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Experimental and Theoretical Study on Free and Force Convection Heat Transfer

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Abstract

In order to improve the learning processes in terms of conduction of heat in a transient state, we present in this work the assembly and development of a team whose objective is to determine the coefficients of convection of water and air that cool two cylinders of different material which are copper and steel, these will be subjected to a free convection in the first place and then give way to forced convection, once obtained the data will be made graphs and tables, which will allow comparison of an experimental and theoretical values. In this way the students of the engineering faculty can have a physical experiment on the phenomenon that occur in the heat transfer given during the class, which will allow them to strengthen their knowledge.

Keywords: Transient state, conduction, forced convection, free convection, heat transfer

1 Introduction

The practical experiments in the learning processes of engineering students are very important, since the experimental activity complements the teaching and learning process of the sciences [2]. Taking into account that the training engineers will face situations that require an effective decision-making, it is necessary to have a university education that complements the general basic knowledge and transversal knowledge related to its integral formation, together with the specific knowledge and capacities oriented to their incorporation into the workplace [7], [11]. In order to complement and strengthen the theoretical concepts that are taught in classrooms, the development of teams that allow the application of what is studied during the course should be promoted, an aspect that has been taken into account in the projects for the restructuring of undergraduate curricula, master's and doctorate under the approach of self-learning and self-management by the student [10]. Several studies have shown that students perceive and process in different ways the information they receive and hence have different unconscious patterns to acquire knowledge; that is, they have different learning styles [5], [13], According to a study carried out in Mexico, engineering students showed preference for active (72%), sensory (83%), visual (86%) forms of learning, indicators that show that experiments in laboratories or practices have a greater impact on the teaching-learning process in engineering [6].

With the objective of promoting the learning of heat convection in a transient state at the experimental level, commercial solutions have been developed, such as the HT17 thermal transfer equipment in transient regime version 6, designed by Armfield, with which it is sought to provide analytical solutions for temperature distribution and heat flow as a function of time and position for solid geometric bodies that are suddenly subjected to convection in a fluid at constant temperature, the equipment basically consists of a 3kW heater for the water bath, a duct , thermocouples and a variable speed pump that ensures that hot water passes around the body subject to evaluation [9]. On the other hand, the company P.A. Hilton Ltd has created a heat exchanger, which has the water called H103G, which consists of concentric tubes where hot water flows and the cooling water flows through the annular space in order to allow students to investigate the behavior of the numbers Reynolds, Prandtl and Nusselt [8], [16].In addition to this, multimedia tools for a better understanding of the phenomena that occur in heat transfer [14]. Amatrol presents a model, CD-11604 which, through attractive interactions and 3D animations accompanied by text and audio, explains the heat transfer by conduction and convection in a more didactic way for the students [1]. But all these solutions that have been presented have their limitations, since these equipment’s are expensive, which makes the disposition to acquire them more difficult in addition that to handle the equipment it needs an adequate training or orientation, in order not to do an evil use and avoid damages, from here lies the importance that the students themselves develop their equipment. The main contribution of this work is to present the development of an economic equipment to validate the data obtained experimentally with the theoretical values for the phenomenon of heat transfer by heat convection in a transient state. For this analysis was designed the equipment that uses a thermocouple is recorded the temperatures in the time in a cylinders of bronze and steel, which were subjected to cooling processes with air and water of forced and freeway, allowing to determine the coefficients of convection for each case, in addition to the Nusselt number.

2. Methodology

This section presents the technical description of the equipment developed, its constituent elements and functional characteristics, as well as the experimental procedure that was carried out for the development of the experimental theoretical study. Finally, the fundamental equations used for the theoretical calculation of the convective coefficient are shown.

2.1. Equipment Description

For the realization of this experiment it is very important to have specific instruments and equipment, as shown in Fig. 1, one of them is the thermocouple (3) which is the most common temperature sensor used industrially. A thermocouple is made with two wires of different material attached at one end, when applying temperature in the union of the metals a very small voltage is generated (Seebeck effect) of the order of the millivolts which increases with the temperature [12]. The thermocouple is connected to an Arduino (2), which is an open source physics development platform, based on a simple microcontroller board and a development environment to create programs, which had the function of carrying the data recorded by the thermocouple to a computer (1), where said data was recorded. On the other hand, as a temperature gradient over time, it became necessary to use an oven whose function was to generate heat, which is transferred to the steel and bronze cylinders for a certain time so that afterwards the cooling is carried out with the respective fluid , either air or water. For forced convection in air there will be a fan which increases wind speed, the instrument used to know the variables in this condition was the anemometer to measure both wind velocity and temperature [15]. In addition to the aforementioned, other implements were also needed to facilitate the handling and collection of data such as the thermometer, timer, tweezers, gloves, balance, fan (4), hopper (7) and acrylic tube (5).

