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EXPERIMENTAL DETERMINATION OF SURFACE EMISSIVITY USING THE COOLING PROCESS OF A SOLID IN AMBIENT AIR

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Abstract. This work describes a quantitative experiment that evaluate the surface emissivity of a heated steel cylinder subjected to a cooling process to the surrounding air. The experiment was designed for practical undergraduate classes and employs low-cost equipment and easy-to-perform tests, that were carried out with two identical cylinders, one painted in black and the other in silver, in order to demonstrate that the radiation heat rate is determined by the characteristics of the radiant surface. The employed methodology highlights the importance of adopting a thermal balance that includes the mechanisms of convection and radiation heat transfer simultaneously, as it provides slight differences between experimental and theoretical convective heat transfer coefficients. The little deviations in the results obtained with the silver cylinder assures that the proposed method is suitable for determining the emissivity of a solid surface.

Keywords: unsteady heat transfer, emissivity, convection and radiation, cooling of a solid, simple low cost experiments

1. INTRODUCTION

Heat transfer textbooks generally shows the three heat transfer mechanisms in separate sections and many of those books devote entire chapters to more specific topics, such as one-dimensional steady-state heat conduction (Kreith and Bohn, 2003; Welty et al., 2017). Studying each mechanism in a different section is a learning approach that has some advantages, but it could make students believe that real-world heat transfer problems could be solved taking into account only one of the three mechanisms. This misunderstanding is more common when the student deals with transient heat transfer in a solid surface immersed in a fluid, such as a metal object exposed to the ambient air.

In order to avoid the problem described in previous paragraph, this article presents an didatic experiment that shows that we must consider coupled convective and radiative heat transfer in the external surface of a metal cylinder in quiescent air.

1.1 Transient heat transfer in a solid surface

In the cooling process of a heated solid exposed to surrounding air, some authors take in account only the convective heat transfer that occurs in the solid interface and they predict the thermal behavior of this system based on Newton's cooling law (Antonietti et al., 2011; Junior and Goncalves, 2016). Thus, the heat balance applied to a control volume delimited by the solid interface leads to a first-order differential equation whose resolution tells us that the temperature of the solid reduces exponentially with the time.

The approach described in the previous paragraph is called lumped capacitance model and is presented in heat and mass transfer textbooks for undergraduate courses. However, by despising the radiation mechanism in the cooling process

of a solid in the surrounding air, the experimental convective heat transfer coefficient will be very different from its theoretical value (Maliska, 2004; Cengel, 2012; Seara et al., 2011).

This article will use experimental results of steel cylinders cooling tests to evaluate the importance of convection and radiation mechanisms in the transient heat transfer process of a solid exposed to ambient air. In order to evaluate the influence of the type of paint on the heat radiation rate, a black cylinder and a grey one are used.

2. THEORETICAL FUNDAMENTALS AND MATHEMATICAL MODELLING

Lumped capacitance model is based on the assumption that a solid body has 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),

$$\frac{T-T_\infty}{T_0-T_\infty} = e^{-\left(\frac{h.A}{m.C_p}.t\right)} \quad , \tag{1}$$

where T and T_0 are the temperature of the solid, respectively, at a certain time and at the beginning of the cooling process; A, m and C_p are the area, mass and specific heat of the solid. The convective heat transfer coefficient, the elapsed time and the temperature of the surrounding air are h, t and T_∞, respectively.

Although, when it is taken in account convection and radiation heat transfer in the solid interface, the total energy balance should be written as

$$m.C_p.\frac{dT}{dt} = -h.A.(T - T_\infty) - \varepsilon.A.\sigma.(T^4 - T_\infty^4) \quad , \tag{2}$$

where dT/dt is the temperature variation rate, ε is the emissivity of the solid surface and σ is the Stefan-Boltzmann constant. This differential equation could be converted into an algebraic one, if it is considered a finite period of time, as shown below

$$m.C_p.(T_f - T_i) = -h.A.(\bar{T} - T_\infty).\Delta t - \varepsilon.A.\sigma.(\bar{T}^4 - T_\infty^4).\Delta t \quad , \tag{3}$$

where T_i and T_f are the initial and final temperature of the solid in the time interval Δt. The medium temperature of the solid during this time interval is represented by $\bar{T}$. In eq. (3), the left hand side quantifies the variation in the internal energy of the solid the during a finite period of time. The amount of convective and radiative heat transferred during this period are evaluated, respectively, by the first and second term in the right hand side of this equation.

