Estimation of the temperature of a radiating body by measuring stationary temperatures of a thermometer placed at different distances

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† Deceased March 2016

Abstract

The paper presents a novel method for determining the temperature of a radiating body. The experimental method only needs the utilization of very common instrumentation. It is based on the measurement of the stationary temperature of an object placed at different distances of the body and on the application of the energy balance equation in a stationary state. The method permits to obtain the temperature of an inaccessible radiating body when radiation measurements are not available. The method has been applied to the determination of the filament temperature of incandescent lamps of different powers.

Keyword: Energy balance equation; Incandescent lamp; Radiant temperature

1. Introduction

The temperature of a radiant body has been determined by several methods. Optical methods for measuring the incandescent object are widely known and used universally [1]. One of the more studied systems has been an incandescent lamp. Incandescent lighting is very economical and nonhazardous to manufacture, although less energy efficient than other lighting technologies. For this reason the estimation of the temperature of the filament of an incandescent lamp has been studied extensively [2-4]. In heating and cooling systems, radiative exchanger and radiant temperature gain importance. Radiating heating systems are a preferable alternative to produce more comfortable environment. For this reason, the knowledge of the temperature of a radiant body is an important theme.

A small object irradiated by a radiation source can reach a steady state within a stable environment. The temperature of the object in that state could be evaluated by performing a detailed energy balance. To accomplish this balance it is necessary to know: 1) the temperature of the radiation source, 2) the geometry of the radiation source and its emittance, 3) the geometry of the object and its behavior against radiation, 4) the position of the object with regard to the source, 5) the temperature of the environment, and 6) the detailed thermal conduction or convection existing between the object and its environment.

Supposing that, except the source temperature, all the necessary physical information about the object and the source is known, a detailed energy balance could be made for the object, while the temperature of the object could be measured at the steady state at a given distance between the object and the source. If this approach is applied to multiple steady states corresponding to different distances between source and object, the unknown source temperature can be calculated. Further, if the object is a thermometric bulb, its temperature can be directly measured. This would be necessary, for example, if the source temperature measurement is inaccessible and radiation measurements are not available. Moreover, the necessary instrumentation for the experimental method proposed is very common in laboratories.

In what follows, it is shown that setting a detailed energy balance for the thermometer in the steady state, on one hand, and performing a series of simple experimental measurements, on the other hand, it is possible to determine the temperature of the source. By the way, the spatial temperature field induced by radiation corresponding to the stationary states of the thermometer is determined.

2. Experimental setup

An incandescent lamp and a calibrated thermocouple were used as radiation source and thermometric bulb, respectively. Both were placed in an elementary optics bench, which permitted to measure the distance, *R*, between both with millimeter precision. A spherical lamp, with a diameter of 0.045 m, was used to simplify the geometry. The lamp filament forms a flat arch, located in the mid-point plane of the lamp. Both filament and glass bulb of the lamp act as radiation sources with different temperatures (figure 1). A thermocouple was used as thermometer (figure 2). The thermocouple welding, of copper and nickel, has approximately the shape of a small cylinder of diameter of 0.0002 m. To simplify the geometry of the thermometer, it is covered with a square foil housing. This cap is approximately flat (except for the slight deformation caused by the thermocouple), and its surfaces approximate two squares, each with an area of 0.0001 m^2. The temperature measurement is carried out with the usual electronic instrumentation, which permits to measure temperature within 0.1 K.

Figure 1. Standard incandescent lamp used as radiation source.

In the optical assembly, the plane containing the filament and the plane of the cap are parallel placed. An imaginary axis perpendicular to both planes passes approximately through the centers of the lamp and the cap (figure 2). In these terms, it can be assumed as a good approximation that the radiation source acts as a point source. In fact, the bulb spherical symmetry allows that it can be considered as a central point. Moreover, the filament can be considered as a series of point sources that form an arc of approximately 0.005 m around the center of the lamp. In turn, the series of point sources can be considered as a single source placed at the center, at the same distance that between the lamp and the thermometer.

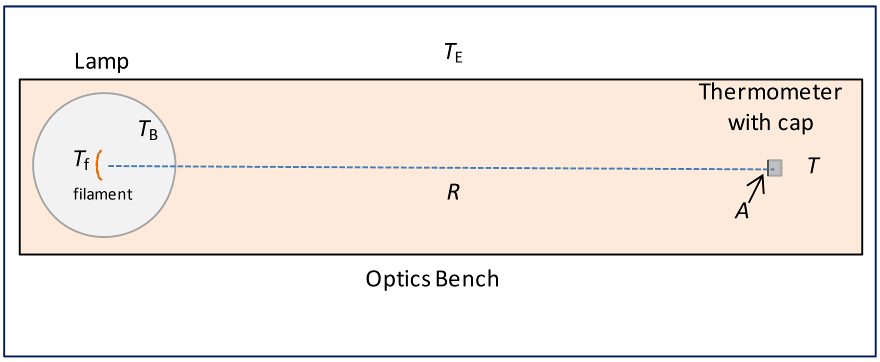

Figure 2. Sketch of the system. T_F: filament temperature; T_B: glass bulb temperature; T: thermometer temperature; T_E: environmental temperature; R: distance between thermometer and lamp; A: cap surface.

