# Radiation in the coffee cup

João Paulo M. Ferreira

Universidade Católica Portuguesa, CBQF - Centro de Biotecnologia e Química Fina – Laboratório Associado, Escola Superior de Biotecnologia

Rua Diogo Botelho 1327, 4169-005 Porto, Portugal

Email: jpferreira@ucp.pt

## Abstract

It is commonly assumed that radiative heat transfer only plays a relevant role in situations involving temperatures of several hundred degrees Celsius and above. Other common misconceptions relate to the cooling of metallic vs non-metallic objects, and the effect of their color. A series of alternative demonstrations that counteract these beliefs and show the role played by radiation in the cooling of common tableware containing hot liquids are described here. The experiments require basic equipment, easily available even at home. The cooling curves obtained can be modeled with Newton´s law of cooling and the corresponding heat transfer coefficients estimated. The results elucidate the influence of surface emissivity on radiative heat transfer, and that this mechanism has a non-minor share on cooling processes even at temperatures below the normal boiling point of water. A final demonstration concerns heating of the same systems and corroborates the previous conclusions.

**Keywords**: heat transfer mechanisms; heat radiation; emissivity; convection; Newton´s law of cooling; heat transfer coefficient.

## 1. Introduction

An important topic in science education is thermal radiation, in particular infrared (IR) radiation. Besides the fact that we live immersed in this type of radiation, the technological applications of IR are extremely diverse: in thermometry (Usamentiaga et al 2014); in the design of insulated containers for storage and transport of food and biologicals; in building construction, where the development of special insulating layers, paints with particular optical properties, or of glasses with reflective properties (so called e-glasses); in technical textiles, with the development of radiative modulating textiles, that contribute to body thermal management (He et al 2023); in the medical field, with applications of thermography in diagnostics and in radiative therapies for a large range of pathologies, such as musculoskeletal (Tsagkaris et al 2022), or chronic wounds (Oyebode, Houreld and Abrahamse, 2020), among others; IR is yet used in telecommunications; in astronomical studies, etc..

In our common daily life, the play of IR radiation is also multifaceted. For instance, when ambient temperature is below ca. 30 °C, radiation is the main mechanism of heat loss by the human body (He et al 2023); or in several cooking appliances, such as conventional ovens, that make use primarily of heat radiation.

Besides the above, quite often the topic of thermal radiation does not get due attention in curricula. It is true that a more comprehensive approach of the subject is not accessible to secondary school students, or requires a too long lecture time, quite often not available. This applies even to coverages at university level, in science and engineering majors. Connected with this, often it is stated "radiation only matters in situations involving high temperatures, not the most common ones; in these, conduction and convection are the relevant mechanisms of heat transfer." In this way, it is common to quantify heat transfer with the coupling of radiation with convection, this is, using "combined" heat transfer coefficients (Çengel, Boles and Kanoglu 2023), without getting into the specifics of the first mechanism.

In recent years, thermal imaging cameras have become popular, particularly with the advent of models that operate linked to modern smartphones. These devices became reasonably affordable. Multiple pedagogical activities have been proposed with the use of such cameras, in this and other periodicals (Ludwig and Carpineti 2020; Paulins et al 2016; Kácovský 2019; Haugland 2008; Vollmer 2009; Oss 2021; Carpineti et al. 2019). The fact the technique originates colorful images is an attractive feature for youngsters. However, it has its limitations, in terms of accuracy in temperature readings, and in enabling more precise quantitative results (Kácovský 2019).

Here, alternative demonstrations are proposed, which require even simpler equipment, and can be done at school or at home. The activity is based on the cooling curves of hot drinks or semi-liquid foods, such as coffee, tea, soup, etc., contained in common ceramic or glass tableware. A previous report has analyzed such cooling processes and quantified the role of different heat transfer mechanisms, with emphasis on evaporative cooling (Ferreira 2024). In that work, the model of coupled convection-radiation was used and combined heat transfer coefficients were determined. This is a common procedure for situations involving moderate temperatures (Çengel and Ghajar 2020). Now, additional cooling curves are presented that will lead to evaluation of the contribution of radiation in the above common cooling processes. The study is complemented with two situations of heating the same systems also under the influence of radiation.

The presentation to students, or other audience, of the laws governing thermal radiation is optional and depends on their background and learning objectives. The basics involve the Stefan-Boltzmann law, which states that heat emitted per unit time ($\dot{Q}$) by a perfect emitter is proportional to its absolute temperature to the fourth power:

$$\dot{Q} = \sigma A T^4 \tag{1}$$

where σ is the Stefan-Boltzmann constant ($\sigma = 5.670 \times 10^{-8}$ W·m$^{-2}$·K$^{-4}$) and $A$ is the surface area of the body. If a body is not a perfect emitter, then a correction factor is introduced:

$$\dot{Q} = \varepsilon \sigma A T^4 \tag{2}$$

with $\varepsilon$ being the emissivity of the surface ($0 < \varepsilon < 1$). This parameter depends mainly on the material involved, but also on the finishing of the surface. But an object also absorbs radiation from its environment. In case it is uniformly enclosed by an environment at temperature $T_a$, the net heat transfer by radiation becomes:

$$\dot{Q} = \varepsilon \sigma A \left(T^4 - T_a^4\right) \tag{3}$$

Very seldom this is a realistic assumption, as generally the surroundings involve a set of different objects and surfaces, each with its own radiative properties and orientation relative to the object under analysis. The introduction of these factors in the model is quite complex and beyond the level generally covered in undergraduate courses. Fortunately, in many cases, we can forgo such treatments and a much simpler approximation gives good results.

