Stefan–Boltzmann law for the tungsten filament of a light bulb: Revisiting the experiment

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A classical laboratory experiment to verify the Stefan-Boltzmann radiation law with the tungsten filaments of commercial incandescent lamps has been fully revisited, collecting a fairly large amount of data with a computer-controlled four-channel power supply. In many cases, the total power dissipated by the lamp is well described by a sum of two power-law terms, with one exponent very close to 4, as predicted by the radiation law, and the other very close to 1, as for simple heat conduction. This result was true even for filament surfaces with a shiny metallic appearance, whose emissivity should vary with temperature. © *2013 American Association of Physics Teachers.*
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I. INTRODUCTION

Laboratory experiments to demonstrate the Stefan–Boltzmann radiation law using the tungsten filament of a traditional incandescent lamp have been described several times, both in regular journals[1–5] and in internal reports available on the web.[6–9]

In principle, the experiment is quite simple: the $I(V)$ relationship of the lamp is measured from zero to the full working voltage. From these data, the power $P = IV$ supplied to the filament is computed. When the steady state is reached, this power is dissipated into the environment by radiation and conduction/convection. The filament temperature is obtained by computing $R = V/I$ and using the accurate data tables of resistivity vs. temperature available in literature.[10,11]

In such an experiment, one should find the relationship,[1]

$$P = \epsilon S\sigma(T^4 - T_0^4) + k(T - T_0), \qquad (1)$$

where T_0 is the ambient temperature, ϵ and S are the filament emissivity and surface area, σ is the Stefan–Boltzmann constant, and k is the thermal resistance of the lamp from filament to environment.

In the ideal "blackbody" case, $\epsilon = 1$. The surface of a metal, however, typically behaves as a "graybody," with $\epsilon < 1$ and a dependence of ϵ both on wavelength and temperature. Tungsten is no exception, as shown by a large amount of data available in the literature.

The properties of tungsten have been widely studied since the beginning of the last century,[12,13] because of its importance in the illumination and radio valve industries. More recent studies[14,15] have been motivated by tungsten's possible use as a secondary standard source of radiation in the so called "striplamp."

A comparison between Eq. (1) and the measured $P(T)$ relationship yields an estimate of how much a tungsten filament behaves as a blackbody or graybody.

In Refs. 1 and 3, reasonable agreement has been reported after accounting for a dependence of emissivity ϵ on the surface temperature T. But the opposite conclusion was reached in Ref. 5, where it is suggested that filament emissivity is nearly independent of temperature. This different behavior might be ascribed to the surface conditions: in Ref. 1, it is reported that an oxidized filament surface should have

a small dependence of emissivity on temperature, while a clean bright metal surface should show a significant deviation from Eq. (1). In Ref. 2, experimental results pointed to an emissivity independent of temperature, but a check on the filament after breaking open the bulb showed the presence of a clean, unoxidized surface that should instead have given a significant $\epsilon(T)$ dependence. This paper closes by stating that "the problem remains unsolved."

Over the last several years, we have used this experiment in a physics laboratory class on data acquisition systems as an example of a computer-controlled experiment with data analysis and comparison to a well-known physical law. Agreement between our experimental results and Eq. (1) has always turned out to be very good—good enough to give rise to suspicion of an artifact.

Hence, in this work, the experiment has been fully revisited using the computer-controlled approach that allows, with relatively little effort, the collection of a larger amount of data than possible with a manual instrument, with better regularity and uniformity.

From a didactical point of view, the use of the computer in no way makes the experiment easier to perform. Instead, without a thorough understanding of what is going on in the computer-instrumentation setup, it is quite easy to fall into one of the common pitfalls that the use of computer control presents. This is an important didactical point, given the almost universal use of computer-controlled instrumentation in the scientific laboratory. In fact, it is important to avoid any tendency to blindly trust an experimental result on the basis that the computer, an accurate machine, performed the experiment and produced the result.

A human experimenter will usually notice when a parameter of interest is drifting and can attempt to take data when a steady-state condition is reached. The computer is not so smart and, unless specifically programmed to avoid it, can perform measurements at a rate that is far too fast to allow a sufficient decay of a transient state. This is certainly the case during the process of warming and cooling of the light bulb filament.[4] Moreover, measurements on light bulbs are deceiving: while apparently simple to the level of seeming banal, an accurate analysis of the acquired data shows indeed that it is almost impossible to perform a real stationary measurement, and therefore a smarter experimental approach is required.