3. Stationary energy balance

The different energy contributions to the energy balance of the thermometric bulb in steady state are: 1) the radiant fluxes of the filament, J_f, and of the glass bulb lamp, J_B, incident upon the surface, A, of the face of the cap exposed to the lamp through the solid angle, $A/(4\pi R^2)$, defined by this surface at the distance R from the center of the lamp. Furthermore, the radiant flux, J_A, incident upon both sides of the cap from the environment, 2) the radiant flux, J_m emitted by both sides of the cap of the thermometric bulb, 3) the convective flux, J_{cv}, over the cap in the laboratory environment, and 4) the conductive flux, J_{cd} from the thermometric bulb via thermocouple leads, towards the environment. In the steady state, the incoming and outgoing fluxes should be equal in absolute value, so that the net flux through the thermometric bulb is constant. Taking into account that the radiant fluxes of the filament, of the glass bulb and the environment are incoming fluxes, and the radiant flux of the thermometric bulb cap and the convective and conductive fluxes are outgoing fluxes, the balance is symbolically expressed:

$$(J_f + J_B)\frac{A}{4\pi R^2}\sigma_m + J_A - J_m - J_{cv} - J_{cd} = 0 \qquad (1)$$

In the first term of equation (1), both radiation fluxes are multiplied by the solid angle subtended by the cap and by the factor σ_m, which represents the absorptivity of the aluminum cap which covers the thermocouple.

The different terms in equation (1) are defined as follows. The radiation emitted by a real surface S at thermodynamics temperature T_S is given by the Stefan-Boltzmann law as

$$J = S\varepsilon\sigma T_s^4 \qquad (2)$$

where σ is the Stefan-Boltzmann constant and ε the emissivity of the surface [5].

According to equation (2), the radiant flux of the filament can be expressed as [5,6]:

$$J_f = S_f \varepsilon_f \sigma T_f^4 \left(1 - \sigma_{Bf}\right) \tag{3}$$

where S_f and ε_f are, respectively, the area of the emission effective surface and the emissivity of the filament, T_f is the temperature of the filament, and (1-σ_{Bf}) is the correction factor due to absorption of the filament radiation by the glass bulb of the lamp. σ_{Bf} is the absorptivity for the visible light spectrum of the filament.

The radiant flux of the glass bulb lamp can be expressed, according to equation (2) as [5,6]:

$$J_B = S_B \varepsilon_B \sigma T_B^4 \left(2 - \sigma_{BB}\right) \tag{4}$$

where S_B is the area of the emission surface of the lamp bulb, ε_B is its emissivity, and T_B is its temperature. The term (2-σ_{BB}) is the correction factor that takes into account the bulb radiation absorbed by the bulb itself. Both, inner and outer sides of the bulb, emit mostly infrared. After multiple reflections, the internal radiation goes out of the bulb, with the exception of the amount absorbed by it. σ_{BB} is the absorptivity for the emission spectrum of the bulb itself.

The radiant flux incident upon both sides of the cap from the environment can be expressed as [5,6]:

$$J_A = 2A\sigma_m \sigma T_E^4 = 2AC\varepsilon_m \sigma T_E^4 \tag{5}$$

where T_E is the environmental temperature, and the other symbols have been previously defined. The relationship between the absorptivity σ_m and the emissivity ε_m, is expressed by $C = \sigma_m/\varepsilon_m$. The behavior of the environment can be assimilated, for simplicity, to a black body cavity of temperature T_E.

The radiant flux emitted by both sides of the cap of the thermometric bulb can be expressed as [5,6]:

$$J_m = 2A\varepsilon_m \sigma T^4 \qquad (6)$$

where T is the thermometric bulb temperature.

The convective heat transfer acts on a surface S can be conveniently expressed by Newton´s law of cooling as [7]

$$J = Sh(T_S - T_\infty) \qquad (7)$$

where h is the convection heat transfer coefficient, and T_∞ is the temperature of the fluid sufficiently far from the surface.

