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EXPERIMENTAL STUDY OF FILM COEFFICIENT IN THE COOLING OF A SOLID IN AMBIENT AIR

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Abstract. *This work describes a quantitative experiment that evaluates heat transfer during the cooling of a steel cylinder employing temperature sensors. An equation considering convection and radiation heat transfer in a solid is deduced from the energy balance equation and a convective heat transfer coefficient, also known as film coefficient, is determined for each time interval. Experimental results are compared with theoretical values of this parameter, calculated with available correlations in the literature. This work shows the importance of considering together the mechanisms of convection and radiation in ambient air cooling. It also provides good results with the use of low cost equipment and a test of easy execution.*

Keywords: *Heat transfer, cooling of a steel cylinder, convection, radiation.*

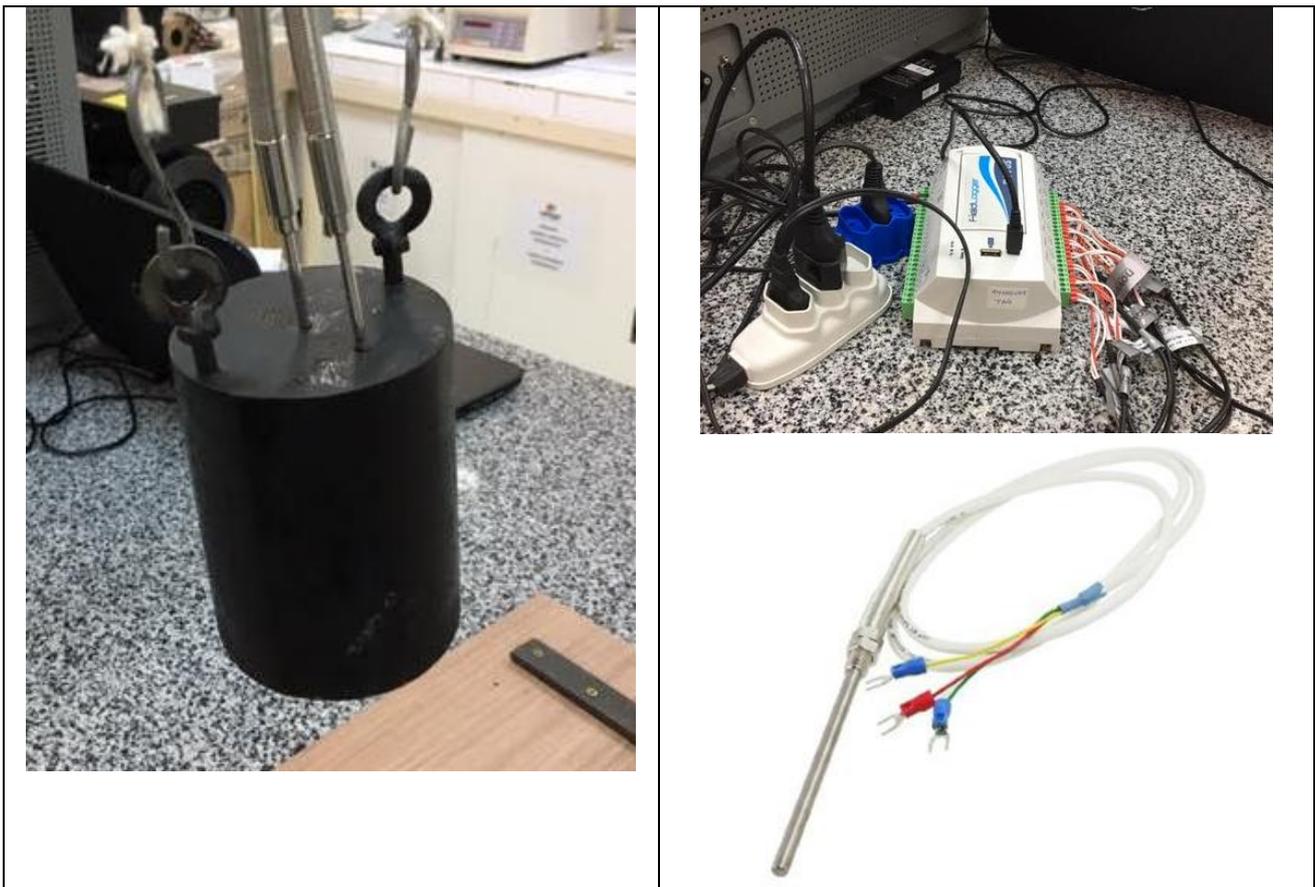
1. INTRODUCTION

The disciplines of Transport Phenomena are fundamental in engineering. The correct interpretation of momentum, heat and mass transfer processes are fundamental for the disciplines of professional formation. One of the ways to motivate the student in pursuit of this goal, avoiding the mere theoretical-expository approach of these equations, is the realization of practical classes that allow the visualization of the physical phenomenon object of study and the numerical quantification of its effects, as shown by D'angelo and Zemp (2014) and Fernandes (2013). Therefore, this work presents a simple experimental didactic module. The experiment consists on the cooling of a solid steel cylinder, which is exposed to the ambient air. Its temperature varies with time, being monitored with thermocouples, and this data is transferred to a data acquisition system, as Junior and Gonçalves (2016). The numerical results obtained are presented. After that, a overall heat balance is applied to the cylinder, in order to estimate the film convective coefficient of heat transfer. The work discusses the value of the convective coefficient of heat exchange by means of convection and radiation. It compares the value of the convective experimental coefficient considering only the convection mechanism with the experimental coefficient obtained when convection and radiation mechanisms are taken in account simultaneously. These experimental values are compared with the theoretical values obtained with the correlations in the literature.

2. METHODOLOGY

2.1 Experimental Procedure