## 2. Practical activities

The subject can be launched in classes by asking students the question: if hot water (or tea, coffee, etc.) is placed in the ceramic mug and in the aluminum cup shown in figure 1, which of them will cool faster? Having collected the answers from the class, demonstrations can start.

Figure 1. The aluminum and ceramic cups used in the first activity described.

The basic materials are a digital oven thermometer, a digital kitchen balance, ceramic and glass mugs, and aluminum cups. A common infrared thermometer will enrich the demonstration. For each container, a Styrofoam cover that fits the top should be cut; an 18 mm-thick board was used here. Glass or ceramic containers can be filled close to the top with water at room temperature and then heated in a microwave oven close to boiling. For metallic ones, water can be boiled in an electric jar and then transferred. The weight of water placed in the container should be measured. The container is then covered with the Styrofoam disk and the oven thermometer is lowered, passing through this disk, and positioning the sensor tip in the center. Figure 2 shows the set up.

Figure 2. The set-up for carrying out the cooling experiments, showing the oven thermometer in place, the chronometer, and the IR thermometer used for reading the temperature of the outside surface temperature of the mug.

When the water temperature reaches e.g. 90 °C, time counting starts. The time of each degree Celsius transition is taken, till the water reaches 40 °C or slightly below. During the process, the temperature of the outside face of the cup can be taken at several times using the IR thermometer.

## 3. Results and Discussion

**Demonstration 1**. Figure 3 shows the time – temperature profile for the ceramic and aluminum cups shown in figure 1, filled initially with hot water. One can see that, in opposition to the common expectation, the aluminum cup took considerably longer to reach 40 °C: 127 min vs 90 min. The mass of water was essentially the same in the two containers and the water-wall lateral area was even slightly higher for the ceramic cup. That expectation is based on the knowledge that aluminum has a much higher thermal conductivity (237 W/(m·K)) than ceramics (1.5 W/(m·K)), coupled with a thinner wall for the metal cup (5.2 mm vs 0.5 mm).

Students should be guided to reason that heat transfer from the water to the room air involves convection between the liquid and the internal walls of the container, conduction through the walls, and a mix of convection and radiation from the outside face of the container to the air. In these experiments, cooling by evaporation at the liquid surface is inhibited by the Styrofoam covers (Ferreira, 2024). Temperature readings with the IR thermometer showed that the outside face of the ceramic mug is around 3.5 °C lower than the water one at the early stages of the process, with this difference becoming smaller as the water cools, ending in ca. 1.5 °C (Figure 4). This was also observed previously with a ceramic bowl (Ferreira 2024), and it means that the main resistance to heat transfer from the mentioned three sequential steps is the walls – air one.

This conclusion applies to all cases and does not explain the relative positioning of the two curves in Figure 3. The important factor is the different radiative properties of ceramics and aluminum. Students should be presented with this topic, introducing the characterizing parameter emissivity. The value of emissivity of standard aluminum is 0.09, while for ceramics is 0.92 (with slight variations, depending on the type and finishing of each material) (Çengel and Ghajar 2020). Therefore, the metallic cup loses considerably less heat by radiation than the ceramic one, leading to a slower cooling. It is also instructive that students use the IR thermometer during the cooling with the aluminum cup, observing that it gives (false) low readings, in this case between ca. 34 °C and 27 °C along the process, therefore much lower than the real wall temperatures.