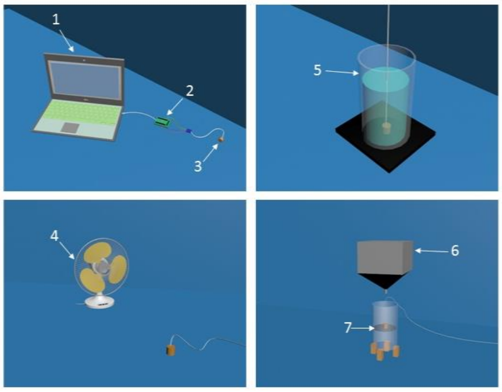

Figure 1. Instruments and equipment used for practice

2.2.Experimental procedure:

Below is shown in the Fig. 1 an overview of the steps taken for development and data collection. In the development of the practice, the procedures for the study of convection in the air (free and forced), and water (free) were very similar, starting from taking the cylinders of two types of different metals, one of bronze, which has a diameter of 0.032m, with a mass of 0.178g and another of Steel whose diameter is 0.035 m with mass of 0.2g, bearing in mind that each cylinder must have installed in its center and thermometer to record the temperature at each instant. The cylinders are placed in the oven for 20 minutes to be heated, then are removed and their temperatures are recorded, once this is allowed to cool with ambient air, as indicated in Fig. 2 at a given time (convection fresh air, later several temperature records are taken with respect to the time, all this data is stored in a computer that must be connected to the thermocouple by an Arduino. The process is then performed again but using a fan as a cooling medium at a distance of 0.5 m and temperatures are recorded (forced air convection), followed by the heating steps, but when cooled, the cylinder is introduced into a test tube with 700 ml of water, as indicated in Fig. 2, after the time already determined the temperatures (free water convection) are removed and recorded. The cooling time periods for free air convection were 20 minutes, recording the temperatures every 10 seconds, while for free convection by water the cooler was allowed to cool until the temperature stabilized, recording it every second.

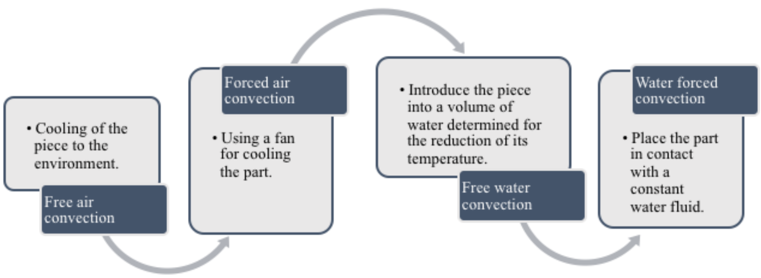

Figure 2. Experimental steps for the development of the experiment

2.3.Fundamental Equations:

For the case of the convection of heat in transient state, the balance of energy applied to the solid in cooling in transitory state is given as:

$$\dot{Q}_{cv}(t) = \frac{dE(t)}{dt}, \quad (1)$$

where $\dot{Q}_{cv}(t)$ is the heat transfer by convection and is given by Newton's law of cooling as follows

$$\dot{Q}_{cv}(t) = hA_{CV}(T_0 - T(t)). \quad (2)$$

Replacing (2) in (1) is obtained

$$hA_{CV}(T_0 - T(t)) = mCp\frac{dT_{(t)}}{dt}. \quad (3)$$

Solving the first-order difference equation by the method of separating variables has

$$\frac{(T_{(t)} - T_{(\infty)})}{(T_{(i)} - T_{(\infty)})} = e^{\frac{-hA_{CV}}{mCp}t} , \quad (4)$$

The total amount of heat transfer between the body and the surrounding medium during the interval from time t = 0 to t is simply the change in the energy content of that body:

$$Q = mC_p(T_2 - T_1) , \quad (5)$$

For forced convection with water, it must be taken into account that $Re = \frac{vD\rho}{\mu}$ and $Pr = \frac{Cp\mu}{K}$, in this way find the Nusselt number which is

$$Nu = C * Re^a * Pr^{\frac{1}{3}}, \quad (6)$$

where the constants "C" and "n" are determined according to the Reynolds number obtained, using the Table 1.

