INFLUENCE OF COLOR ON RADIATION HEAT TRANSFER RATE: MODELING AND EXPERIMENTATION

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Abstract*. The main purpose of this work is to present a laboratory experience about infrared radiation heat transfer, through which is analyzed the influence of the body color that emits the radiation. To reach this objective, three metallic cans were prepared. The first one was covered by black paint, the second one by white and the third can remained unpainted. The cans were then filled with hot water at the same temperature, about 80ºC, and exposed to a cooling process in a black chamber opened in its top. The water temperature evolutions of the three cans were measure in function of the time. Though the black objects emissivity for the visible radiation wavelengths is very large, the water temperature evolutions of the cans showed that the infrared radiation heat transfer rates were practically identical for the white and black cans. However, for the unpainted can, the heat tranfer rate was significantly smaller. This result suggests that infrared metallic radiators, like the domestic fridges condenser coils, must be covered by paint. Meantime, the color used in the painting is not relevant. A study of measurement uncertainties also is presented in this article. A simple dynamic numerical model based in the conservation energy principle and the heat exchanges by radiation and convection between the cans and the environment was developed, and it is presented in the first part of this article. The classical fourth-order Runge-Kutta method was used to solver the temperature equation of this model. The metallic cans temperature evolutions obtained with this model were used in the analyses on the viability of the data acquisition system employed in the experimental tests.*

Keywords*: Radiation heat transfer, Modeling and experimentation, Engineering education.*

1. INTRODUCTION

Heat transfer occurs through three different ways: conduction, convection and radiation. This last one is ruled by complex mechanisms and, perhaps for this, it's not difficult to find concept mistakes about this subject. Ideas about emissivity, reflectivity and absorvity of bodies are sometimes mistaken, when analyzed for different wavelengths, specially visible and non visible ranges. Theory about heat transfer by conduction, convection and radiation are found in several good texts (Holman, 2002; Incropera, 2007).

It's known that radiation heat transfer is present in several process of heat exchange (heating or cooling), once it doesn't need material means to occur. The most common example of this process can be felt and observed daily. Due the high temperature of the sun, at every moment, millions of kilojoules of energy are unleashed and they travel across the space, without matter, under the form of electromagnetic waves, until reach the surface of the Earth, heating it and ensuring the life throughout the planet.

The radiation intensity that an object is capable of emitting is directly connected with its emissive power, that show us the amount of radiation emitted by superficial area, and also by the amount of irradiation reflected by this object. The sum of these flows is known as radiosity.

An object on the surface of the Earth is exposed to a solar electromagnetic radiation, which is inside the visible specter range. Nevertheless, absorbing this energy, the body becomes warm and it starts to emit radiation in a wavelengths corresponding, in general, to the infrared range.

The specter through which an object will emit heat will depend, mainly, on oscillations and transitions of the large number of electrons that comprise matter, further, of course, of its temperature.

Colors are also capable of exert influence over absorption, emission and reflection of heat. One example is the use of black color on solar heating plates, in order to improve absorption. The mirrored films are another example, highly reflective, generally applied on windows to reduce energy transmission.

Black paint is widely employed on coils of refrigerators and freezers. Apparently, the purpose of the usage of this color would be the improvement of heat loss to the environment, through the emission of radiation, considering the fact that a good absorber in one given wavelength is also a good emitter in this same wavelength. Do darker heat exchangers really exchange more heat? If so, why does it happen? Does the black color is more efficient on heat emission than the lighter colors? Given these questions, the main objective of this work is to compare the influence of light and dark colors on the heat transfer from metallic objects, thus finding answers to those questions. Two interesting articles on this subject were written by Leff (1986) and Bartels (1990).

To obtain the purposes this work, an experiment was developed, in which three metallic cans, each one with volume of 350 ml and painted of different forms, were filled with hot water. Thus, the walls of the cans were also heated. Next, the metallic cans were cooled by radiation and convection. The cooling rates of the cans were measured with the help of thermocouples plunged into the hot water and attached to a data acquisition system. A comparative study between the temperature evolutions of the three cans allowed to answer the questions put above.