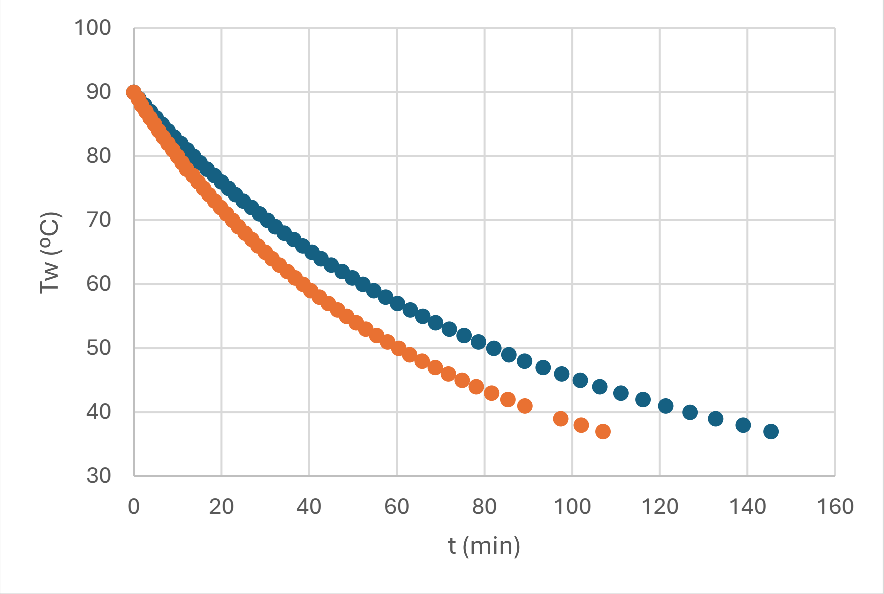

Figure 3. Cooling curves of water in a ceramic mug (orange dots) and in an aluminum cup (blue dots).

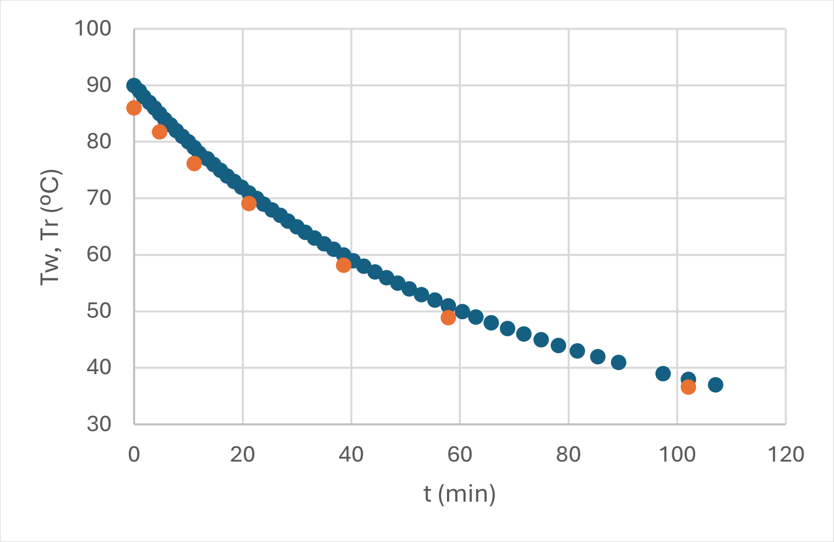

Figure 4. The cooling curve of the ceramic mug, with the water temperature (blue dots) and the temperature of the outside surface read by the IR thermometer (orange dots).

Attending to the small temperature difference between the water at the center of the mug and the outside face, one concludes that the water temperature should have small differences throughout at each time. In this case, Newton´s law of cooling might apply, leading to the model relation:

$$T - T_a = (T_i - T_a)\exp\left(-\frac{t}{\tau}\right) \tag{4}$$

with $T_a$ being the ambient temperature, $T_i$ the initial temperature of the system (here, water, with the symbol $T_w$ onwards), and τ the thermal time constant, corresponding to

$$\tau = \frac{m_w\ c_w}{h\ A} \tag{5}$$

where $c_w$ is the specific heat capacity of the water, *h* the overall heat transfer coefficient, and *A* the surface area for heat transfer (Çengel and Ghajar 2020; Vollmer 2009). Equation (4) suggests a linearization of $ln(T_w - T_a)$ vs *t*. This representation for the two cooling curves above is in figure 5. Both have an excellent R2 value, meaning that Newton´s law is indeed obeyed.