2.1 Heat transfer convective coefficient in the interface solid-fluid

When the temperature of a heated solid is continuously measured during its cooling process, it is possible to apply eq. (3) in a fixed time interval; and the variation in the internal energy of this solid can be easily calculated. However, in order to evaluate the heat transferred by convection and radiation it is necessary to quantify the parameters h and ε.

The convective heat transfer coefficient, h, depends on the surface geometry and the conditions of boundary layer. In free convection, when heat is transferred between a moving gas and a solid, typical values of h range between 2 and 25 $W/m^2.K$ (Kothandaraman, 2006; Holman, 2010).

The parameter h could be defined by Nusselt number, Nu, which is the ratio between the convective and the conductive heat transfer and is given by

$$Nu = \frac{h.L_c}{k_f} \quad , \tag{4}$$

where k_f is the thermal conductivity of the air in the boundary layer, evaluated at film temperature. In heat transfer and fluid dynamics, the film temperature is an approximation to the temperature of a fluid inside a convection boundary layer; and, in it is calculated as the arithmetic mean of the temperature at the surface of the solid and the temperature of ambient air. L_c represents the characteristic length of the flow in the solid-fluid interface, and it is determined by the surface shape.

Free convection occurs in the heated surface of a solid exposed to ambient air; and Grashof number, Gr, which represents the ratio of the buoyancy force to viscous force acting on the fluid, controls the boundary layer on the interface and could be written as

$$Gr = \frac{g.\beta.\Delta T.L_c{}^3}{\nu^2} \qquad , \qquad (5)$$

where g is the gravitational constant, β is the reciprocal of the film absolute temperature, ΔT is the difference between the surface temperature and ambient air temperature, and ν is the air kinematic viscosity at film temperature. Another dimensionless group that must be estimated in free convection is Rayleigh number, Ra, which describes the behaviour of fluids when the mass density of the fluid is non-uniform. The mass density differences are usually caused by temperature differences, and when it occurs, Ra is the ratio of the time scale for diffusive thermal transport to the time scale for convective thermal transport. Ra is defined as the product of the Grashof and Prandtl number. The last one is the ratio between momentum diffusivity and thermal diffusivity, so Ra is written as

$$Ra = \frac{g.\beta.\Delta T.L_c{}^3}{\nu.\alpha} \qquad , \qquad (6)$$

where α is the thermal diffusivity of air at film temperature.

Nusselt and Rayleigh numbers, in free convection, are related in the following form

$$Nu = C.Ra^n \qquad , \qquad (7)$$

where the constants C and n depend on the geometry of the surface. In a cylinder, the bottom and the top are horizontal plates, and the curvilinear lateral area can be approximated as a vertical plate. The top area of a heated cylinder is the upper surface of a hot plate, and the bottom of this solid is the lower surface of a hot plate; and, for upper and lower hot plates, the analytical relation between Nu and Ra are, respectively, given by eqs. (8) and (9). In both cases, the characteristic length of the surface is the ratio between area and perimeter.

$$Nu = 0,54.Ra^{0,25} \qquad\qquad\qquad Nu = 0,27.Ra^{0,25} \qquad\qquad (8) \text{ and } (9)$$

In a vertical plate, the characteristic length is the height of the plate and the relation between Nu and Ra is

$$Nu = 0,59.Ra^{0,25} \qquad\qquad (10)$$

The theoretical values for h in the three different surfaces of the cylinder – lateral, top and bottom – are estimated with eqs. (4) to (10). The convective heat transfer coefficient in overall cylinder surface is the weighted average, relative to the area, of these three values.

The next step is to quantify the radiative heat transfer.

2.2 Emissivity of the solid surface

Emissivity, ε, is defined as the ratio of the energy radiated from a material's surface to that radiated from a perfect emitter, known as a blackbody, at the same temperature and wavelength and under the same conditions. So, it is a dimensionless number, which varies between 0 and 1. The emissivity of a surface depends not only on the material but also on the nature of the surface. For example, a clean and polished metal surface will have a low emissivity, whereas a roughened and oxidised metal surface will have a high emissivity. The emissivity also depends on the temperature of the surface as well as wavelength and angle.

In our experiment, in order to minimize the deviation among experimental and theoretical values, one cylinder was painted in black cylinder, because the emissivity of a black surface ranges from 0,95 to 0,99 (Bramson, 1968; Kreider and Kreith, 1978). So, the maximum theoretical error of ε is about 4%. This cylinder was employed in the first part of the experiment. Emissivity of the silver cylinder is determined employing a heat balance in the solid surface during its cooling in ambient air, as it will be shown in the next section.