II. THE EXPERIMENT

A. Hardware and software

All measurements were performed with a four-channel programmable power supply (Agilent 6627A) using the self-contained voltage and current measurement and readback capability. The power supply was connected to a personal computer running a Linux operating system through a GPIB interface and bus. The control program was written from scratch in C, making use of the Linux-GPIB library;[16] it contained about 650 lines of code and was designed to execute a number of nested loops with the commands for the instruments on the GPIB bus. Multiple instances of the program can be run asynchronously to control simultaneously the four independent channels of the power supply and perform four concurrent measurements. (A similar arrangement is used in the laboratory class to allow several groups of students to perform their experiments independently of each other, sharing the GPIB controller and the instruments on the bus, with due use of locks and semaphores.)

Voltage and current measurement resolution was specified by the manufacturer as either 6 mV, 2 mA or 15 mV, 0.8 mA, depending on the channel range; the specified accuracy was 0.05% for voltage and 0.1% for current, plus an offset of maximum 20 mV, 10 mA or 50 mV, 4 mA, depending on the range.

Laboratory temperature was continuously recorded during all measurements with a platinum thermometer (Pt100) connected to a Keithley DMM199 or HP3478A multimeter. The thermometer accuracy was better than ±0.2 K, but because of temperature gradients in the laboratory an accuracy of ±0.5 K is more realistic.

Data processing and plots were made using the GNUPLOT[17] graphing utility, with the help of some short shell scripts.

A total of eight lamp models were tested, chosen from available spare parts. Their characteristics are listed in Table I. Lamps were always connected to the power supply using a four-wire configuration, with power and sense wires directly soldered to the lamp base to avoid the ohmic drop of socket contacts.

The budget for the experiment was modest. The most expensive piece of equipment was the GPIB interface [National Instruments PCI-GPIB, about 500€ ($650), but cheaper solutions are possible]; the power supply and the multimeter were purchased reconditioned for 450€ ($585) and 300€ ($390), respectively. Requirements for the computer are minimal (a machine assembled with junk parts has been used) and software was entirely open source, requiring no (monetary) cost.

Table I. Lamp type, manufacturer, number of samples, nominal power and voltage, and bulb diameter of the tested lamps.

n_l	Manufacturer	Samples	Power (W)	Voltage (V)	Diameter (cm)
1	Unknown	1	50	12	3.5
2	Unknown	1	30	6	3.5
3	Philips	3	25	24	6.0
4	Osram	1	25	12	4.5
5	Leuci	2	15	12	4.5
6	Osram	2	10	12	1.6
7	Tecnid	2	5	14	1.8
8	Leuci	1	3	12	1.7

B. Measurement procedure

All measurements are performed by scanning the potential from 0 to the nominal working voltage and back to 0, with a step size of 0.1, 0.2, or 0.4 V, respectively, for the 6, 12, and 24 V rated lamps. The current was typically recorded for a time of 20 s, with a cadence of 0.5 s. The long stay on each potential value was intended to record the time evolution of the current after each step. In some cases, the voltage was taken slightly beyond the nominal rated value, to extend the explored filament temperature range.

The reason for the double voltage scan, up and back down, comes from the presence in the current transient of two very different time constants, one of the order of a few seconds, the other of many tens of seconds. This makes it practically impossible to perform truly stationary measurements, at least at low filament temperatures, as shown below.

The temperature of the filament is determined through a procedure similar to that in Ref. 3. For each lamp, the resistance R_a of the filament at a given ambient temperature is measured. From the data tabulated in Refs. 10 and 11, the tungsten resistivity ρ_a is determined at the same temperature, and the geometric factor $g = \rho_a/R_a$ is computed. From the $I(V)$ data obtained with the voltage scan, the filament resistivity $\rho(T) = gV/I$ is computed for each measured point, and using the tabulated data again, the temperature is calculated.