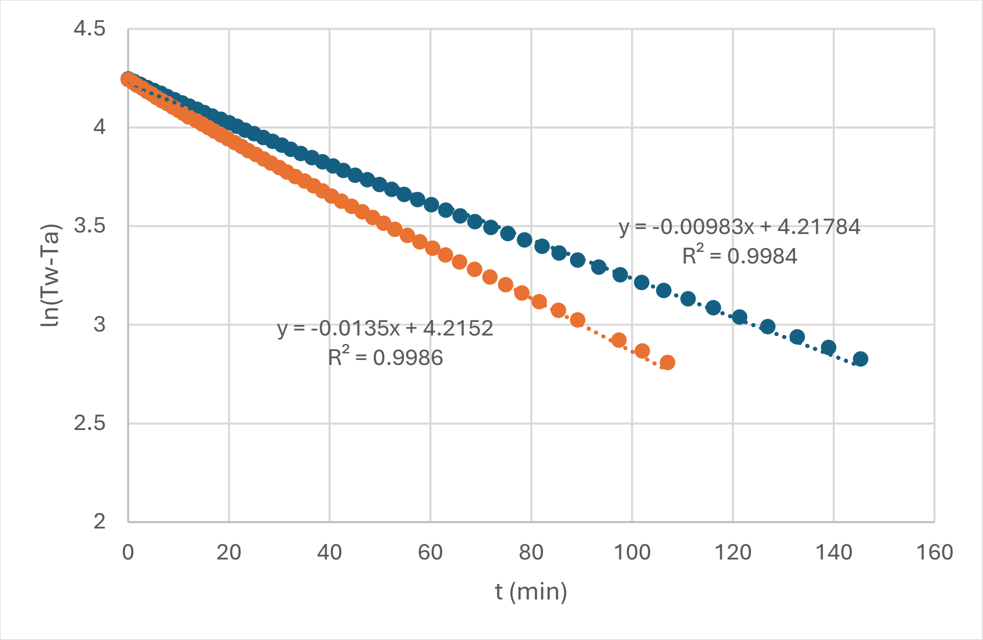

Figure 5. Plot of *ln*($T_w - T_a$) versus time for the cooling experiments with the ceramic mug (orange dots) and with the aluminum cup (blue dots).

From the slope of each fit, one can estimate the overall heat transfer coefficient. Using the known value of specific heat capacity of water and the lateral surface area between cup internal wall and water (the bottom area was not included as the cups sit in Styrofoam), one arrives at the values $h$ = 13.7 W/($m^2$·K) for the aluminum and $h$ = 16.8 W/($m^2$·K) for the ceramic cup.

These overall coefficients must be close to the outside wall-air one, as this is the main resistance. Let us note that these two values are well within the range reported for similar situations of natural convection involving a solid surface and a gas: Çengel and Ghajar (2000) and Vollmer (2009) indicate a 2 – 25 W/($m^2$·K) interval for such coefficients.

The second value is ca. 23 % higher than the first, a result that could potentially be higher if a more polished, brighter aluminum container was used.

The fact that Newton´s law was obeyed even in the case of the ceramic cup means that, during the process, prevails the regime in which radiation is also approximately linear with temperature difference. Vollmer (2009) has analyzed the conditions under which this approximation holds. He concluded that it is valid for temperature differences with the environment up to a certain value, that depends on the ratio of convection to radiation heat transfer. Such limit can be as low as 30 K, but in other situations can be as high as 200 K, increasing with the ratio of those two heat transfer mechanisms. One other report suggested the criterium ($T$–$T_a$) << $T$ for validity of

Newton´s law (O´Sullivan 1990). The conditions of these experiments fall under both criteria, as demonstrated by the good fit to Newton´s law. The values of *h* estimated include the contribution of radiation but, due to the low emissivity of aluminum, this case translates predominantly natural convection. For the ceramic cup, the *h* value is a combined convection-radiation, and we can interpret the difference of this value to the one of aluminum as the contribution of radiation. One concludes that, even at the (moderate) temperatures hot foods and drinks are prepared, emission of radiation can be of significance.

**Demonstration 2**. In the second set of experiments here reported, the same glass cup, without and with a wrapping of aluminum foil, was used (figure 6).

Figure 6. Glass mug with the removable hand and base on (left), and wrapped with aluminum foil (right), used in cooling experiments.

The cooling curves are in figure 7, where we can see that the foil retarded considerably the process. Due to the high conductivity and thin structure of the foil, its resistance to conduction is negligible and the observed effect is due to its high reflectivity for the IR radiation emitted by the cup walls and, consequently, low emission to the room air.

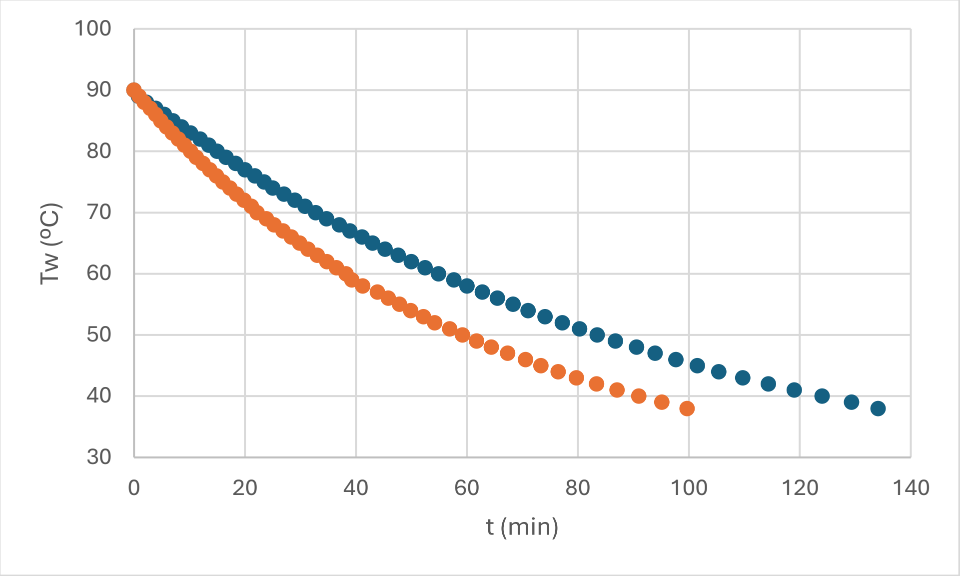

Figure 7. Cooling curves of water in a glass cup (orange dots) and in the same cup covered with aluminum foil (blue dots).