Before presenting the experimental results, a theoretical study on the problem will be made and a simple model to find the water and cans temperatures in function of the time will be developed.

2. MATHEMATICAL MODEL

To discuss heat transfer from a hotter body to the environment, at a lower temperature, consider a heated body giving heat to its surroundings by convection and radiation, as shown by Figure 1, where T_∞ is the environment temperature, T_{viz} is the surroundings temperature, T_{sup} is the temperature of the surface of the body and $T_\infty < T_{sup}$.

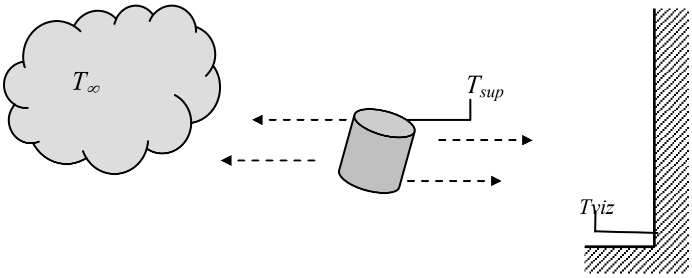

Figure 1 – Heat transfer from a body to the environment.

In order to study the effect of the pigmentation on the heat transfer by radiation, it's necessary to smooth the influences of the other forms of heat transmission. When comparing two different pigmentations, only the colors of the bodies must change. Other parameters, such as initial temperature, environment conditions and instruments, must be kept constant.

The cooling of a body by radiation is the transfer of energy from this body to its environment under the form of electromagnetic waves in a given time interval. Equation (1) represents the energy transferred from a body by radiation.

$$q_{rad} = A\varepsilon\sigma(T_{sup}^4 - T_{viz}^4) \quad (1)$$

In this expression, q_{rad} is the amount of heat [W], A is the area of heat exchange [m²], ε is the emissivity, σ is the constant of Stefan-Boltzmann (σ = 5,67x10^{-8} W/m^2.K^4), T_{sup} is the body temperature [K], T_{viz} is the environment temperature [K].

For the proposed experiment, the fluid inside the metallic cans is water, and is this amount of fluid that will suffer cooling when exposed to the environment temperature. Therefore, there will be a coefficient of convective heat transfer between the center point of the can and its surface, and between this surface and the environment. As long as a difference of temperature exists between the water and the external environment, the inner temperature, T_{int}, will be slightly superior to the temperature of the surface of the can, T_{par} , as shown by Figure 2. The Equation (2) describes this process.

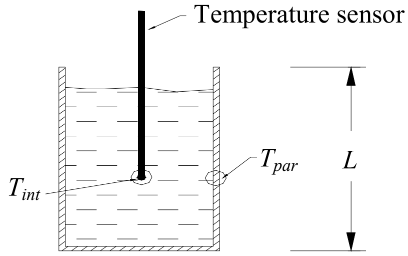

Figure 2 – Can filled with water ($T_{int} > T_{par}$).

$$q_{conv} = Ah(T_{par} - T_{int}) \quad (2)$$

In this equation, q_{conv} is the heat lost by the fluid [W], A is the area of the can surface [m²], h is the convective coefficient [W/m²K], which may be taken from:

$$h = \frac{kNu_L}{L} \tag{3}$$

In this equation, L is the can height [m], k is the thermal conductivity [W/m²K] and Nu_L is the dimensional Nusselt number, which can be calculated with good approach for a vertical flat plate under laminar free convection by following equation:

$$Nu_L = \left\{ 0.825 + \frac{0.387 Ra_L^{1/6}}{\left[1 + (0.492/Pr)^{9/6}\right]^{8/27}} \right\}^2 \tag{4}$$

In this equation, Ra_L is the number of Rayleigh, calculated through equation (5), and Pr is the number of Prandtl.

$$Ra_L = \frac{g\beta(T_{par} - T_{int})L^3}{\nu\alpha} \tag{5}$$

Calculations of this coefficient of convection from the water inside the can show that it's around 180 W/m²K. It means that the thermal resistance between the center point and the surface of the can is small, and can be neglected. Furthermore, the surface of the can is thin and excellent conductor, so it's reasonable to assume its internal temperature to be equal its external temperature.