According to equation (7), the convective flux over the cap in the laboratory environment, J_{cv}, can be expressed as:

$$J_{cv} = 2Ah(T - T_E) \qquad (8)$$

where h is the corresponding convection coefficient, and it has been taken into account that the convection flux acts on both sides of the cap of the thermometric bulb. In this case T_∞ would be the environmental temperature T_E. The convective flux can be estimated from equation (8) considering the cap as a vertical plate of length the edge of the cap. It permits to express h as a function of known parameters as the conductivity, diffusivity and kinematic viscosity of the air (See Appendix).

The rate of heat conduction through a plane layer of area S and thickness Δx can be expressed by the Fourier´s law of heat conduction as [8]:

$$J = -kS\frac{\Delta T}{\Delta x} \tag{9}$$

where k is the thermal conductivity and ΔT is the temperature difference established across the layer.

The conductive flux, J_{cd}, is performed by the two thermocouple wires, Cu and Ni. For both, the length, L, between bulb and measuring equipment is 1 m. The latter, due to its mass, is assumed at environmental temperature. The sectional area of the wire, s, is $2x10^{-7}$ m^2. According to equation (9), the expression for the conductive flux is given by:

$$J_{cd} = s\frac{\left(\kappa_{Ni} + \kappa_{Cu}\right)}{L}\left(T - T_E\right) \tag{10}$$

with κ_{Ni} and κ_{Cu} the thermal conductivities for Ni and Cu, respectively.

To replace the numerical values corresponding to the material properties in equation (1), the following criteria are applied: i) In the spatial measurements, the variation of the temperature of the thermometric bulb is of the order of two dozen degrees above environmental temperature at the most. Therefore a reference temperature intermediate of 300K was taken to evaluate the physical properties of the bulb. ii) To select the physical properties of the glass bulb of the lamp, whose temperature rises a hundred degrees, at most, the values of the absorption and emission properties are taken at 300 K. iii) The emissivity of the filament depends on the temperature, which varies thousands of degrees above ambient. In order to estimate the value of the emissivity corresponding to each temperature, the following experimental relation between filament absolute temperature and emissivity is used [7,9]:

$$\varepsilon_f = (4.4 \pm 0.2)10^{-2} + (1.9 \pm 0.3)10^{-4} T_f - (2.3 \pm 0.7)10^{-8} T_f^2 . \quad (11)$$

The numerical values of different parameters used are shown in Table 1 [8-10].

The area of the effective surface for the radiation of the filament is different for different power lamps. It also depends on the bulbs lamp manufacturer. Normally, the front of the bulb is a semisphere, enabling to consider spherical symmetry for the frontal radiation. All the spherical lamps used in this study (figure 1), have the same value of the bulb surface given in Table 1. The surface of the filament depends on the power lamp. The corresponding area values for 25, 40 and 60 W are given in Table 1.

Table 1. Values of the used parameters

Absorptivity of the lamp in the infrared fringe, σ_{BB}	0.726[a]
Absorptivity of the lamp in the visible fringe, σ_{Bf}	6.69×10^{-3} [a]
Acceleration of Gravity, g	9.81 ms^{-2} [a]
Area of the cap surfaces (squared), A	$(1.00 \pm 0.02) \times 10^{-4}$ m^2
Area of the spherical lamp bulb, S_B	$(6.36 \pm 0.01) \times 10^{-3}$ m^2
Effective area of the filament (60 W lamp), S_f	$(5.2 \pm 0.01) \times 10^{-5}$ m^2
Effective area of the filament (40 W lamp), S_f	$(3.6 \pm 0.01) \times 10^{-5}$ m^2
Effective area of the filament (25 W lamp), S_f	$(2.8 \pm 0.01) \times 10^{-5}$ m^2
Emissivity of the lamp bulb, ε_B	0.9 [a]
Emissivity of the thermometric bulb, ε_m	4×10^{-2} [a]
Kinematic viscosity of the air, ν	1.589×10^{-5} $m^2 s^{-1}$ [a]
Length of the edge of the cap, l	$(1.000 \pm 0.001) \times 10^{-2}$ m
Length of the Cu and Ni wires, L	(1.000 ± 0.001) m
Ratio between cap absortivity and emissivity, $C = \sigma_m / \varepsilon_m$	1.5
Sectional area of the Cu and Ni wires, s	$(2.0 \pm 0.1) \times 10^{-7}$ m^2
Stefan-Boltzmann constant, σ	5.67×10^{-8} $Wm^{-2}T^{-4}$ [a]
Thermal conductivity of the air, k_A	2.63×10^{-2} $Wm^{-1}s^{-1}$ [a]
Thermal conductivity of Cu thermopar, k_{cu}	4×10^{2} $Wm^{-1}K^{-1}$ [a]
Thermal conductivity of Ni thermopar, k_{Ni}	90 $Wm^{-1}K^{-1}$[a]
Thermal diffusivity of the air, χ	2.25×10^{-5} $m^2 s^{-1}$ [a]

[a] Taken from [8-10].The uncertainty is given by the last significant figure.