Figure 8 is the linearization according to Newton´s law for this set of curves.

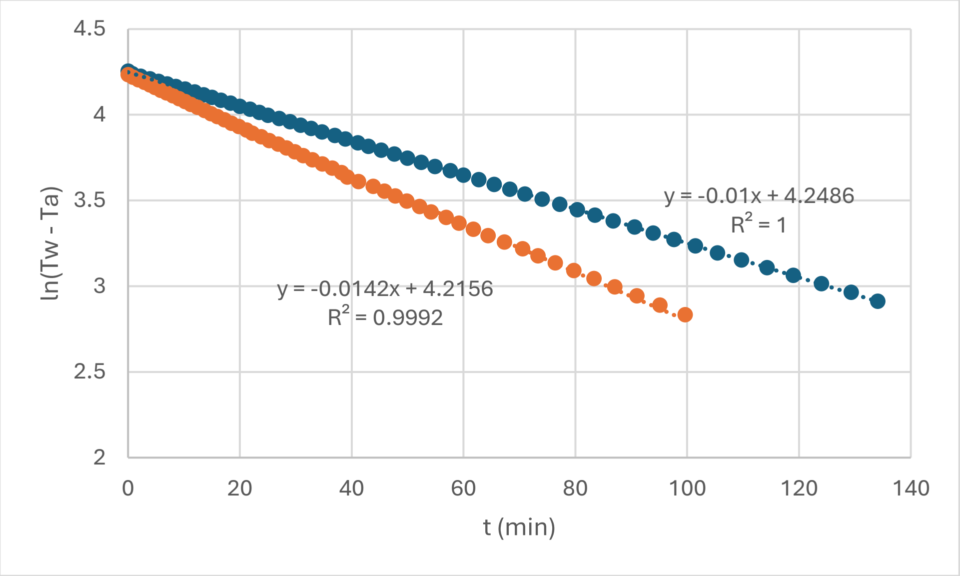

Figure 8. Plot of $ln(T_w - T_a)$ versus time for the cooling experiments with glass cup (orange dots), and with the same cup wrapped in aluminum foil (blue dots).

Again, for both cases there is an excellent linear fit. Based on equation (5), the values $h = 12.4$ W/(m$^2$·K) and $h = 8.79$ W/(m$^2$·K) are estimated for the overall heat transfer coefficients without and with the foil, respectively. Aluminum foil has an emissivity around 0.04. Therefore, on the approximation that the overall coefficient represents the external wall-air one, we can interpret the second value as due only to convection and the first to combined convection-radiation heat transfer. Based on this, we can estimate a contribution of about 70 % for convection (calculated as the ratio of the second to the first *h* value) and 30 % for radiation (the difference) for the cooling process of glass between 90 °C and 40 °C.

**Demonstration 3**. In a third set of experiments, the effect of altering the radiating surface and the effect of color are tested. Identical aluminum cups were painted with spray ink of different colors (figure 9).

Figure 9. Aluminum cups used in cooling runs. From left to right: original and painted blackish green, white, and shiny silver.

The cooling curves registered with these painted cups, and of the original aluminum one, are in figure 10. The respective linearizations are in figure 11.

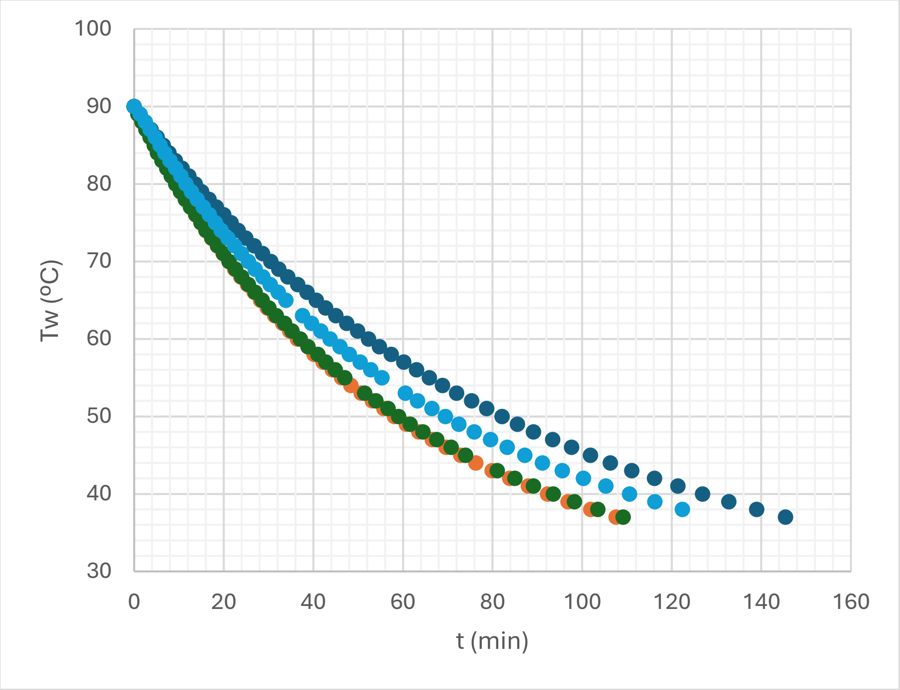

Figure 10. Cooling curves of water in aluminum cups: original (dark blue dots), and painted color white (orange dots), blackish green (dark green dots) and shiny silver (light blue dots).