The experiment consists of cooling a solid steel cylinder, which is exposed to ambient air, in a closed laboratory. The cylinder is heated in a muffle to a temperature of 200 ° C, and then placed to cool in the laboratory. It remains suspended vertically by a string in a metal structure. In this solid there is a central hole and another positioned near its edge, into which are introduced two temperature sensors, type PT 100. These sensors are connected to a data acquisition module. The cylinder, with termocouples inserted in it, the data acquisition module and the type of termocouple used in the experiment are shown in Figures 1 to 3.



Figures 1 to 3 - The solid cylinder with termocouples inserted (left), the data acquisition module (right, above), and the temperature sensors, type PT 100 (right, below).

The two temperature values (center and edge) measured with the two thermocouples are transmitted to the data acquisition system that registers the electronic signals. These are converted into a digital record, and are stored and transferred to a notebook computer, in the form of Excel spreadsheet electronic files, which are shown in Table 1. The ambient air temperature is also measured simultaneously. The data was measured in the time period that began at "11:32:08" and ended at "12:53:42". They were measured in the time period interval of 1 s.

Table 1. Experimental results for the solid and ambient temperatures in °C.

Date	Time	Ambient Temperature	Solid Edge Temperature	Solid Center Temperature
07/10/2016	11:32:08	22,895	199,509	200,051
07/10/2016	11:32:09	22,895	199,503	200,048
07/10/2016	11:32:10	22,896	199,487	200,037
07/10/2016	11:32:11	22,896	199,477	200,029
07/10/2016	11:32:12	22,895	199,453	200,007
07/10/2016	12:00:00	23,131	125,767	126,336
07/10/2016	12:00:01	23,130	125,730	126,297
07/10/2016	12:00:02	23,130	125,710	126,277
07/10/2016	12:00:03	23,130	125,674	126,239
07/10/2016	12:00:04	23,130	125,655	126,221
07/10/2016	12:53:38	23,061	65,727	66,076
07/10/2016	12:53:39	23,062	65,719	66,076
07/10/2016	12:53:40	23,064	65,705	66,061
07/10/2016	12:53:41	23,066	65,697	66,046
07/10/2016	12:53:42	23,068	65,682	66,039

2.2 Theoretical Fundamentals and Mathematical Modeling

In order to make this modeling, we consider a solid body having a uniform temperature. The total energy balance is applied to this solid, and it is taken into account the heat exchanges by convection on its total surface. The total energy balance analytical solution is, as Incropera and Witt (2008)

$$\frac{T - T_{\infty}}{T_i - T_{\infty}} = e^{-\left(\frac{hA}{mC_P} t\right)} \quad (1)$$

The total energy balance is applied to this solid and, when it is taken into account the heat exchanges by convection and radiation by its total surface, the total energy balance results in the expression above

$$mC_P \frac{dT}{dt} = -hA(T - T_{\infty}) - \varepsilon\sigma A(T^4 - T_{\infty}^4) \quad (2)$$

Where m, C_P, T and A are the mass, specific heat, temperature and area of the solid, and t, h, T_∞, ε, σ are the elapsed time, convective heat transfer coefficient, air ambient temperature, emissivity and Stefan-Boltzmann constant, respectively.