3. EXPERIMENTAL PROCEDURE

The experiment was planned in two stages. In the first one, cooling tests with a black cylinder, whose emissivity is previously known, were carried out to compare theoretical and experimental values of the convective heat transfer coefficient, upon thermal balances in one minute intervals.

In the second stage, it was used a silver painted cylinder, and the convective heat transferred during each interval was estimated upon theoretical correlations shown in section 2.1. The radiative heat transferred in the intervals are calculated using the thermal balance proposed in eq. (3).

Six cooling essays using two steel cylinders were performed during the same day. The cylinders radius and height are 36 and 102 mm, respectively, and it have a 3 mm diameter hole in the center and another near the edge. Both cylinders weight 3.264 kg. In the holes were inserted two temperature sensors, type PT 100, connected to a data acquisition module,

which allowed the recording of temperatures in time intervals of the order of 1 second. Temperatures measurements in the center and on the edge of the cylinder are slightly differences during the cooling process, and these measurements are performed to demonstrate that the temperature in the whole solid could be considered uniform. In the cooling tests, the arithmetic mean between the temperatures of the center and the edge was used to evaluate the heat delivered by the cylinder.

The equipment used in these essays is shown in Figure 1. In Figure 2, the black and the silver painted cylinder are hung and cooled in ambient air.

Figure 1. The data acquisition module (left, above); the black cylinder with the temperature sensors inserted in its two holes (right, above); and one of PT 100 sensors used to registrate the cylinder temperature during the cooling process.

The essays with the black cylinder were done in the first part of the experiment, in order to estimate the experimental convective heat transfer coefficient, h_{exp} , whose value is calculated using this formula:

$$h_{exp.} = \frac{(m.C_p.(T_i-T_f)-\varepsilon.A.\sigma.(\bar{T}^4-T_\infty^4).\Delta t)}{A.\Delta t.(\bar{T}-\bar{T}_\infty)} \qquad . \qquad (11)$$

Each essay with the black cylinder takes around 50 minutes. Theoretical and experimental values of h were evaluated at 1 minute intervals. The results obtained in the first part of the experiment show that the correlations presented in section 2.1 can be used to estimate h in the cooling of the steel cylinder. In the second part of the experiment, essays with the silver cylinder were done in order to estimate the emissivity, ε , of this surface, whose value is calculated using this formula:

$$\varepsilon = \frac{(m.C_p.(T_i-T_f)-h_{theor}.A.(\bar{T}-\bar{T}_\infty).\Delta t)}{A.\sigma.(\bar{T}^4-\bar{T}_\infty^4).\Delta t} \qquad . \qquad (12)$$