Taking into account equations (3)-(6), (8), (10) and (11) in the balance equation (1), and the numerical values given in Table 1, an energy balance equation is obtained where the only unknown variables are the filament temperature T_f and the thermometric bulb temperature T, which is dependent of the distance R between the thermostatic bulb and the filament of the lamp.

4. Experimental study

4.1. Thermostatic bulb temperature measurements

A stabilized AC source of 220 V was used to provide the power dissipated to three types of spherical lamps of 25, 40, and 60 W. For all lamps, the temperatures T corresponding to the stationary state of the thermostatic bulb at distances, R, with respect to the center of the sphere of 3, 6, 9, 12, 15, and 18 cm was measured. The results are shown in Table 2.

Table 2. Temperature (T) measured by the thermometer as a function of the distance to the lamp (R).

Power lamp	**60 W**	**40 W**	**25 W**
R(m) (±0.0001)	T (K) (±0.1)	T (K) (±0.1)	T (K) (±0.1)
0.18	293.8	293.6	292.7
0.15	294.1	293.7	292.7
0.12	294.6	294.5	293.3
0.09	296.7	296.2	293.6
0.06	299.7	297.7	295.4
0.03	312.6	308.8	301.5

As can be observed, with all the lamps, the temperature decreases as the distance to the source increases. With the same thermometer, the average temperature of the glass bulb of the lamp, T_B, was also measured by contact. The results are shown in Table 3.

Table 3. Temperature of the glass bulb envelope (T_B), environmental temperature (T_E), and filament temperatures (T_f^{theor},$T_f'^{theor}$) estimated with the least squares method in two distance ranges.

Power Lamp (W)	T_B (K) (± 0.1)	T_E (K) (± 0.1)	T_f^{theor} (K)	$T_f'^{theor}$ (K)
60	388.0	292.9	2940 ± 40	2950 ± 2
40	385.0	292.9	2970 ± 60	2980 ± 40
25	365.0	292.2	2500 ± 140	2530 ± 110

4.2. Attenuation of the radiant energy flux with the distance from the source

With spherical symmetry, the radiation flux decreases with the distance from the center as the inverse square. When the thermometer moves away from the source, it receives a lower flux, according to this law. If we consider the simplifying assumption that the stationary state depends on the amount of radiant energy received by the thermometric bulb, the increase of temperature experimentally measured with respect to the environmental temperature value will be proportional to the received radiant energy. Consequently, it is expected that temperature should also vary as the inverse square of the distance. To check this assumption, the experimental results shown in Table 2 have been fitted to the equation:

$$T = b + \frac{a}{R^2} \qquad (12)$$

The results obtained for parameters a and b and the correlation coefficients are shown in Table 4 for the different source powers. As can be seen, the correlation is high-minded enough to admit the correctness of the hypothesis. But the correlation coefficient cannot be unity due to, among other things, the scattering and absorption of radiation and the nonlinear dissipative contributions.

Table 4. Adjustable parameters *a* and *b*, and correlation coefficient *r* corresponding to equation (12).

Power Lamp (W)	*b* (K)	*a* (10^{-2} K m^{-2})	*r*
60	293.8 (± 0.4)	1.71(± 0.09)	0.995
40	293.6 (± 0.3)	1.38(± 0.06)	0.996
25	292.6 (± 0.2)	0.81(± 0.03)	0.996

5. Measurements and results. Comparison with the theoretical model

5.1. Determination of temperature fields

From the above data, equation (1) would permit to calculate T_f. However this way is not useful, since for each distance would get a temperature and the uncertainty in the determination of T_f is too high. Another method is proposed to reliably determine a single value of T_f. The method consists in applying equation (1) to a hypothetical balance filament temperatures set, taking as bulb temperature T_B the value experimentally measured. The hypothetical temperature set covers the (1000-3500) K interval in ten by ten degrees. Thus, 251 values of T_f are obtained to be replaced in the balance equation together with T_B. This process is applied for each value of the distance *R* to calculate six values of temperature *T* as solution of equation (1). The set of six temperatures for the six distances *R*, named temperature filed obtained with the different values of T_f can be compared to those obtained experimentally.

A reiterative application of the method for each value of T_f allows to predict 251 temperature fields. A least squares method will permit to determine the value corresponding to the temperature field that best approximates the experimental data:

$$\delta = \sum_{i=1}^{6} \left(T_{theor} - T_{\exp} \right)^2 \qquad (13)$$

where T_{theor} is the value obtained by applying the method at a given distance R and T_{exp} is the corresponding experimental data at the same distance. The value of T_{theor} which minimizes the parameter δ is the value which best approximates to the experimental value. The uncertainty in temperature can be determined from the statistical uncertainty associated with the least squares method. Within the uncertainty range, $\delta \pm \Delta\delta$, there are several values, each one corresponding to a different temperature T_f. The level of uncertainty in T_f can be estimated as the extreme values of T_f within this interval [11].