This energy balance is used to estimate the convective coefficient of the heat exchange from the measured temperature values. The ordinary differential equation is solved by the semi-implicit Euler method, as Maliska (2004), obtaining the following discretization:

$$\left(\frac{T^{k+1} - T^k}{\Delta t}\right) = -\frac{hA}{2m} \left[\frac{T^{k+1}}{C_P^{k+1}} + \frac{T^k}{C_P^k} - \frac{T_{\infty}^{k+1}}{C_P^{k+1}} - \frac{T_{\infty}^k}{C_P^k}\right] - \frac{\varepsilon\sigma A}{2m} \left[\frac{(T^{k+1})^4}{C_P^{k+1}} + \frac{(T^k)^4}{C_P^k} - \frac{(T_{\infty}^{k+1})^4}{C_P^{k+1}} - \frac{(T_{\infty}^k)^4}{C_P^k}\right] \quad (3)$$

$$t_{k+1} = t_k + \Delta t \quad (4)$$

Where T^{k+1} , C_p^{k+1} , T_∞^{k+1} are the properties evaluated at time t^{k+1} , and T^k , C_p^k , T_∞^k are the properties evaluated at time t^k and Δt is the time interval. Experimental temperatures values, registered during the colling of the cylinder, are used in this relation. the mass and area of the solid is known. A emissivity value of the 0,97 is employed, since we have a black painted cylinder [4]. The convective heat transfer coefficient , h , is determined at each time interval. These convective heat transfer coefficients obtained experimentally are compared with the theoretical correlations of the literature for the natural convection mechanism, as described below.

Natural convection is a process induced by buoyancy forces that arise from differences in fluid density at distinct points along the solid interface. Correlations based on the Grashoff numbers (Gr), which corresponds to the quotient between the thrust and the viscous forces, are used to estimate the value of the film coefficient. The value of this dimensionless quantity is given by the equation:

$$Gr = \frac{g\beta(T_s - T_\infty)L^3}{\nu^2} \quad (5)$$

in which g , L , β and ν respectively correspond to the acceleration of gravity, the characteristic length of the solid interface being analyzed, the coefficient of thermal expansion, and the kinematic viscosity of the air at the film temperature.

In this work, the dimensionless number of Nusselt, is estimated by the empirical correlation, for natural convection, presented by (CHURCHILL & CHU, 1975). In this correlation the Nusselt number is related to the dimensionless numbers of Prandtl (Pr) and Rayleigh (Ra), as the following expressions

$$Nu = \left\{ 0,825 + \frac{0,387Ra^{\frac{1}{6}}}{\left[1 + \left(\frac{0,492}{Pr} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right\}^2 \quad (6)$$

The dimensionless numbers of the Nusselt, Prandtl and Rayleigh are given by the relations, respectively,

$$Nu = \frac{hL}{k_f}; \quad Pr = \frac{\nu}{\alpha}; \quad Ra = Gr Pr \quad (7)$$

Where α is the thermal diffusivity of the air; h , the film convective heat transfer coefficient at the solid interface, and k is the thermal conductivity of the air at the film temperature. This temperature varies throughout the cooling process and corresponds to the average of the temperature of the fluid, considered constant and equal to T_∞ , and the instantaneous temperature of the solid.

In this work, the convective coefficient of theoretical heat transfer is estimated by Equation (6), and will be compared with the experimental value obtained by Equations (1) and (3).

3. RESULTS AND DISCUSSIONS

The theoretical and experimental values for the convective heat exchange coefficient were estimated for the first 1600 seconds of the experiment, and are shown in the graphs of Figures 4 and 5. They are estimated every second with a time interval of 30 s. The Figure 4 shows the estimation of the convective heat transfer coefficient considering only the heat exchange by convection, using Equation (1). The mean theoretical and experimental values were "6.67" and "18.17", respectively. The relative error between them was "1.72".The mean relative error in modulus was estimated for these values (relative error is defined as the experimental value minus the theoretical value divided by the theoretical value). They had an average relative error in modulus of 1.726, and a maximum relative error in modulus of 1.773. The

Figure 5 shows the estimation of the convective heat transfer coefficient considering the forms of heat exchange by convection and radiation, using Equation (3). It had an average value of 6.89, and a relative error relative to the theoretical value of 0.0326. They had an average relative error in modulus of 0.0847, and a maximum relative error in modulus of 0.244.