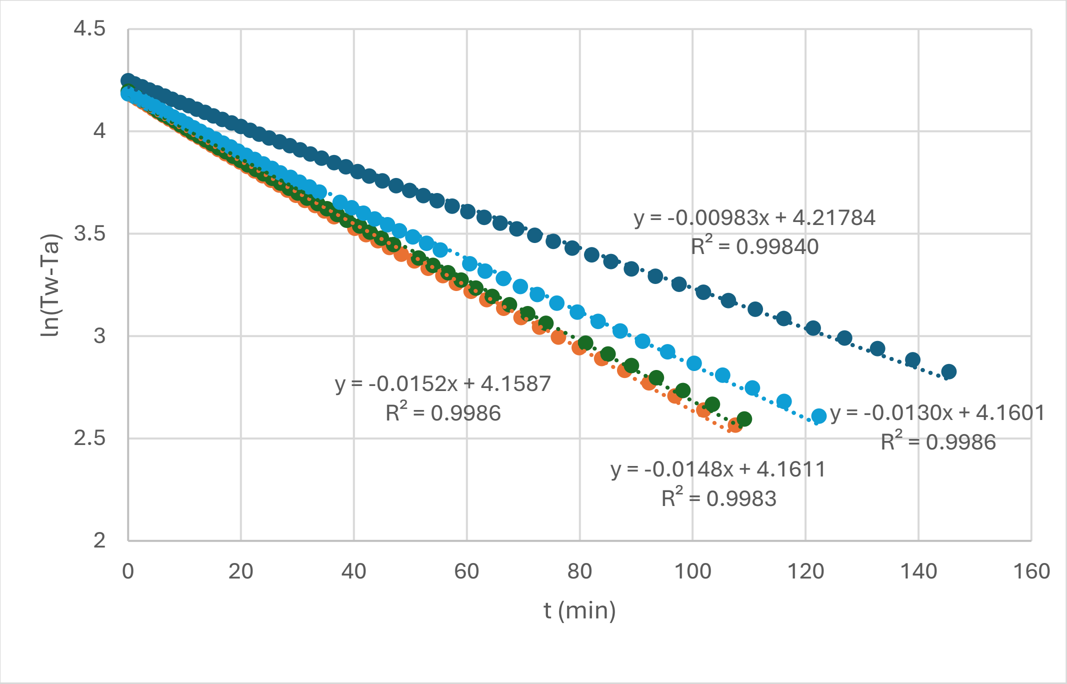

Figure 11. Plot of *ln*($T_w - T_a$) versus time for the cooling runs with aluminum cups: original (dark blue dots), and painted color white (orange dots), blackish green (dark green dots) and shiny silver (light blue dots).

Painting aluminum increased the heat transfer, in all cases. White and a very dark color gave identical cooling curves. It is a common misconception that dark colors lead to faster cooling (and heating), as such surfaces will behave closer to a blackbody. Color has to do with absorption and reflection of visible radiation, and not infrared one (Bartels 1990). Similar standard paints differing in color have identical IR emissivity. This can be verified in several tables of emissivity values available online (e.g., Transmetra, n.d.). Metallic colors are, in general, exceptions. This was observed in this case, with longer cooling times of the silver-painted cup compared with the other colors. The explanation is that metallic-color paints have metallic pigments, namely aluminum (Shaw, 2023). Therefore, such paintings will behave closer to a true metallic surface. Nevertheless, an increase in heat transfer compared to non-painted aluminum was observed also in this case.

The readings of the IR thermometer on the outside surface of these cups corroborate the above facts: the white and blackish cups gave readings no more than 1.5 °C lower than the water temperature, with very reproducible values; The readings of the silver painted were quite irregular, varying with slight changes in the target area; the average difference between water temperature and the IR readings were (falsely) much higher, about 25 °C on the early stages of the cooling, and below 10 °C on the final stages. The non-painted cup gave reproducible readings (although false), varying from 34 °C to 27 °C, as said before. Remind that these thermometers sense the IR radiation emitted by the targeted surface, and assume a certain value of emissivity, generally above 0.90, unless otherwise specified.