Applying the energy conservation principle to the situation presented in the Figure 1, that is the same problem treated in this work, yields:

$$\frac{dU}{dt} = q_{rad} + q_{conv} \tag{6}$$

On the left-hand side this equation is the time derivative of the internal energy of the body studied and the right-hand side represents the sum of heat rate by radiation and heat rate by convection, which values can be availed for similar expressions to the Equations (1) and (2), respectively. Internal energy derivative is given by:

$$\frac{dU}{dt} = mc_v \frac{dT}{dt} \tag{7}$$

In this equation, m is the body mass, c_v is its the specific heat at constant volume and last term is the time derivative of the body temperature. Rearranging the equations (6) and (7), and using the equations (1) and (2), it can be proved that:

$$\frac{dT}{dt} = \frac{A}{mc_v}\left[\varepsilon\sigma(T_{sup}^4 - T_{viz}^4) + h_{ext}(T_{sup} - T_\infty)\right] \tag{8}$$

In this equation, h_{ext} is the external convective coefficient between the body and the environment, calculated by means of equations (3) and (4). Naturally, the above can be adaptable to the problem this work, so m, c_v and T are the hot water mass, specific heat and temperature, while T_{sup}, ε and h_{ext} are the can temperature, emissivity and convective coefficient. With before, T_{viz} and T_∞ are the surroundings and environment temperature, which can be considered equals in this case.

3. EXPERIMENTAL APPARATUS

Figure 3 represents the experimental devices used for the essays realized in this work. Figure 3a shows the experimental apparatus to provide the water and metallic cans heating. It consists of a cast iron plate and a stove operated by alcohol. This system allows a slow and homogeneous heating of the water and the cans, so the temperatures of these masses evolve with time constants very near. Consequently, the final temperatures of both bodies are almost the same. This initial temperature equality is very important to allow that the emissivitys of the three metallic cans are compared between them.

Figure 3b shows the experimental apparatus where the tests were performed. It is comprised by a dark chamber, made with common cardboard, a support for the thermocouples, a base made with an insulating material and the metallic cans with hot water to the same temperature. During the cans and water cooling, the internal wall chamber temperature (T_{viz}) is almost equal to the internal air temperature (T_∞). Therefore, T_{viz} was considered equal to T_∞. This is a advantageous assumption, so the internal air temperature is very easy of measuring, while the internal (and external) chamber wall temperature is not.

Figure 3c shows the three metallic cans used in the tests. As can be seen, one can was completely without painting, being left without any covering of paint, and others two were painted by black and white paint.

Due the geometric disposition between the dark chamber and the cans, the experiment was conducted using two cans each time. Thus, tests with the black can and the unpainted were made first, and next with the black can and the white.