In figures 3-5, some fields of temperature in the environment of the experimental data for the lamps with 60, 45 and 25 W, respectively, are represented.

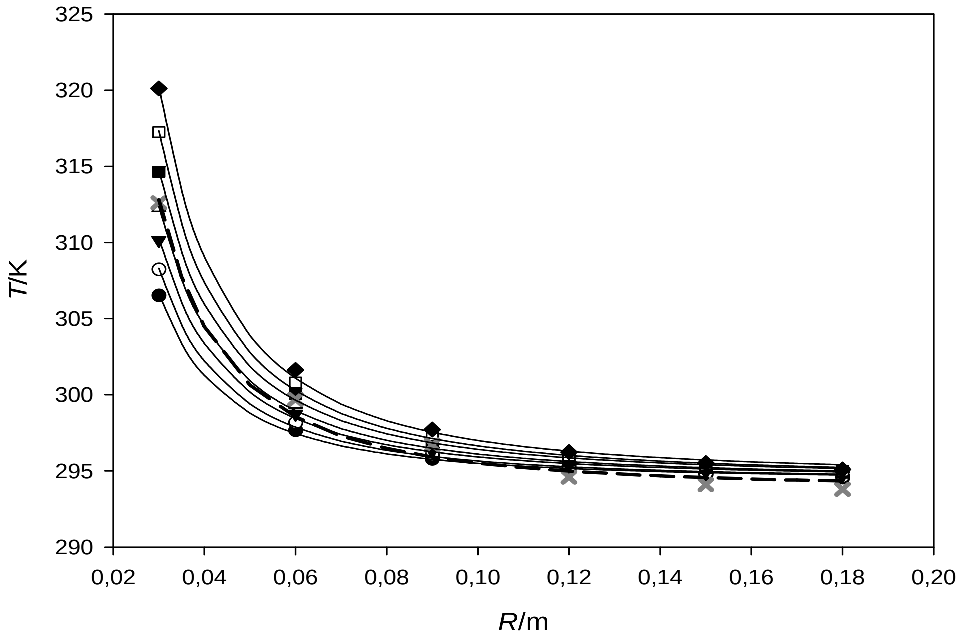

Figure 3. Temperature of the thermostatic bulb as a function of the distance to an incandescent lamp of 60 W power. (Points connected by continuous lines): temperature files estimated by equation (1) at different filament temperatures. (Points connected by a discontinuous line): Experimental measurements. Lines are visual guides estimated from the fits of the experimental points to equation (12).

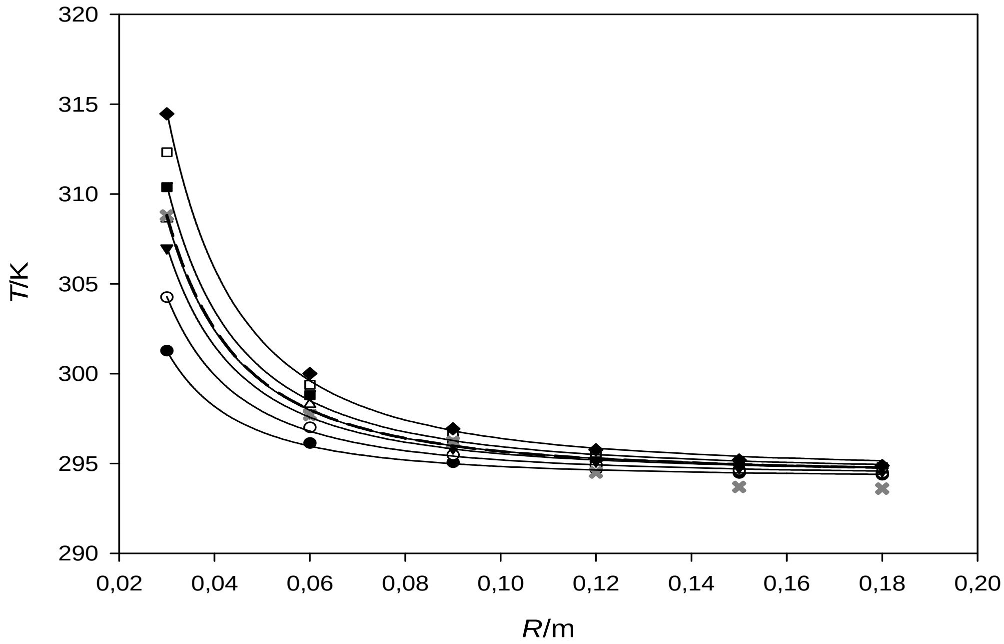

Figure 4. Temperature of the thermostatic bulb as a function of the distance to an incandescent lamp of 40 W power. (Points connected by continuous lines): temperature files estimated by equation (1) at different filament temperatures. (Points connected by a discontinuous line): Experimental measurements. Lines are visual guides estimated from the fits of the experimental points to equation (12).