Incidentally, the data in Ref. 10 by Jones and Ref. 11 by Jones and Langmuir are almost identical, with only small differences of a few units in the last digit; only the values at 1200 K differ significantly. However, a revision of all data tabulated in Table I of Ref. 10 appears to reveal a misprint in this table. Therefore, the data version in Ref. 11 has been used in this work. The variation of the g factor with temperature has been ignored, as it was ignored in the determination of the reference data.

The determination of the cold filament resistance R_a could not be made with a simple resistance measurement because even a small applied voltage causes a large change in the filament temperature. As an example, a 24 V bulb powered at 0.8 V already reaches a filament temperature of around 500 K.

The cold filament resistance was therefore determined by measuring the $I(V)$ relationship at small voltages, using the same scan procedure described above with a smaller voltage step (20 or 40 mV). The $I(V)$ data so obtained were fitted with a second-degree polynomial and R_a was calculated from the slope dV/dI of the curve, extrapolated to $V = 0$. This procedure has the added benefit that the constant voltage and current offset errors in the power supply measurements mostly disappear with the derivative, greatly increasing the measurement accuracy at low voltage levels.

The voltage range used in the fit was selected for each lamp, to the limit of validity of the second-degree polynomial expansion, by repeating the fit with a progressively decreasing upper limit. Initially, with a wide voltage range the fit terminates with a large χ^2 value, which progressively decreases as the voltage range shrinks until it becomes stationary. The limit is selected as the last value that has given a χ^2 decrease.

All fits were calculated using the Marquardt-Levenberg algorithm, available with the GNUPLOT program.

C. The steady state

A critical aspect of the experiment is to obtain data that are free from the drift caused by the warming and cooling of the lamp.
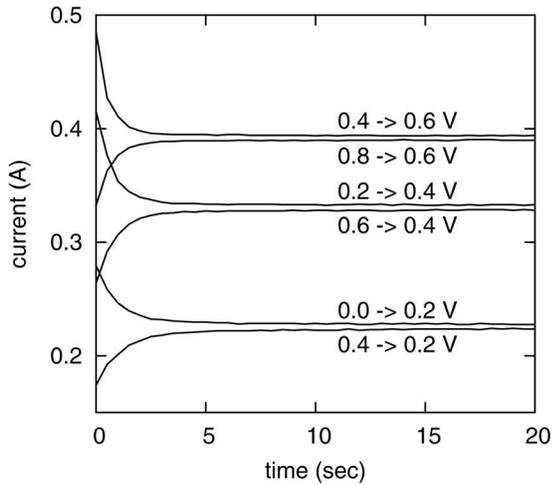
Fig. 1. Plot of the current after the first three up-going and last three down-going voltage steps for a 12 V, 15 W lamp.

As an example, in Fig. 1 the current is plotted after the first three upward and last three downward voltage steps for a 12 V, 15 W lamp ($n_l = 5$ in Table I). Other lamps show similar behavior. After an up-going voltage step the current shows a large overshoot, then decreases towards the final steady-state value while the filament warms up and increases its resistance. Conversely, during the down-going scan the current jumps to a lower value, then rises to the steady-state value while the filament cools down and the resistance decreases. The time constant of this process is on the order of a couple of seconds, as can be seen in the plot, with the warm-up faster than the cool-down. After this relatively fast decay phase, it is clearly visible in the plot that there is a second phase of decay towards the steady-state with a much longer time constant, on the order of several tens of seconds. This second process is probably due to the warming and cooling of the glass bulb.

In any case, it is not practical to wait after each voltage step for a time long enough to allow a complete decay of the transient state; the total measurement time would become prohibitively long. Hence, measurements have been performed adopting the dual scan procedure, up and back down, discarding the data affected by the first fast and asymmetrical decay and averaging the remaining data. There is no strong reason not to assume that this second decay phase is sufficiently symmetrical that the averaging process should effectively compensate for its effect.

As the voltage increases, this problem becomes less and less important, but it cannot be neglected if filament temperatures near and below 1000 K are to be included in the analysis.

III. RESULTS

A. Calibrations

The g factors obtained for all lamps are summarized in Table II. Each factor was measured several times during the experiment and averages are reported in the table together with their standard deviations.

