [4]; it also focuses on self-learning processes through the development of finite element methods applied to the problem of heat transfer with the use of commercial programs [5].

The phenomenon of radial heat conduction has been extensively studied at theoretical level, in which stand out works that propose mathematical solutions to differential equations with different boundary conditions, such as the investigation of thermal stress theory based on the conduction equation of heat with the derivative of time-fractional of Caputo [6]; another publication refers to a model supported with a solution of the Fourier series for the heat conduction in spheres with a concentric spherical nucleus [7]some authors present the results of the modeling and mathematical simulation studies of a regenerator filled with spherical form of alumina with different diameters considering two mathematical models: convection and radial conduction [8]. At numerical level, modeling and simulations have been developed with the help of Computational Fluid Dynamics (CFD) programs for the determination of heat transfer over a canned food product [9]; in addition, efficient numerical methods are presented with high precision to solve multidimensional heat conduction problems [10].

In order to provide the learning of radial heat conduction in steady state condition, some manufacturers have developed certain devices to give rise to this study. Ediboncompany [11] has built a radial heat conduction module which is a desktop equipment for the study of the principles of radial heat conduction and to allow the measurement of conductivity in a solid brass disc; it has temperature sensors, flow control valves, heating resistance, PID controller, among other devices. GUNT corporation[12] offers to his users a radial and linear heat conduction unit which has a linear and a radial experimental assembly, each fitted with a heating and cooling element. The test equipment is supplied with indicating and adjustment tools, a set of measuring objects, a set of hoses and a CD with GUNT software + USB cable. On the other hand, Armfield [13] presents the computer controlled heat conduction device HT12C; this accessory includes a solid disc of material that is heated in the center and cooled in the peripheral part, creating a radial thermal jump with its corresponding radial heat flow. It has six thermocouples type K located in different radios of the heated disc, fast couplings for a more agile connection of the cooling cylinder to the cold-water supply, a regulator to minimize the effect of the pressure fluctuations in the network supply.

Undoubtedly, the equipment produced by the companies mentioned make a significant contribution in the teaching-learning processes of students in theheat transfer subject, however, most of the elements that make up such devices present high costs in the market and mostly, they represent a difficult purchase for entities that does not have the capacity to make large investments. On the other hand, each manufacturer offers software for data collection in the equipment, which, in most cases, has a license that must be renewed from time to time, translating into a greater expense for the institution. They also need to provide training for people whose aim is to manipulate the units, due to the tools are different and require a specific operation for each one. These trainings, just like the licenses, must be canceled to the distributor, increasing the cost of equipment acquisition.

The main contribution of this work is to develop a theoretical-practical guide for the study of the radial heat conduction in steady state for the engineering student, based on the construction of the radial heat conduction unit manufactured by students of Mechanical Engineering from Universidad del Atlántico. The purpose of this guide is to test the phenomenon of heat transfer by radial conduction, to verify the concept of the thermal conductivity that is linked to this mechanism of heat transfer and to analyze its effect on the temperature'sdistribution, successively, to carry out the preparation of temperature profiles in different types of materials. In a similar form as the way how companies present it, it will be possible to realize the data collection by means of an Arduino MEGA whose will be connected to a computer; this implies a great saving of money, since it does not need the software license for its application.

Development of the theoretical-practical guide

The theoretical-practical guide was elaborated by the authors to facilitate the execution of the laboratory experience where the radial heat conduction phenomenon is evidenced, in order to favor the learning for undergraduate students of Mechanical Engineering in a significant way. In the first part, the basic concepts are presented to interpret the heat transfer mechanism, then the guidelines for the realization of the experience are shown and, finally, is provided the necessary elements for the data registration, which should be analyzed to establish relevant conclusions.

The development of the theoretical-practical guide was based on the discovery method 'active-productive', which enhances productive thinking, helps students to know and practice research techniques and, encourages greater possibility of transfer the knowledge learned to some different situations, etc. [14-15].

In this sense, authors have developed guides for the simulation of thermodynamic processes, with which they verified the positive effect of the use of computational tools on student learning in air conditioning processes [16]. Were made some guides' descriptions to explain the cognitive progression of students through activities that promote their independent work [17].It is composed by the introduction, fundamental equations, objectives, equipment description and the methodology. Figure 1 shows the theoretical part.