4. RESULTS AND DISCUSSIONS

The decaiment of the temperature in the six essays were plotted in a one single graph (Figure 3), so it is possible to verify that the cooling of black and silver cylinder occurs in a different speed. This graph also shows that the three essays with the black cylinder provides almost the same curve, and it also occurs with the silver one.
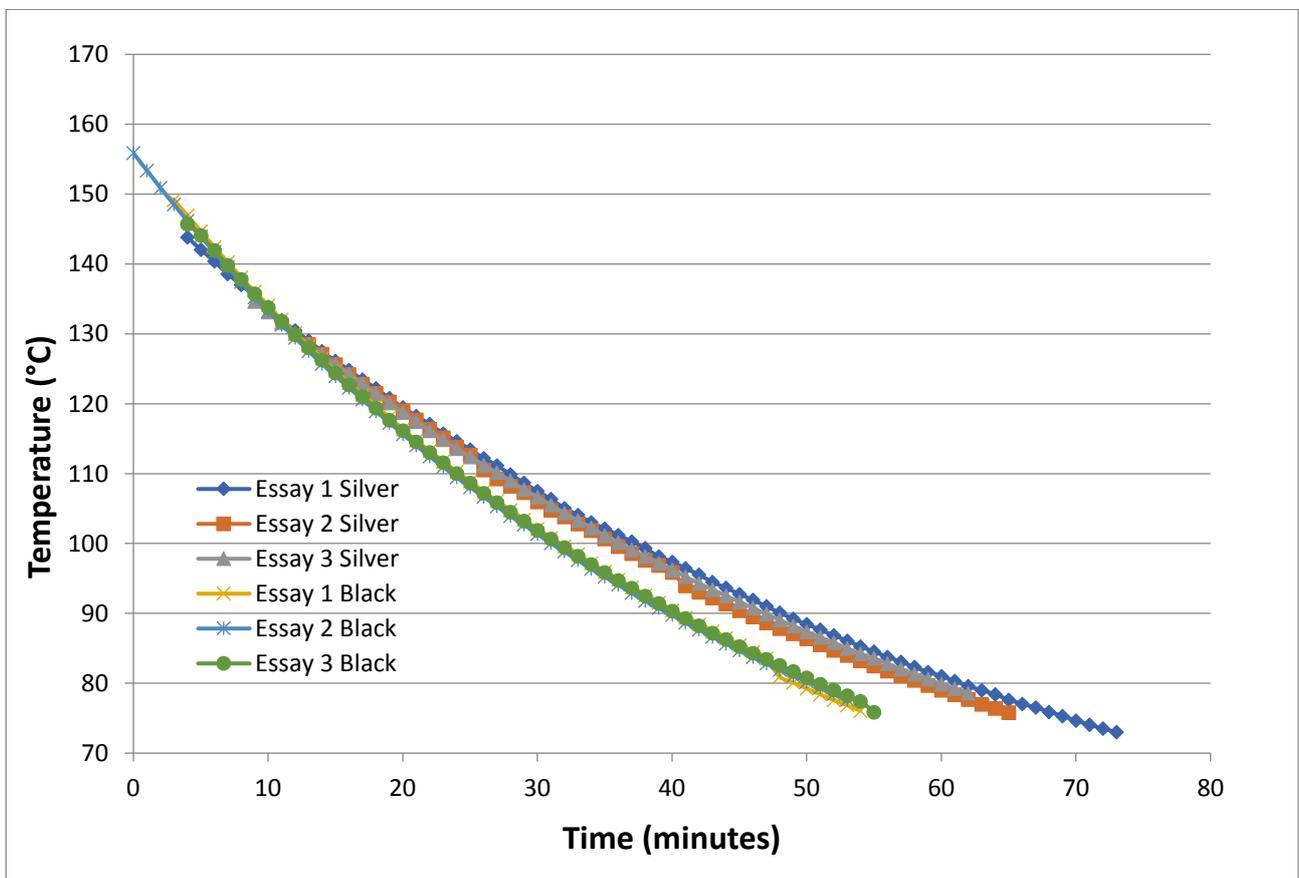
Figure 2. Cylinders cooling process.

Figure 3. Cylinder temperature versus elapsed time of the cooling process.

The results obtained, during a period of ten minutes, in one of the essays performed with the black cylinder, considering ε equals to 0.97, are shown in Table 1. The theoretical values for h varies between 7.717 and 7.458 W/(m^2.K); and experimental values, from 5.327 to 6.429 W/(m^2.K). The maximum relative error in this period was 28.84%, and the medium error, 23.48%. The others two essays with the black cylinder provides similar results, and the medium error obtained in the three essays was 21.52%.

Table 1. Experimental results for an essay with the black cylinder

Ambient temperature, °C	Cylinder temperature, °C	Q rad., J	Q conv., J	h theoretical, W/(m2.K)	h experimental, W/(m2.K)	Relative error (%)
23.925	131.824					
23.943	129.893	1938.53	1249.28	7.717	6.241	19.12
23.971	128.042	1887.34	1163,18	7.687	5.917	23.02
23.979	126.267	1838.97	1077.59	7.658	5.579	27.15
23.956	124.431	1791.74	1220.20	7.629	6.429	15.73
23.978	122.746	1746.21	1011,38	7.600	5.423	28.65
23.976	121.022	1702.60	1112.95	7.572	6.072	19.80
23.960	119.400	1660.54	984.48	7.544	5.464	27.57
23.948	117.673	1619.02	1190.04	7.516	6.721	10.57
24.106	116.129	1578.55	926.69	7.487	5.327	28.84
24.005	114.568	1540.58	989.26	7.458	5.786	22.43

The black cylinders curves in Figure 3 show that there is a reproducibility of the cooling tests; and, Table 1 indicates that the experimental values of h oscillate at a lower level than the theoretical values of this coefficient. Furthermore, for the data presented in Table 1, the relative deviation of the experimental values of h from its arithimetic mean is 5.86%. This low deviation shows that the actual convective heat transfer rate is less than its theoretical value and this can be caused by the air flow interferences that occur at the boundaries between the three surfaces of the cylinder.