The reported errors refer only to measurements' reproducibility and do not contain systematic effects of the instrumentation. The same instrument was used both for calibration and measurements, and therefore systematic scale-factor errors cancel out. The most important remaining errors in the determination of temperature are the uncertainty

Table II. Geometric g factors and errors for all lamps used in the experiment. n_l: lamp number; W: nominal power (watts); V: voltage (volts); n_r: number of measurements.

n_l	W	V	n_r	$g(\times 10^{-6}$ cm$)$	$\pm$
1	50	12	3	28.42	0.06
2	30	6	9	58.20	0.09
3.1	25	24	12	3.597	0.002
3.2	25	24	5	3.539	0.002
3.3	25	24	16	3.586	0.003
4	25	12	1	14.41	
5.1	15	12	12	8.033	0.005
5.2	15	12	7	8.131	0.008
6.1	10	12	10	4.541	0.012
6.2	10	12	6	4.774	0.003
7	5	14	1	1.635	
8	3	12	2	1.563	0.05

in the ambient temperature (± 0.5 K) and instrument nonlinearities, to be evaluated to less than $\pm 0.1\%$.

B. Measurements and fits

A total of 78 measurements were performed on 12 different lamps. Figure 2 shows four examples of power vs. temperature curves, obtained with four different lamps. All measured curves have been fitted with the function,

$$P = A(T^a - T_0^a) + B(T - T_0)^b, \tag{2}$$

and results from the fits are summarized in Table III.

Equation (2) contains both the Stefan–Boltzmann radiation law with a possible dependence of emissivity on temperature, and a heat loss term with a temperature dependence that can account for simple conduction (linear in temperature, $b = 1$) or convection ($b > 1$). The search for the a and b exponents during the fit was left completely free and open to any results.

In most cases, measurements were repeated several times on the same lamp, repeating the fit for each of the measured curves and averaging results for a, b, A, and B. For each parameter, two errors are shown: the asymptotic standard error as reported by the GNUPLOT fit procedure (ϵ_1) and the average standard deviation (ϵ_2) when more results were averaged for the same lamp.
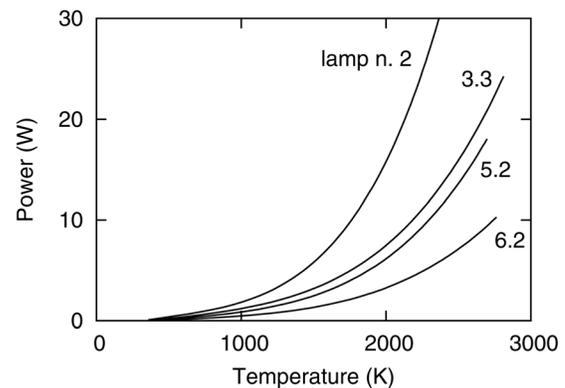

Fig. 2. Power as a function of temperature obtained with four different lamps.

Table III. Results from least squares fit. n_l: lamp number (type and sample); n_m: number of measurements for each lamp and group of measurements; nominal V, W: lamp nominal voltage (V) and power (W); maximum V, W, K: the values of voltage (V), power (W), and filament temperature (K) at scan end; $\sqrt{\chi^2}$: rms value of the residuals after the fit; a, b, A, B: coefficients of Eq. (2); ϵ_1: the asymptotic standard errors obtained by the fit; ϵ_2: average standard deviation when results are averages of several measurements. Data in columns $\sqrt{\chi^2}$, a, b, A, B, and all ϵ_1 columns are averages of the values obtained by measurement repetition.