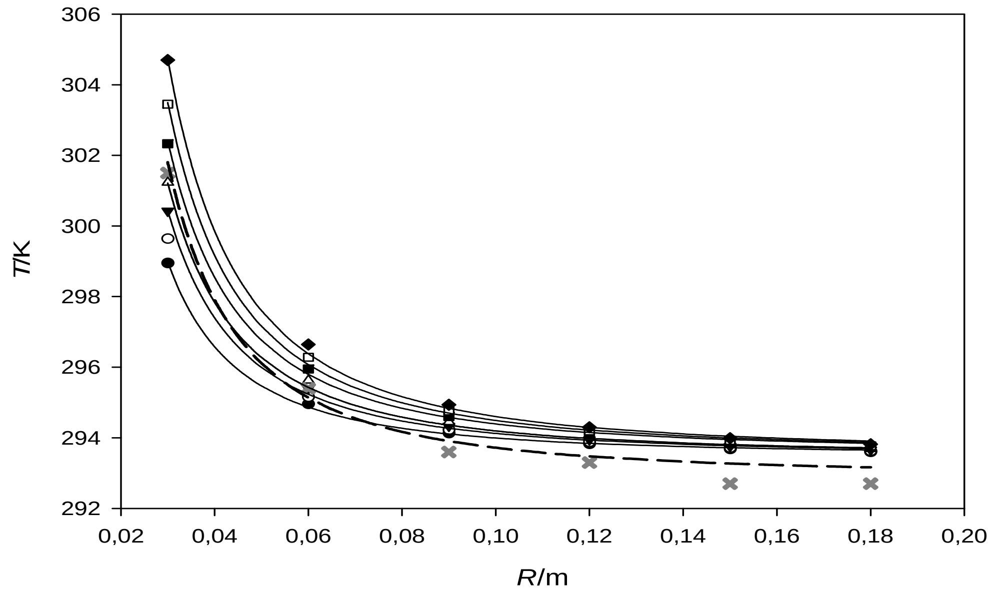

Figure 5. Temperature of the thermostatic bulb as a function of the distance to an incandescent lamp of 25 W power. (Points connected by continuous lines): temperature files estimated by equation (1) at different filament temperatures. (Points connected by a discontinuous line): Experimental measurements. Lines are visual guides estimated from the fits of the experimental points to equation (12).

The six points representing each temperature range are shown connected by lines as visual guides. These guide lines have been obtained from the fits of the corresponding calculated six points to equation (12). As can be expected, the value of temperature decreases with the distance to the source.

5.2. Comparison between temperature fields and experimental data in the vicinity of the minimum. Determination of the filament temperature

The six experimental points are also shown in figures 3-5 connected by a thicker discontinuous line (corresponding to the fit of the experimental values to equation (12)). As can be observed, there is a temperature field graph that better overlaps with the experimental graph, which corresponds to the field that minimizes equation (13). It is also observed that the temperature fields graphs and the experimental data slightly diverging towards different directions when the distance to the source increases. The difference is less than two degrees for the highest distance R = 18 cm. By applying equation (13), the best filament temperature, T_f^{theor}, and its uncertainty can be estimated. The results are also shown in Table 3 for the different lamps.

5.3. Optimal range of distances to the least-squares fit

It is intended that the experimental measurement is unsophisticated and feasible with few resources. Therefore, instead of "preparing" the environment for the experiment, it is preferable to demarcate a range of distances where the observed discrepancies are minimum. In this way, the fit is improved and a better value of T_f is obtained. An observation of figures 3-5 permits to see that the divergences between the temperature fields and the corresponding experimental values become higher at distances larger than

0.09 m. In the interval between 3 cm and 9 cm, it is seen that the experimental data and field data have a higher coincidence. Furthermore, in this interval, the measured temperatures exceed four or more degrees the ambient temperature, which allows to introduce more than three measurement points in that interval, without overlapping the temperature values corresponding to the stationary states.

To show the improvement of the adjustment in this range, the least squares and the corresponding values of the filament temperature have been determined again for the three lamps. The new values estimated for the filament temperature, T'^{theor}_f, are shown in Table 3. At a power given, both values are similar, but the uncertainty is lower in the second fit. The values obtained for the filament temperature are the typically obtained for this kind of lamps [3,4,11] with other methods.