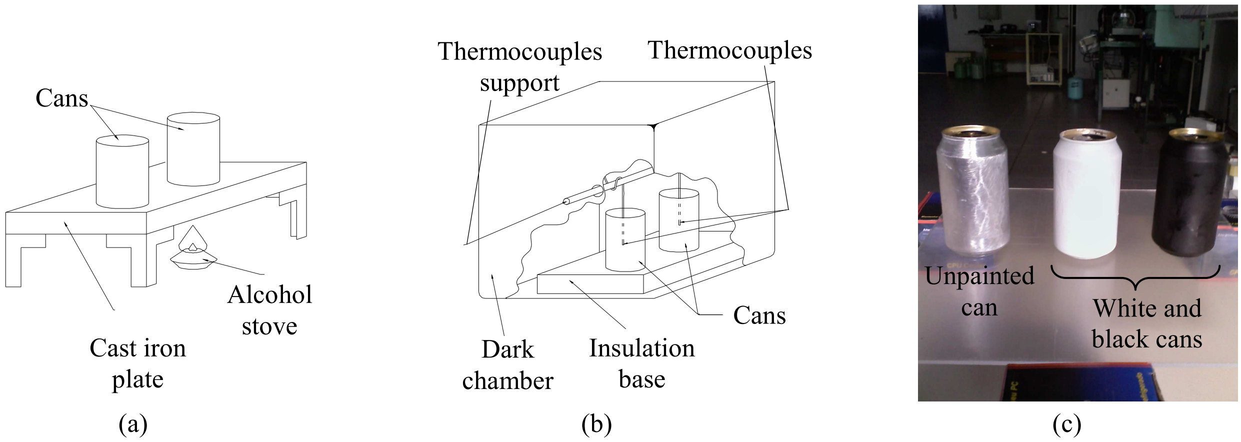

Figure 3: Experimental devices: (a) water and cans heating system; (b) dark chamber of tests; (c) metallic cans of tests.

A test plan was elaborated before to do the experimental procedures. This plan was supported by the ideas proposed by Figliola (2000). The first step of the experiment was to fill the cans with water. To do this, a becker with 500 ml of capacity and 5 ml of error was used. After that, the cans were put on the cast iron rectangular plate, as shown by Figure 3. When the boiling temperature of the water was reached, the cans were placed on the insulating surface and kept inside the dark chamber. The K-type calibrated thermocouples, linked in an acquisition data system, were inserted in the cans. From this point on, the data acquisition system captured the temperature data during around 3 hours, at a rate of 12 measurements per minute.

4. MEASUREMENT UNCERTAINTIES

In order to measure the temperature of the water inside each can, thermocouples K-type (copper-constantan) were used. To calibrate these thermocouples, two basis points were taken, the 0ºC (fusion of the ice), and 97,31ºC (boiling temperature of the water in Belo Horizonte). As a comparison system for the calibration, a standard thermometer of mercury with operation range –10ºC a 40ºC, accuracy of 0,05ºC, and another with operation range 90ºC a 100ºC, with accuracy of 0,01ºC were chosen. For each one of the points, ten measurements were made. Thus, two equations of calibration were found, one to each thermocouple, as follows:

Thermocouple 1:

$$T_c = 1.06899T_m - 3.32648 \quad (9)$$

Thermocouple 2:

$$T_c = 1,08385T_m - 4.3956 \quad (10)$$

In these equations, T_c is the actual temperature and T_m is the measured temperature obtained through the thermocouples linked to the data acquisition system. Both temperatures, T_c and T_m, are given in Celsius degrees. After this calibration, both thermocouples were linked to the data acquisition system of the laboratory, model 3497A, controlled by a microcomputer HP85.

In this work, there are, basically, two uncertainties that must be controlled. The one is associated with the water volume used. The second, and much more important, is the uncertainty of the data acquisition system, which includes the thermocouple error and the system error itself, due interference and noises of the network. The uncertainty of temperature T can be calculated by the following expression:

$$u(T)=\left|\frac{\partial T}{\partial m}\right|u(m)+\left|\frac{\partial T}{\partial T_0}\right|u(T_0)+\left|\frac{\partial T}{\partial t}\right|u(t) \tag{11}$$

In this expression, t is the time, m is the mass and T_0 is the initial temperature.

In a dynamic state experiment, uncertainty analyses are much more difficult than that for a steady-state experiment. As the temperatures change in time, it's important to know the response time of the measurement instruments. The time response of each thermocouple for a temperature variation of 1°C is supplied by the manufacturer, and it is 1.5 s. The model developed in this article can be used to produce the temperature evolutions of the metallic cans, so to value the time constant of the cooling process of each body. The thermocouples will be adapted to measure the temperature evolutions if, in first seconds of the cooling, a temperature change of 1°C to take place in a time much bigger than 1.5 s, that is the time constant of the thermocouples. It is important that this analysis is done in first seconds because the temperature changes are bigger in this stage of the cooling process.