It is important to emphasize that the lumped capacitance model couldn't be used in the proposed experiment because radiative and convective heat transfer have the same order of magnitude on free convection cooling process in ambient air. The graphic in Figure 4 compares theoretical values of h with the experimental ones obtained when lumped capacitance model is applied and when the model proposed in this article is applied.
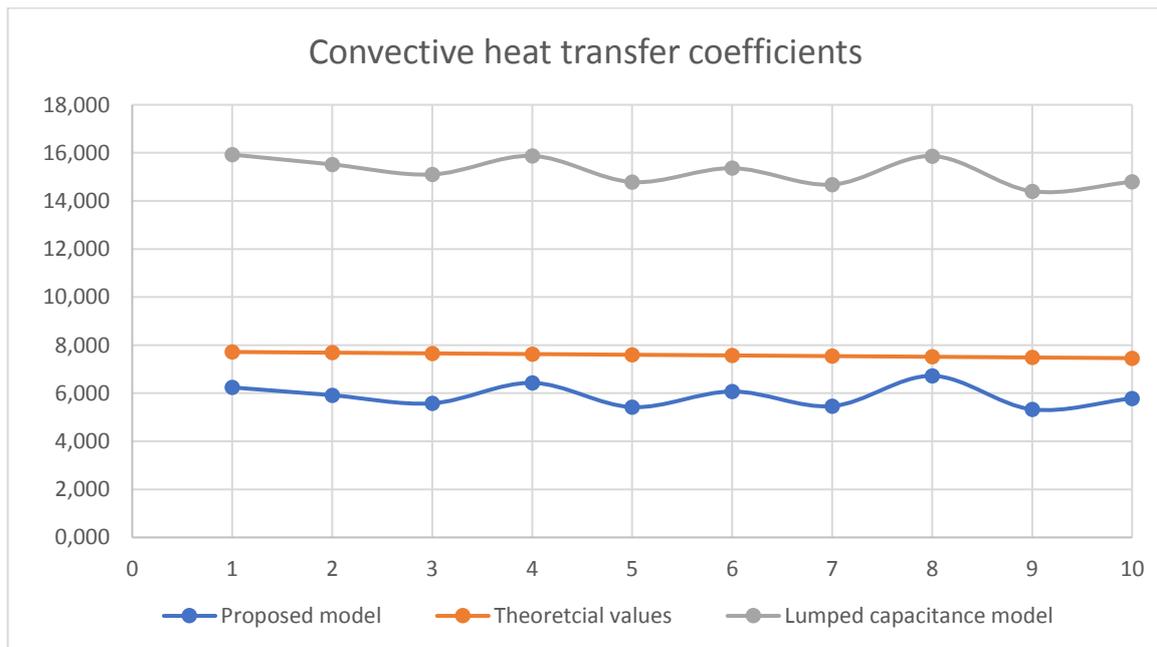

Figure 4 – Experimental and theoretical values of h, in W/(m^2.K), during the ten minutes period of the black cylinder cooling process shown in Table 1.

The next step of the experiment consists in evaluate the surface emissivity of a silvery cylinder during the cooling process of this object. The heat transferred by convection during the cooling process is obtained using the convective heat transfer theoretical coefficient. The results obtained in the first part of experiments show that the magnitude of the deviations between theoretical and experimental values of h are relatively low, making possible the use of the proposed model for didactic purposes.

The results obtained in one of the essays performed with the silver painted cylinder, are shown in Table 2, whose experimental values for ε varies between 0.429 and 0.513.

Table 2. Experimental results for an essay with the silver painted cylinder

Ambient temperature, °C	Cylinder temperature, °C	Q conv., J	Q rad., J	ε experimental	Relative deviation (%)
24.663	134.672				
24.685	133.134	1583.85	965.06	0.465	4.86
24.599	131.615	1557.62	954.79	0.470	3.87
24.631	130.099	1531.56	971.30	0.488	0.13
24.614	128.580	1504.89	998.99	0.513	4.95
24.608	127.092	1478.90	969.26	0.508	4.03
24.565	125.641	1453.83	929.58	0.498	1.89
24.547	124.289	1430.12	785.73	0.429	12.12
24.594	122.894	1406.10	877.83	0.489	0.13
24.553	121.540	1382.35	828.83	0.472	3.31