Note, first, that the lamp with lower power has the filament temperature hundred degrees lower than the higher powers. It can make a comparative assessment of different energies radiating lamps using, according to equation (2), the ratio of the fourth powers of the temperatures of the filaments. Thus, $(2530/2950)^4 = 0.541$ indicates that the flux of energy from the lamp of 25 W is half that the lamp corresponding to 60 W. Second, if the Wien displacement law is used, $\lambda T = 0.002898$ mK, the displacement of the radiation spectrum to the longest wavelengths can be evaluated. For $T_f = 2930$ K, the maximum is at $\lambda = 989$ nm, while for $T_f = 2530$ K, the maximum shifts towards $\lambda = 1145$ nm. In addition, the area of the curve is reduced. For a given λ, Rayleigh scattering of radiation by the atmosphere is proportional to λ^{-4} [13]. For a comparative assessment of the amount of flux into the bulb of the thermometer, the following approximation could be used: considering that the areas corresponding to the short wavelengths are small in both cases, the integration interval can be extended to the whole frequency spectrum. In this case, according to the Planck's law, the ratio between the fluxes for two lamps of temperatures T_1 and T_2 will be given by $(T_1/T_2)^8$ [6]. In the case of the lamps of 25 and 60 W, the ratio is 0.29, which indicates that the flux into the thermometer from the lamp of 25 W is less than a third of that comes from the higher power lamp. Third, as was above discussed, higher power lamps keep differences over 4 K between the temperature field and the ambient temperature at distances R less than 9 cm. However for the lamp with 25 W, this difference can only be maintained at distances less than 6 cm. Figures 3-5 show that for all lamps the discrepancies between the temperature ranges and the experimental data appear at temperature differences between 3 and 4 K. For lamps of 60 and 40 W, it corresponds at distances greater than 9 cm, while for the lamp of 25 W, it corresponds at distance greater than 6 cm. It is expected that at higher power lamps, the discrepancies appear at higher distance.

This fact may be due to the flux of heat dissipated into the environmental air. At the distances at which a temperature difference of approximately 4 degrees is achieved, the dissipation mechanism would bifurcate from convective to conductive. For temperature differences less than approximately 4 K, the driving mechanism for the heat transfer to the environment would be the conduction, while at higher temperature differences, the mechanism would be the convection. From this bifurcation point, the balance equation should be modified by replacing the convection for conduction mechanism for the farther distances. However, as the purpose is to determine the filament temperature, to apply the proposed method, the appropriate space interval should be selected depending on the lamp power.

The reason of the bifurcation may be due to the actual conductive flux exceeds the hypothetic convective flux contained in the balance equation at temperatures above 3-4 degrees above the environmental temperature. A consequence of this is that the thermometric bulb becomes cooler than predicted by the balance equation and discrepancies are observed between theoretical and experimental temperatures.

The thickness *L'* of the air conductive layer evacuating the same heat convection in the boundary which produces the transition from one regime to another can be estimated in the limit, where the conduction is passed to convection for a temperature difference of 4 degrees, by equaling the convective flux, given by equation (8), and the conductive flux, which would be given by the expression:

$$J_{cd}' = 2A\frac{\kappa_A}{L'}\left(T - T_E\right) \tag{14}$$

For T-T_E ~ 4K, it is obtained that both fluxes are equal for L'~0.0034 m. With this data, the heat dissipated by the conductive mechanism can be estimated from equation (14) as a function of the temperature of the thermometer.

The conductive flux (straight line), estimated by equation (14), and the convective flux (broken line curve), estimated by equation (8), are shown as a function of the thermometer temperature in figure 6 for an environmental temperature of 292.9 K and temperature differences, with respect to environmental temperature, between 0 and 7 K. It can be seen that below four degrees, the actual driving evacuates more heat than the convective term.