The temperature time evolutions were determined solving Equation (8) for two aluminum cans, one painted by black and other without painting. In this equation, h_{ext} was supplied by Equations (3) and (4), c_v = 920 J/kg.K (aluminum specific heat at 300 K), m = 350 g (that is the water mass inside each can), A = 0,0264 m^2 (cylinder-area of diameter 70 mm and height 120 mm), $T_\infty = T_{viz}$ = 25°C and the temperature T_{sup} was considered 82°C at time t = 0. The black and unpainted can emissivitys were considered ε_b = 0.80 and ε_a = 0.10, respectively. These values were obtained of Holman (2002) for a temperature of 300 K. The numerical fourth-order Runge-Kutta method supplied for a MATLAB code was used (Campos, 2007) and the graphic showed in the Figure 4 was generate. It represents the solution of equation (8) during 10000 seconds.

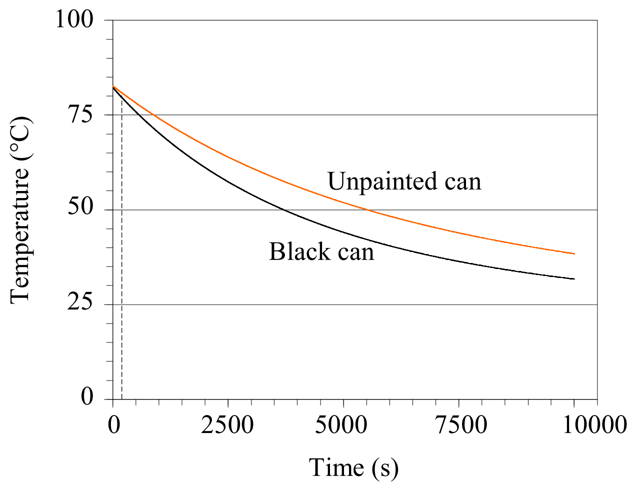

Figure 4 – Curves numerically calculated.

Many results can be obtained of the Figure 4. The vertical sketched line shows that the time to reduce the black can temperature of 1°C was around 100 seconds, so much less than the time constants of the thermocouples (1.5 s). For unpainted can, this time is still bigger. Thus, the thermocouples are adapted for the measurement in dynamic process.

The evolutions showed in the Figure 4 can used to compute $\partial T/\partial t$. Substituting the values these derivative in the Equation (11) yields the average values of $u(T)$ equals to 1.15°C. As the difference of temperature between the two cans at the end of the experiment time was around 6ºC, the experiment is viable to compare the emissivitys of the metallic cans.

3. RESULTS

After the completion of the essays, pairs of clouds of points were obtained, representing the decreasing of the temperature along time for the pairs of cans analyzed. Figure 5 shows the mass of points gathered for the black-painted can and the unpainted one. The continuous green line represents the average temperature for the air at the moment of the experiment. It can be seen that the decreasing of temperature as a function of time for both bodies follows the exponential tendency, and the cans, at zero time, have approximately the same temperatures (82ºC). At the end of the experiment time, difference between the temperatures is around 7.5ºC. The environment temperature measured by the data acquisition system oscillates around 21ºC.

Figure 6 shows the mass of points obtained for white-painted can and the black-painted one. Again, the green line represents the average temperature of the environment at the moment of the experiment. It's possible to see the exponential decreasing of temperature again, but this time, the mass of points for both bodies are practically put one upon each other. The initial and final temperatures for this essay were, respectively, 82ºC and 32ºC. The environment temperature oscillated around 22ºC.

The uncertainties $u(T)$ were calculated again with the help of the experimental curves shown in the Figures (5) and (6). The obtained results were practically the same those obtained previously through the modeling. Also it can be observed in these curves that the cooling processes are slow, so that the time response of each thermocouple is sufficient small to allow a reliable reading in dynamic regime.