The mean values for ε in the three essays performed with the silver painted cylinder were 0.483, 0.465 and 0.489. It is important to notice that literature establishes the range of 0.45 to 0.52 for the emissivity of a painted aluminum surface (Toloukian and Ho, 1972; Siegel and Howell, 1992; Iuchi and Wada, 2003). Consequently, the mean emissivity estimated in all the essays remain into the theoretical range of this parameter. The graphic in Figure 5 compares the experimental values of ε with the mean of this parameter during the essay whose results are shown in Table 2.
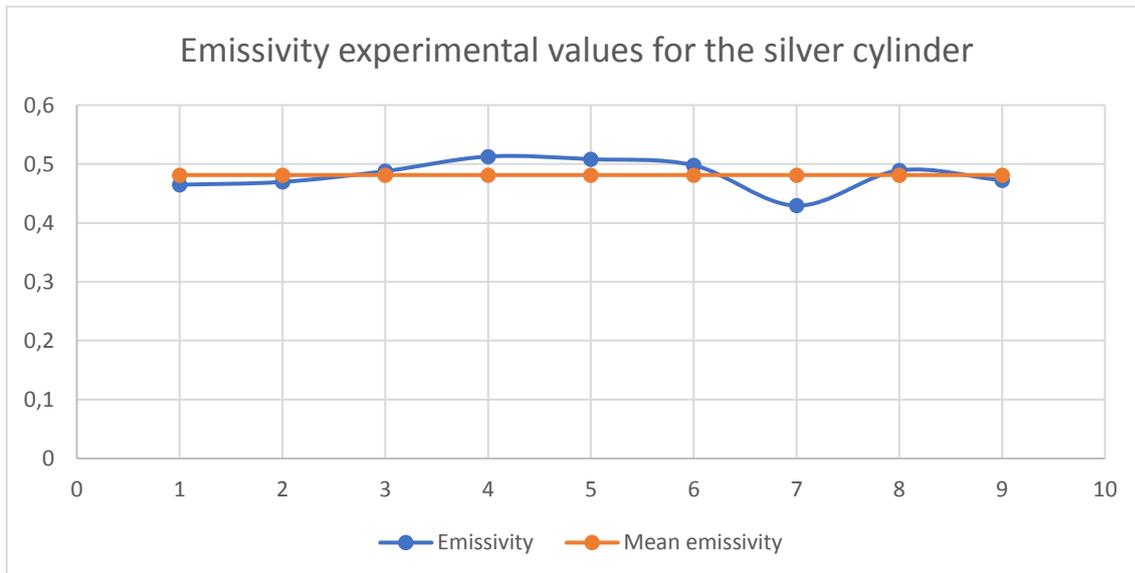

Figure 5 – Emissivity experimental values during the essay of the silver cylinder cooling process shown in Table 2.

In the three essays, the medium relative errors between the values obtained at each interval and the mean emissivity experimental value were 8.18% , 6.80% and 4.44%. This low deviation of the experimental data supports the methodology described in this article to estimate, for didatic purposes, the emissivity value of a surface.

However, emissivity varies significantly with the color and texture of the surface coating, so that it is very difficult to obtain a precise value for a given solid object. Thus, the authors consider that the estimated ε values for the silvery

cylinder are consistent with the actual value of this parameter. Thus, the test performed is suitable for use in a radiation heat transfer practical class.

5. CONCLUSIONS

In this work, a time-discrete thermal balance was used to simulate a real physical system, and the quantitative results were satisfactory. The experiment was designed to study, in undergraduate courses, the cooling process of a solid to ambient air, with the use of low cost materials. The thermal balance that was employed includes convective and radiative heat transfer mechanisms, emphasizing that both are important in the cooling process.

The experimental procedure is quite simple and enables the realization of essays that can be easily executed.

Differences among theoretical and experimental values of h in the first stage of the experiment are essentially associated to the interferences that occur in air flow at boundaries of the three surfaces of a cylinder. In turn, the deviations of the experimental data in relation to its own average are due to, among other factors, disturbances in the flow produced by currents of air and instrumental errors in the recording and the temperature measurements.

The cooling process of a silver painted cylinder was performed to determinate the emissivity of its surface. It is important to remark that emissivity varies significantly with the color and texture of the surface coating, so that it is very difficult to obtain a precise value for a given solid object. In section 4, it was shown that the experimental ε values obtained for the silver painted cylinder are consistent with the theoretical value of this parameter. Thus, the test performed is suitable for use in a radiation heat transfer practical class.

The experiment provides students with a better understanding of convection and radiation mechanisms, and highlights the influence of the surface type on the radiation heat rate.

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