CHAPTER 2. RADIAL HEAT CONDUCTION IN STEADY STATE CONDITION

2.1. INTRODUCTION

In the industry, there are many applications where it is common to find heat transfer processes by conduction, such as heat treatments made to steels, heat conduction in materials machined result of high cutting speeds, use of steel and its alloys in the design of heat exchangers, among others. Because of this, it is essential that the student of related careers perceive and be in contact with the phenomenon of conduction.

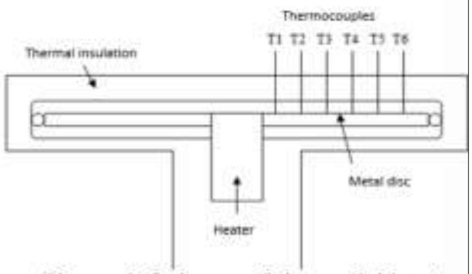

Figure 1. Scheme of the radial heat conduction unit

The implementation of a radial heat conduction unit shown on Figure 1 allows to the student carry out a theoretical-practical experience in which he performs the experimental verification of the phenomenon of heat transfer by radial conduction, without ignoring the presence of another forms of losses of heat. Also, it can verify that the thermal conductivity is an independent property of the geometry and analyze this effect on the distribution of the temperature, also the elaboration of temperature profiles in different types of materials.

2.2. FUNDAMENTAL EQUATIONS

Heat conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles [1]. Conduction can take place in solids, liquids, or gases. In gases and liquids, conduction is due to the collisions and diffusion of the molecules during their random motion. In solids, it is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons. A cold canned drink in a warm room, for example, eventually warms up to the room temperature as a result of heat transfer from the room to the drink through the aluminum can by conduction.

The rate of heat conduction through a medium depends on the geometry of the medium, its thickness, and the material of the medium, as well as the temperature difference across the medium, using equation 1 as follow:

$$\dot{Q}_{cond} = KA\frac{T_1-T_2}{\Delta X} = -KA\frac{\Delta T}{\Delta X} \qquad (1)$$

[1] Heat and Mass Transfer: Fundamentals & Application. Fourth Edition. Yunus A. Cengel & Afshin J. Ghajar. McGraw-Hill, 2011.

Figure 1.Introduction and fundamental equations in the learning guide.

The guide is focused on using the student's previous knowledge to initiate the relationship with radial heat conduction and discover its applicability in current industries, where students can consolidate what they have learned in classes and thus acquire the necessary experience for their professional life. In addition to that, they will be able to understand, relate, and verify, like it is expressed in the objectives described in Figure 2.

2.3 OBJECTIVES

1. To prove through the practice the phenomenon of heat transfer by radial conduction in steady state condition.
2. To determine experimentally the thermal conductivity in different materials.
3. To analyze the temperature distribution based on the thermal conductivity of each material.
4. To elaborate temperature profiles in the radial system for different materials.

Figure 2.Main objectives for the development of the experience

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2.3. EQUIPMENT

The main components of the experimental equipment developed are showed on Figure 4.

Figure 2. Radial heat conduction experimental equipment. a) Real Picture, b) Schematic Diagram.

Figure 2-b shows the schematic diagram of the equipment, in which stand out the following components:

1. Thermocouples type k, are sensors which have the function of measure the temperatures of the disc that is being heated. They are separated 2 cm between theirs.
2. The metal disc is the interchangeable element used for the study. There are three discs available for purpose: Carbon steel disc, stainless steel and aluminum with diameters of 119 mm and 3 mm of thickness.
3. Thermal insulation, is a cylinder made of nylon that has the function of avoiding the loss of heat to the outside, making real the condition of steady state.
4. PID controller is an instrument used to establish the temperature of the heat transferred to the disc. It has a temperature sensor in his input (thermocouple) and an output connected to a regulating element (heater). Also, verifies the temperature inside the disc remaining constant.
5. Arduino MEGA is a microcontroller that for purposes of this practice works as a bridge between the thermocouples and the data processing device (computer), showing the different readings made by thermocouples.

Although the figure does not clearly show the heater, it is that provides the heat transfer to the disc. It has a power of 50 W that results in the heat conducted.