The overall heat transfer coefficient translates the differences among the cooling processes, with the values for all the above cases summarized in table 1:

Table 1. Values of overall heat transfer coefficient (*h*) obtained in cooling experiments with the different cups.

| | Ceramic | Glass | | Aluminum | | | |
|---|---|---|---|---|---|---|---|
| | | Original | With foil | Original | Blackish green | White | Brilliant silver |
| $h$/ W/(m$^2$·K) | 16.8 | 12.4 | 8.79 | 13.7 | 20.6 | 21.1 | 18.1 |

Taking the *h* value of original aluminum as due to convection and the blackish or white ones as reflecting convection and radiation, a contribution of 33 % for radiation and 67 % for convection (evaluated as the ratio of the two *h* values) is suggested, a partition very similar to the one obtained in demonstration 2.

### Demonstration 4

Students might wonder about the behavior of these systems in an opposite situation, that is, when being heated by exposure to an environment emitting radiation. A complimentary demonstration, that corroborates the results of the previous one, is suggested.

The aluminum cups – original, white, and black greenish-, were filled with water taken from the fridge. The Styrofoam lids and bases were wrapped in aluminum foil, to avoid their thermal degradation. The cups were placed in a small conventional oven, without forced convection (figure 12), pre-warmed at 80 °C.

Figure 12. Aluminum cups filled with cold water and placed in a small conventional oven.

Temperature was measured just every 30 minutes, as the thermometer did not fit inside the oven, and this had to be opened for the effect. Figure 13 presents the data.

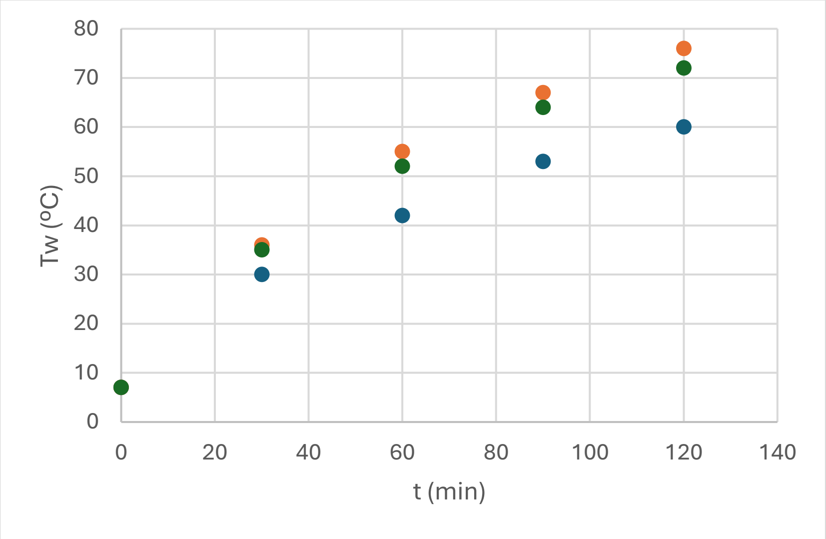

Figure 13. Time – temperature profiles of aluminum cups placed in an oven set at 80 °C: original (blue dots), and painted white (orange dots), and black greenish (green dots).

The water in the non-painted cup received less heat than in the other two. The mechanisms of heat transfer in this type of oven are also natural convection and radiation. As the oven walls are warmer, the cups will have a net gain of thermal radiation. When discussing the radiative properties of materials, students should be presented with absorptivity (and reflectivity), besides emissivity. A good / bad emitter is also a good / bad absorber, with emissivity equaling absorptivity (Çengel and Ghajar 2020). Therefore, aluminum is a poor absorber, but painting increased its absorptivity of IR radiation. A data treatment according to Newton´s law as done in the previous demonstrations (not shown) gave estimates of overall heat transfer coefficients of similar magnitude, but slightly higher: 15 W/(m$^2$·K) for original aluminum, and 25-26 W/(m$^2$·K) for the two painted cups. The fact that the external air – cup walls is the main resistance in the overall heat transfer contributes to this observation.

The same three cups filled with cold water were also exposed to sunlight, on a hot and clear summer day, between 1 and 3 pm, and in a place rather protected from drafts. Water temperature was taken every 20 minutes, with the results shown in Figure 14.

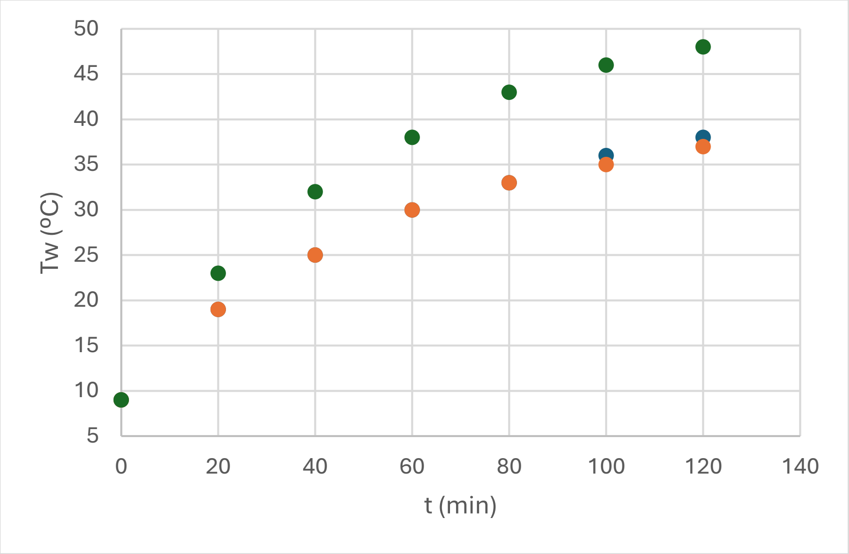

Figure 14. Time – temperature profile of aluminum cups exposed to sunlight: original (blue dots), and painted white (orange dots), and black greenish (green dots).