Table 1 "C" and "n" values according to Reynolds number [3]

Reynolds	1 – 40	40 - 10^3	10^3 - $2x10^5$	$2x10^5$ - 10^6
C	0.75	0.51	0.26	0.076
n	0.4	0.5	0.6	0.7

With these constants the number of Nusselt and later the coefficient of convection

$$Nu = \frac{hLc}{K} \rightarrow h = \frac{2NuK}{r}. \quad (7)$$

The expected values to be obtained in the convection coefficients must be very close to the theoretical values shown in the table 2.

Table 2. Theoretical values of the convection coefficient [3]

Fluid	Free conv. air	Forced conv.air	Free conv.wáter.	Forced conv. water.
Theoretical value	2-25	25-250	20-1000	50-20000

3. Results and Discussion

Using the equations described above and with the experimental data obtained after the practice of free convection in water and air, in addition to forced convection in air for bronze and steel have the following values.

Table 3. Data obtained experimentally

Experiment	ΔT (°C)	Q (J)	q (W)	h(W/m^2°C)
Free air steel	183,5	15927,8	13,2731667	27,7147888
Forcing steel air	236,75	20549,9	17,1249167	44,3149851
Free steel water	120	10416	96,444444	487,056256
Bronze free air	144,5	9902,58	8,2521541	24,574976
Bronze free air	242	16584,2	15,645528	44,188918
Bronze free water	109,75	7521,16	69,640439	435,74636

The realization of the experiment, the times for free convection in both steel and bronze were very long, arriving about 3600 seconds to reach the temperature of the surrounding environment, for calculations was taken a time of 1200 seconds after heating since this first stage the temperature drop was very stable, hence the data obtained for the temperature gradient. When the forced convection experiment with air was performed, the time to reach the ambient temperature was reduced by almost half compared to free convection, the behavior in steel and bronze was very similar in terms of its temperature drop with respect to time. In the free convection with water the temperature drop was more drastic, the ambient temperature was reached in approximately 80 seconds in both materials, as soon as the cylinder touches the water there is a thermal shock which caused the temperature to drop more than 30 ° C in a few seconds. The total amount of heat transfer between the body and the surrounding medium over a time interval is slightly higher in the steel than in the bronze, one reason why this is given is that the steel cylinder had more mass than the cylinder of bronze in addition the temperature gradient was also a little greater in the steel what resulted in an increase in the Q. For forced convection with water the properties of the water at 26 ° C were evaluated, which are shown in table 4.

Table 4. Water properties

Water to 26 (°C)	ρ (kg/m^3)	C_p (J/kg°C)	μ (kg/m.s)	K (W/m°C)
Values	996,8	4179,6	0,0008724	0,6086

With these values the Reynolds and Prandt numbers were determined, which were 25594.13 and 5.991, respectively, with the help of table 1 according to the interval where the Reynolds number remained, the constants "C" and "n "So that the equation of Nusselt would be as follows

$$Nu = 0.26 * 25594.13^{0.6} * 5.991^{\frac{1}{3}}, \quad (8)$$

with a Nusselt of 208.46 and using equation (10) the forced convection coefficient in water for the steel and bronze cylinder was determined, all the data obtained for the forced convection are shown in table 5

Table 5. Forced convection data

Experiment	ΔT (°C)	Q (J)	q (W)	h (W/m^2°C)
Forged steel water	137,25	11913,3	476,532	14499,286
Water forced bronze	195,25	13380,482	257,31697	15858,594

In the analysis of the variation of the temperature with respect to the time between the steel and the bronze for each case, in order to compare its behavior in each material. Transient heat conduction is characterized by the variation of temperature with respect to time, in Fig. 3a it can be seen that the slope in the steel and the bronze is smaller with respect to the other cases, since in the convection free time is much higher, steel was heated to a higher temperature is why its curve is above that of bronze, but its behavior in general is very similar. In Fig. 3b it is noted that both the steel and the bronze were heated to almost the same temperature, they have a uniform descent and the bronze arrives first to stabilize its temperature that based on table 5. The total amount of transfer of heat between the body and the surrounding medium between the bronze and the steel in forced convection, its value in both cases is very close.