Undoubtedly, the most important observation that can be done on these results is the fact that a black body does not present an infrared radiation heat transfer rate bigger than that of a body with another color, since the curves of the white can is practically identical to the black can. However, the heat transfer rate of the can without paint is significantly less than the rate of the painted cans. Therefore, the cooling of the unpainted can is very slow. So, in the case of infrared radiation, the paint in fact is that provides a bigger emissivity to the body, and not the paint color.

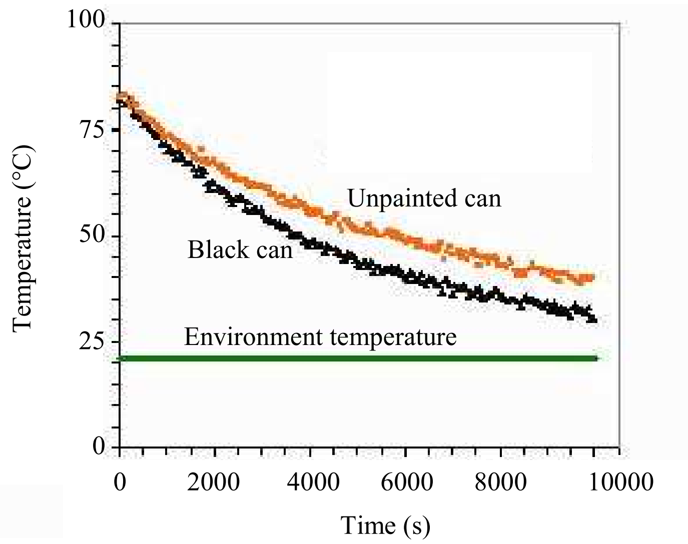

Figure 5: Comparison between the unpainted can and the can painted in black.

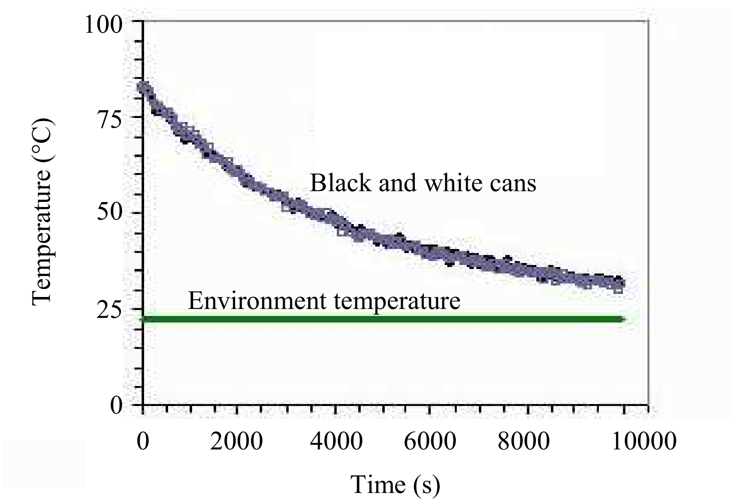

Figure 7: Comparison between the cans painted in black and white.

4. CONCLUSION

From the results obtained, it can be seen that, for the infrared wavelengths, the different colors don't have predominant influence on the heat transfer rate of bodies, once the black and the white paints had the same performance. The inexistence of painting on the surface of one can contributes for the reduction of the heat transfer rate, because the emissivity of exposed metal is lower than the emissivity of an paint for this same wavelength.

So, it doesn't matter which color a surface is painted with. As long as it's emitting in the infrared range, it's sufficient the painting for causing improvement of energy loss. This is the case of domestic fridge condenser coils.

With concerns about engineering teaching, the experimental procedures described, along with its mathematical broach, can be used as basis for briefings in practical classes of heat transfer, whereas this experience is easy to reproduce, has relatively low costs for its deployment and discuss fundamentals of radiation.

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