Now, the water in the blackish green cup warmed considerably more than in the white and non-painted cups. The dark surface is a better absorber of solar radiation than the white painted or the metallic one. It is interesting that the last two showed overlapping curves. A substantiated explanation for this observation would require further research, in particular to find the radiative spectrum of the different surfaces; furthermore, the open-air conditions bring additional variables to the process. The key message of this demonstration is that the emissivity of materials depends on the wavelength of the radiation (Bartels 1990), namely visible or solar vs long infrared.

## Conclusions

Four demonstrations are proposed to show the role of radiation on heat transfer at temperatures below the normal boiling point of water and using common containers for liquid foods. The activities can go hand in hand with discussions of thermal properties of materials, namely thermal conductivity, and emissivity. The results show that radiation has a significant role even at such temperatures. They also show the low emissivity of a metal surface, which can be increased just by painting. Furthermore, the activities demonstrate that the radiative properties of materials vary with the nature, or wavelength interval, of the radiation.

With this knowledge, students can better understand several natural phenomena and a multitude of common products and processes that involve IR and visible radiation.

**References**

Bartels R A 1990 Do darker objects really cool faster? *Am. J. Phys.* 58 244-248

Carpineti M, Cazzaniga L, Perotti L, Giliberti M, Cavinato M and Ludwig N 2019 Embedding Physics into technology: Infrared thermography and building inspection as a teaching tool – a new participated strategy approach to the physics of heat transfer and energy saving for professional schools *Can. J. Phys.* **47** 1019

Çengel Y A and Ghajar A J 2020 Heat and Mass Tranfer: Fundamentals and Applications 6th Edition (New York, McGrawHill)

Ferreira J P 2024 How a soup bowl and a coffee cup cool down *Phys. Educ.* **59** 055020

Haugland O A 2008 Keeping the Coffee Warm: A Challenge for Amateurs and Professionals *Phys. Teach*. **46** 372-374

He M, Zhao B, Yue X, Chen Y, Qiu F and Zhang Tao 2023 Infrared radiative modulating textiles for personal thermal management: principle, design and application *Nano Energy* **116** 108821

Kácovský P 2019 The visit of a thermal imaging world in one physics lesson Phys. Educ. **54** 045011

O´Sullivan C 1990 Newton´s law of cooling-A critical assessment *Am. J. Phys*. **58** 956-960

Oss S 2021 Infrared visualization of lumped and non-lumped thermal transient processes in an introductory laboratory *Eur. J. Phys.* **42** 015101

Oyebode O, Houreld N N and Abrahamse H 2021 Photobiomodulation in diabetic wound healing: A review of red and near-infrared wavelength applications *Cell Biochem. Funct.* **39** 596-612

Ludwig N and Carpineti M 2020 Frying an egg to study heat transport: an engaging and didactic experiment *Phys. Educ.* **55** 025016

Paulins P, Krauze A, Ozolinsh M and Muiznieks A 2016 Warming of water in a glass *Phys. Educ.* **51** 025013

Shaw J 2023 What to Know About Metallic Paint https://blog.myperfectcolor.com/what-to-know-about-metallic-paint#:~:text=Metallic%20coatings%20are%20made%20with%20a%20variety%20of,and%20sizes%20that%20help%20contribute%20to%20the%20effect accessed July 21, 2024

Tsagkaris C, Papazoglou A S, Eleftheriades A, Tsakopoulos S, Alexiou A, Gaman M-A and Moysidis D V 2022 Infrared Radiation in the Management of Musculoskeletal Conditions and Chronic Pain: A Systematic Review *Eur. J. Investig. Health Psychol. Educ.* **12** 334-343

Usamentiaga R, Venegas P, Guerediaga J, Vega L, Molleda J and Bulnes F G 2014 Infrared Thermography for Temperature Measurement and Non-Destructive Testing *Sensors* **14** 12305-12348

Transmetra (n.d.) Table of Emissivity of Varios Surfaces (for Infrared Thermometry) https://www.transmetra.ch/images/transmetra_pdf/publikationen_literatur/pyrometrie-thermografie/emissivity_table.pdf accessed July 22, 2024

Vollmer M 2009 Newton´s law of cooling revisited *Eur. J. Phys.* **30** 1063-1084