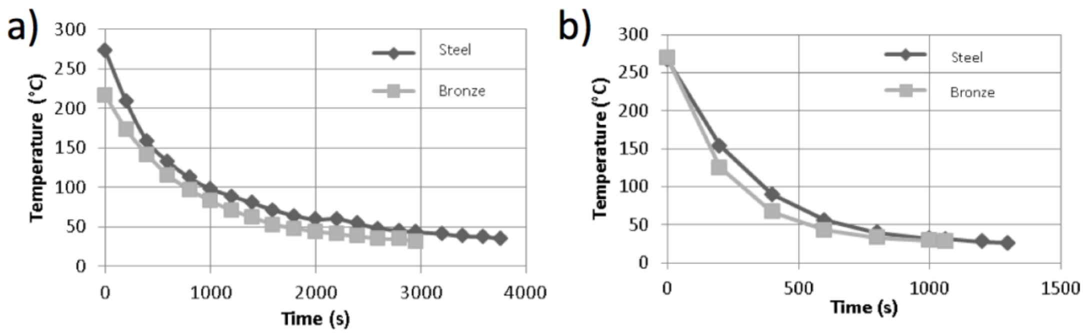

Figure 3. Temperature profile, a) Free air convection, b) Forced air convection

In Fig. 4a it can be seen that as soon as the cylinder touches the water there is a sudden drop in temperature to 70 ° C, from then on it continues to descend but in a less dizzying manner until finally the cylinder and water reach a same temperature, as in the case of Fig. 3 where the curve of the steel is above that of the bronze. In Fig. 4b, where forced convection in water is shown, the whole process occurs in the first 20 seconds, and since there is a moving fluid in this case, water, there will be a Reynolds. Convection coefficients for this case are so high.

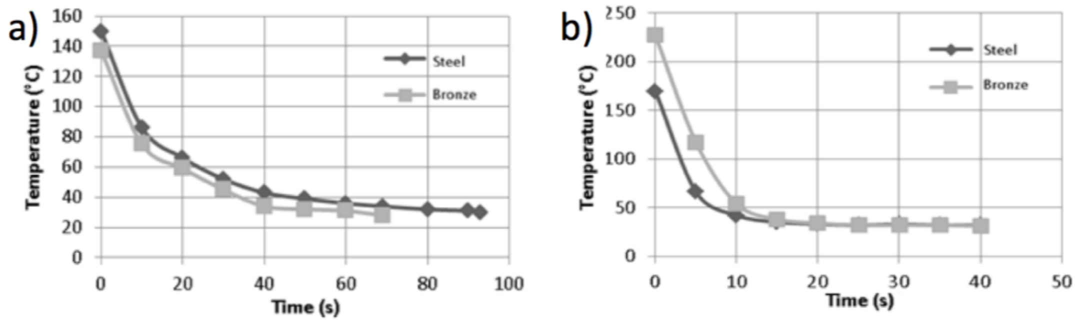

Figure 4. Temperature profile, a) free water convection, b) forced water convection

4. Conclusions

It was presented a proposal in which undergraduate students of the engineering faculty can build a team at very low costs compared to the options that are in the market and thus conduct studies on the transfer of heat by convection in a transient regime. The objectives were fulfilled to their full extent, at the time of the temperature records the thermocouple at times yielded values that were not concordant, so there was a need to perform more than one pass and to be attentive to the behavior of temperature over time. The main objective was the determination of the coefficient of convection in water and air taking as object of study a cylinder of copper and one of bronze, the data obtained for the coefficient of convection in air and for the water (free) that are shown in the (III) are within the range of theoretical values that are shown in table (II), except for steel when it was in free convection with air, which is above the range, giving a 10.8% error in this case, the data obtained for the bronze being slightly smaller. On the other hand the values for the convection coefficient when it was forced in water, table (V), however in other tables of different literatures, the value found could be out of range, and these differences are due to the multiple variables which can vary the results when the water is in motion. In a general balance the experimental data according to the theoretical data so it gives validity to the realized during the experiment.

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