The description of the equipment used to carry out the practice (Figure 3) and the procedure to be followed for its correct functioning are presented (Figure 4). There is also a space for collecting the data and the analysis made during the experience.

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2.4. EXPERIMENTAL PROCEDURE

To carry out this experiment the following procedure must be carried out using the two discs supplied (carbon steel, aluminum and stainless steel). For each material, the temperatures thrown by the thermocouples must be recorded.

No.	Procedure
1	Make sure that the main switch is initially off.
2	Locate the disc in the thermally insulated nylon cylinder.
3	Turn on the main switch.
4	Set the initial temperature with the PID controller.
5	Wait for a certain time interval to check the steady-state condition in the system (at least 10 minutes).
6	Record all data in Table 1.
7	Repeat the procedure by varying the temperature in the range of 55°C to 75°C.
8	Plot the temperature profile vs position in Figure 4 and Figure 4.
9	Simulate the experience with the help of software simulate and get the temperature at each point.
10	Plot the results obtained experimentally and the simulation.
11	Perform the corresponding analysis and draw conclusions.

Table 1. Data register

Material		Aluminum			Stainless steel		
Run	T_0(°C)	T_1(°C)	T_2(°C)	T_3(°C)	T_1(°C)	T_2(°C)	T_3(°C)
1	55						
2	60						
3	65						
4	70						
5	75						

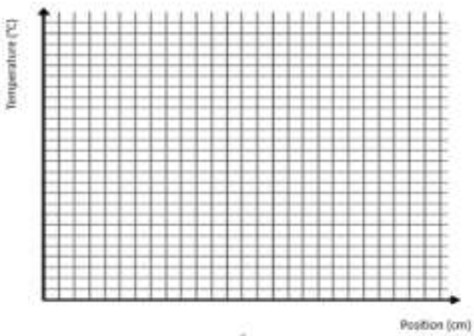

Figure 3. Temperature (°C) versus position (cm) Stainless steel.

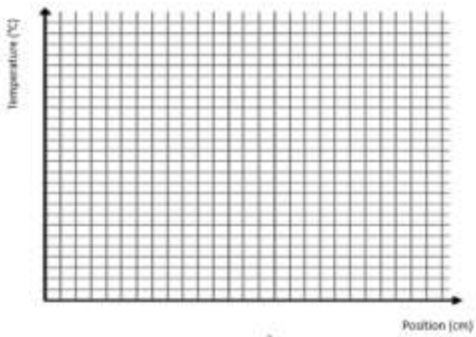

Figure 4. Temperature (°C) versus position (cm) Aluminium.

DISCUSSION:

Figure 4.Experimental procedure in the laboratory.

It is expected that students understand the parameters involved in the radial heat conduction process, their correlation with concepts such as thermal conductivity and the way how they interact.

Results and discussion

To verify the contribution of the radial heat conduction module over the consolidation of theoretical and practical knowledge in heat transfer, the work team effectuate the laboratory experience.

In the first instance, the carbon steel metal disc was chosen, subjected to heating at a certain temperature and has been waited a time to achieve the steady state condition; the selected temperature ranges from 55°C to 75°C and for each of them different data were taken from the thermocouples. Having done this for the aluminum disc, it was proceeded to register data into the Microsoft Office spreadsheet tool (Excel) and was simulated it in the Solid Works CAD software; Likewise, the results obtained were compared with the theoretical concepts shown in the literature.

Figure 5 shows the results of the simulations performed with Solid Works, a very useful software that allows the development of heat transfer studies. The initial conditions established to reproduce the simulation were the heat power (electric energy of the heater), the temperatures in the disc core and its periphery. When the graphics were plotted together with the results findings made experimentally it was found the differences between them are minimal, so it is affirmed that the module of radial heat conduction is advantageous for the analysis of conduction phenomenon.