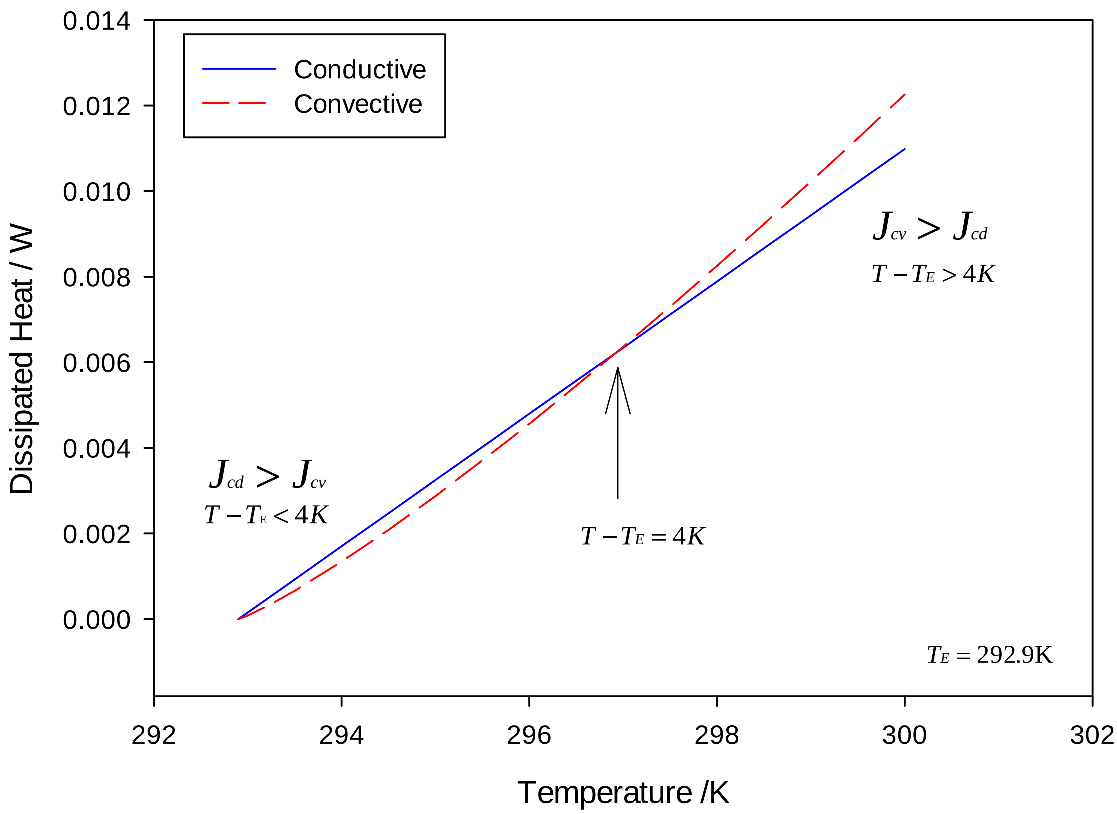

Figure 6. Conductive flux (straight line), estimated by equation (14), and convective flux (line broken curve), estimated by equation (6), as a function of the thermometer temperature.

6. Conclusions

The temperature of a small radiant body with approximately spherical geometry can be determined with standard laboratory instrumentation and simple measurements. The proposed method can be applied to any body with a simple geometry, the latter condition being only necessary to simplify the stationary energy balance equation. The used instrumentation is reduced to an elemental optical bench and a thermocouple thermometer with tenths of a degree accuracy.

The most appropriate measurement zone is in a range of object distances from 3 and 9 cm for typical temperatures of the incandescent filaments (2500 to 3000 K). In that zone, five or six temperature measurements can be performed, since the difference between the thermometer and ambient temperatures is equal to or greater than 4 K and the heat is dissipated by the convection mechanism. This allows to fit the experimental data to the approximate curve generated from the balance equation corresponding to the radiant temperature by using any calculation program.

Together with its experimental simplicity, the mayor advantage of the new proposed method is the ability to adjust by the method of least squares the experimental data to the more approximate temperature field, allowing to predict the object temperature and its uncertainty interval.

Another achievement is the indirect verification, via the stationary balance at different distances of the radiant object, of the radiant flux variation with the inverse square of the distance to the object.

Finally, in the case of incandescent lamps, the proposed method represents a novel method for determining the filament temperature. From a teaching point of view, the method could be very helpful to understand the different heat transfer mechanisms.

Appendix. Convective flux

The convective flux, J_{cv}, can be calculated for the case of a vertical plate, of length the edge of the cap, *l*, by using empirical correlations [7,8]. In this case, the convective flux can be expressed as:

$$J_{cv} = 2A\frac{\kappa_A}{l}N_U \tag{15}$$

where κ_A is the conductivity of the air and N_U is the Nusselt number that, for natural convection over a vertical flat plate at a constant temperature, can be expressed by the empirical correlation [7,14]:

$$N_U = 0.68 + \frac{0.67 Ra^{1/4}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{9/16}\right]^{4/9}} \tag{16}$$

Ra and *Pr* are, respectively, the Rayleigh and Prandlt numbers given by:

$$Ra \equiv \frac{g l^3 \left(T - T_E\right)}{\frac{\left(T + T_E\right)}{2} \chi \nu} \tag{17}$$

$$Pr \equiv \frac{\chi}{\nu} \tag{18}$$

where g is the acceleration of Gravity, l is the length of the cap, and χ and ν are, respectively, thermal diffusivity and kinematic viscosity of the air.

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