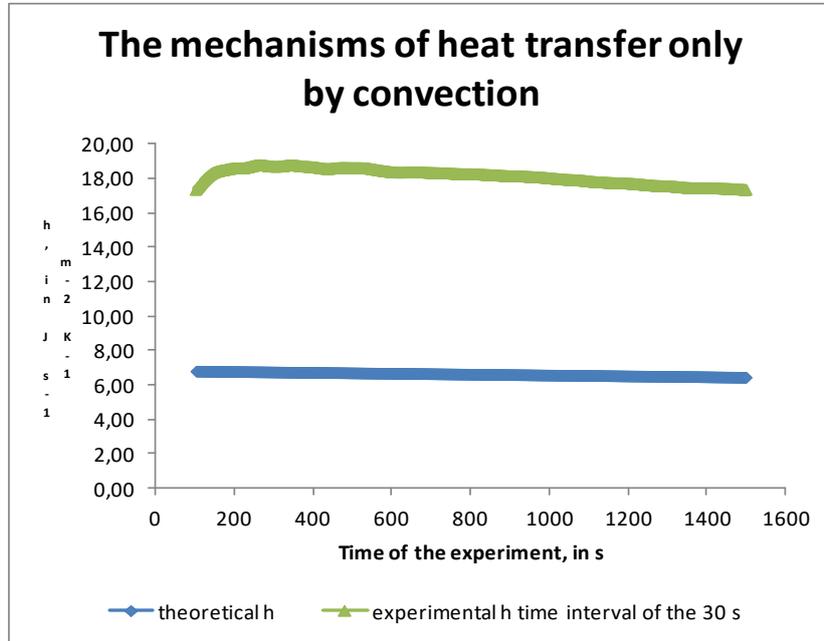


Figure 4. Experimental and theoretical convective heat transfer coefficient only by convection.

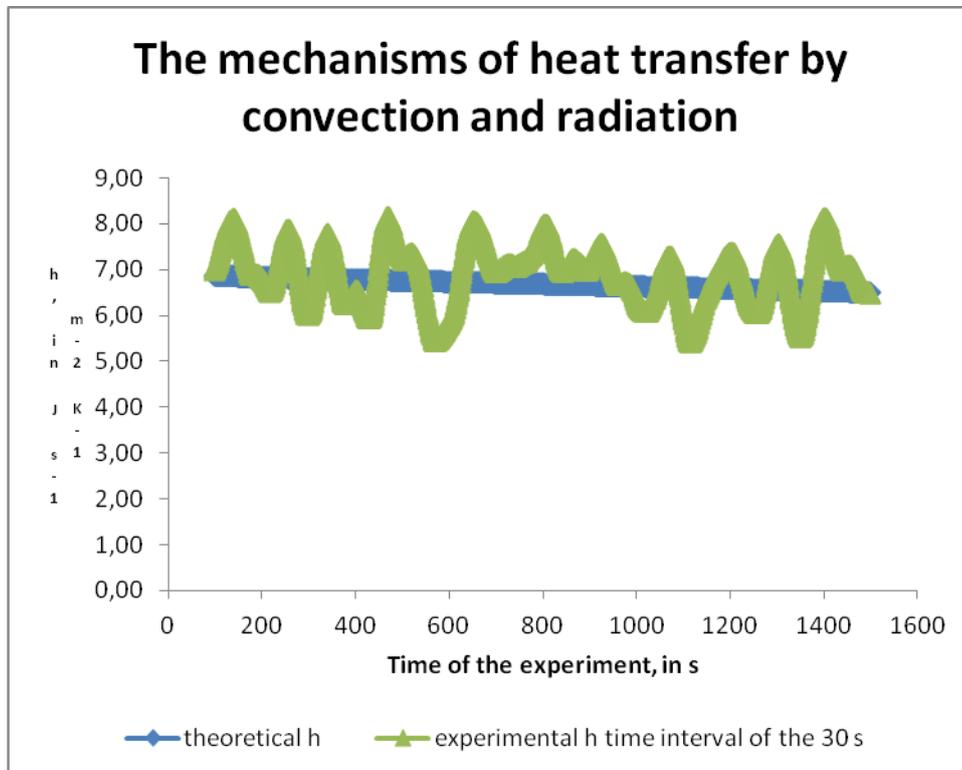


Figure 5. Experimental and theoretical convective heat transfer coefficient by convection and radiation.

The results show that the modeling also taking into account the heat exchange by the radiation mechanism leads to a value closer to the value of the theoretical correlation. While the modeling using only the convective heat exchange mechanism leads to a coefficient with high value in relation to the theoretical correlation.

4. CONCLUSIONS

The modeling considering the mechanisms of heat transfer of convection and radiation was adequate for this experiment. The results showed the importance of including the exchange of heat by radiation in the energy balance. We will also conduct further experiments to complete this study.

5. REFERENCES

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6. RESPONSIBILITY NOTICE

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