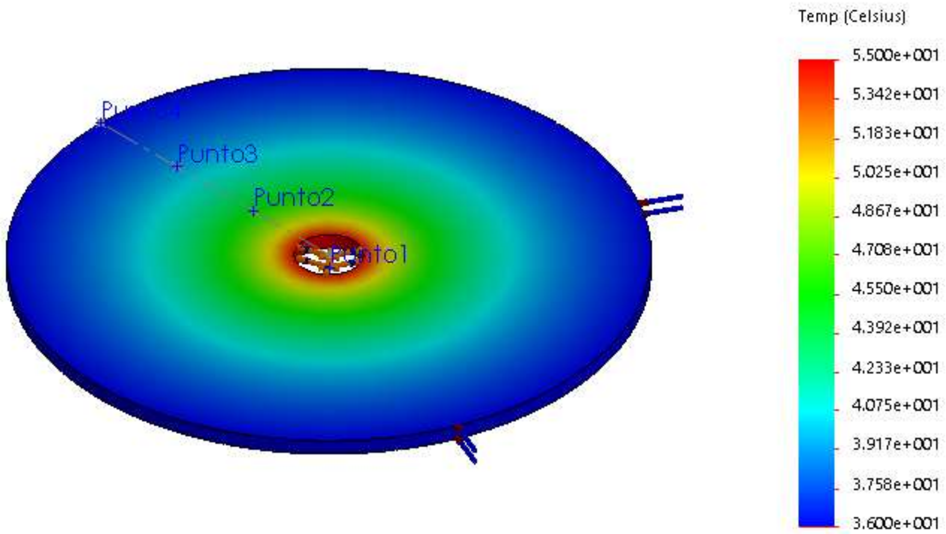

Figure 5. Simulation results for one of the discs.

The temperature profiles versus the position of the stainless-steel disc were plotted (Figure 6) and compared with those cast by the simulation. As can be seen in the figures, the temperature profiles have some variation, being 12% the biggest error found.

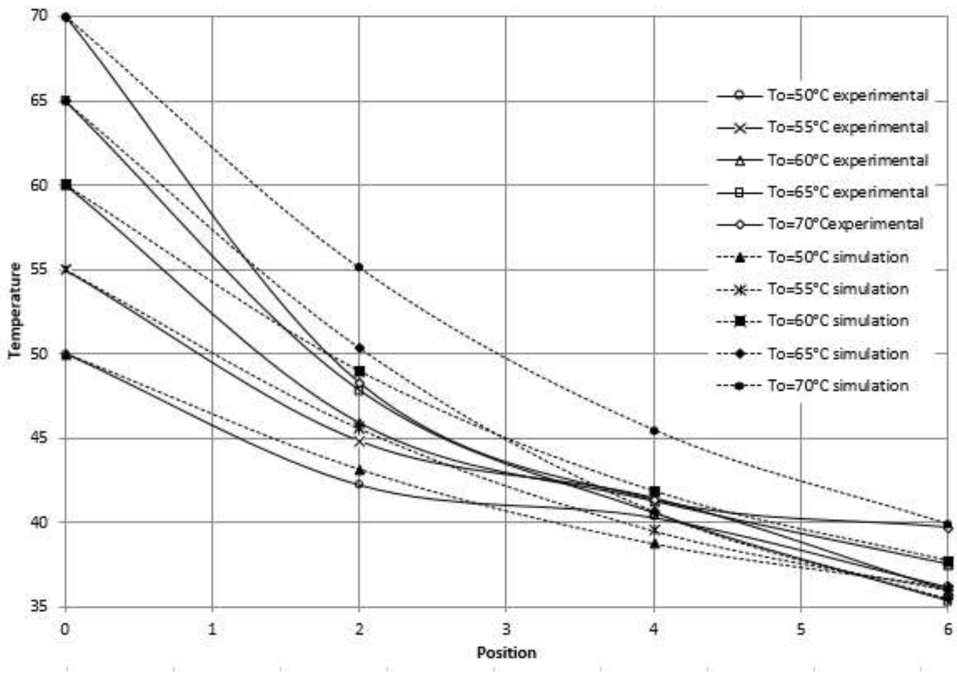

Figure 6.Results of temperatures vs position for stainless steel.

In the case of aluminum, experimental and simulated results were also plotted (Figure 7). For this material, the same tendency of the stainless steel was exhibited with respect to the values of the temperatures, since they have certain dispersions, being the highest error of 13%; that error comprise the difference between the experimentally temperatures found and the simulation.

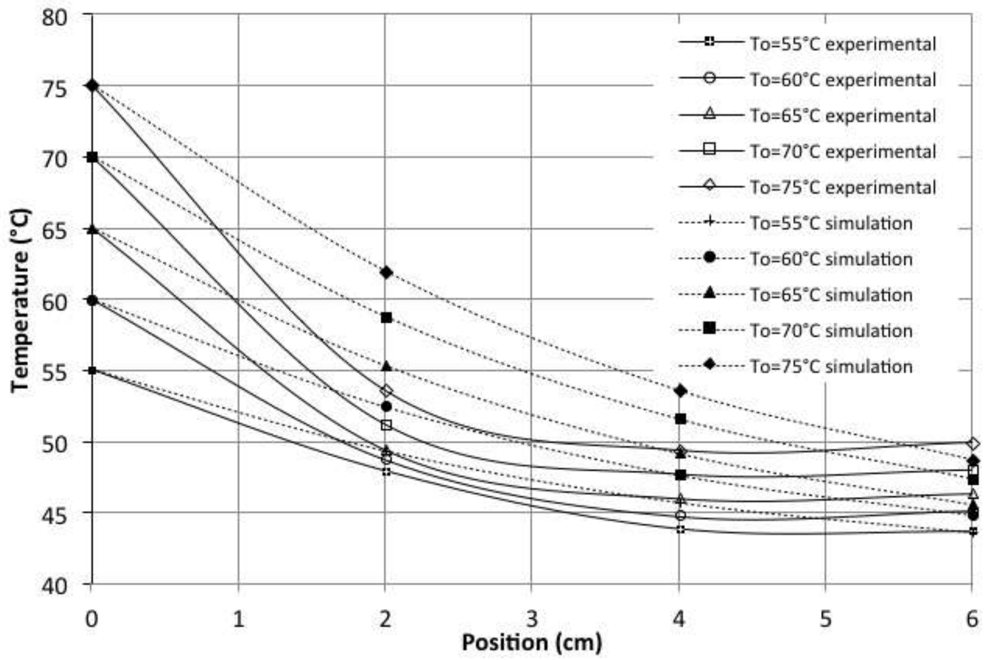

Figure 7.Results of temperatures vs position for aluminum.

As the graphs show, students will be able to analyze the behavior of the radial heat conduction phenomenon for different materials, where the conduct of the temperature with respect to the position can be perceived. From these results, they will have the possibility to examine the influence that the thermal conductivity has on the phenomenon and the variation of the heat according to the temperature that is initially selected.

Although there are some differences in the reading of temperatures experimentally and those obtained by the simulation, the laboratory keeps the main object of study: Look for the student to confirm that the conduction of heat occurs as it is presented in the literature, allowing them to acquire a meaningful learning about the topic and improve their critical thinking. On the other hand, the learner may achieve the ability to distinguish the error in the measurements due to the false contact between the thermocouples and the disc or another reason.

Despite the positive results obtained in the development of the theoretical-practical guide, due to the low errors presented, certain limitations were found because the team does not possess an instrument that facilitates the measurement of the electric power consumed by the heater in order to satisfy the temperature established trough of the PID controller; therefore, made difficult the experimental determination of the thermal conductivity for the materials since, it was counted on a single equation where the values of the thermal conductivity and the heat transferred were unknown.

Conclusion

A radial heat conduction module was implemented for the study of the conduction heat transfer mechanism, which seeks to visualize the main concepts associated with it, where the student can experimentally prove the phenomenon of heat transfer by radial conduction, verify the thermal conductivity and elaborate temperature's profiles for different types of materials.

Additionally, the theoretical-practical guide was developed to allow the student to be contextualized with the knowledge and guidelines necessary to carry out the experience. It presents the theoretical part with the fundamental equations that model the phenomenon, as well as the objectives to be achieved; also, a brief description of the equipment components and the methodology to be followed together with the respective tables, graphs and conclusions to make the laboratory more didactic.

Performance tests were applied on the equipment where the experience was executed and it was corroborated the data obtained with the theoretical concepts and simulations to calculate the errors. From these results, it is evident that the implementation of experimental laboratory tests that allow the contemplation of heat transfer phenomena can ensure that the students achieve a meaningful learning, taking as its main axis the teaching of an adequate theoretical base, whose consequences will be students better prepared to face challenges in the industry, the proper use of the different tools with which they will have daily contact and trust in terms of decision making.

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