n_l	n_m	Nominal		Maximum			$\sqrt{\chi^2}$	Exponents						Coefficients					
		V	W	V	W	K	mW	a	ϵ_1	ϵ_2	b	ϵ_1	ϵ_2	A	ϵ_1	ϵ_2	B	ϵ_1	ϵ_2
1	3	12	50	12.0	47.7	2832	35	4.26	0.02	0.02	1.09	0.05	0.05	0.90	0.12	0.14	0.70	0.23	0.17
2	9	6	30	6.0	30.2	2370	17	4.25	0.01	0.03	1.01	0.02	0.03	1.30	0.13	0.41	1.53	0.19	0.29
3.1a	1	24	25	24.0	24.3	2815	17	3.99	0.01		1.00	0.02		3.6	0.4		1.2	0.2	
3.2a	1	24	25	24.0	24.4	2768	27	3.84	0.02		0.97	0.04		13.1	2.4		1.3	0.4	
3.3a	1	24	25	24.0	24.5	2789	24	3.92	0.02		0.96	0.04		6.8	1.1		1.5	0.3	
3.1b	10	24	25	24.0	24.3	2819	12	4.06	0.01	0.01	1.07	0.02	0.01	2.1	0.2	0.2	0.79	0.09	0.06
3.2b	4	24	25	24.0	24.2	2788	13	4.04	0.01	0.03	1.05	0.02	0.03	2.6	0.3	0.7	0.91	0.11	0.2
3.3b	15	24	25	24.0	24.3	2810	12	4.06	0.01	0.01	1.08	0.02	0.01	2.1	0.2	0.2	0.72	0.07	0.04
4	3	12	25	12.0	25.7	2693	10	4.11	0.01	0.02	1.11	0.01	0.02	1.75	0.14	0.31	0.66	0.06	0.09
5.1	10	12	15	13.4	17.7	2710	13	4.08	0.02	0.004	1.07	0.03	0.004	1.5	0.2	0.04	0.53	0.09	0.01
5.2	7	12	15	13.4	18.1	2698	10	4.08	0.01	0.002	1.06	0.02	0.002	1.56	0.14	0.02	0.57	0.07	0.007
6.1	6	12	10	13.4	10.1	2696	11	4.10	0.02	0.007	1.09	0.04	0.009	0.78	0.15	0.05	0.25	0.07	0.01
6.2	5	12	10	13.4	10.3	2762	5	4.07	0.01	0.002	1.10	0.02	0.003	0.86	0.08	0.01	0.24	0.03	0.004
7	2	14	5	14.0	4.6	2381	18	4.21	0.01					0.27	0.02				
8	1	12	3	12.0	3.2	2387	4	4.434	0.004					0.034	0.001				

Looking at the data in Table III, it appears that the results can be divided into three groups: lamps 1 and 2, with an a exponent significantly greater than 4; lamps 3, 4, 5, and 6, with an a exponent very close to the ideal value 4; and very-low-power lamps 7 and 8, which show an exponent significantly greater than 4 but need to be discussed separately. The b exponent always turns out to be very close to 1.

C. Errors

The rms value of the fit residuals ($\sqrt{\chi^2}$) is always near 0.1% of full power for all lamps. Figure 3 shows the residual distribution as a function of temperature for the four example curves of Fig. 2.

In determining the power, as during calibration, the systematic errors in the power supply scale do not matter because they are absorbed into the A and B coefficients during the fit. Only resolution and deviations from linearity contribute to measurement errors and these, evaluated to be no more than 0.1%, are compatible with the fit residuals. The contribution to the final errors from the g calibration factors is negligible. The most important term in this contribution is the error in ambient temperature. The effect on the final results has been computed numerically, repeating all calculations after having added to the ambient temperature an offset error of ± 10 K, obtaining the following propagation factors for the numerical values (with P in W and T in K):

$$\frac{da}{dT} = 1.1 \times 10^{-3}\,\mathrm{K}^{-1}, \qquad \frac{db}{dT} = 1.8 \times 10^{-3}\,\mathrm{K}^{-1},$$
$$\frac{dA}{dT} = 4.9 \times 10^{-2}\,\mathrm{K}^{-1}, \qquad \frac{dB}{dT} = 1.2 \times 10^{-2}\,\mathrm{K}^{-1}. \tag{3}$$

With the estimated error in the ambient temperature of 0.5 K, their contribution is one order of magnitude smaller than the power measurement errors. This should be no surprise, because the dependence of the filament resistance on temperature deviates little from linearity, effectively resulting in a scale factor for temperature with an error that again is mostly absorbed in the A and B constants.

A comparison of the ϵ_1 and ϵ_2 values reveals that errors as evaluated by the fit procedure or by measurement repetition are fairly consistent for lamp models 1 to 4. Only for models 5 and 6 the reproducibility resulted somewhat better than overall accuracy.
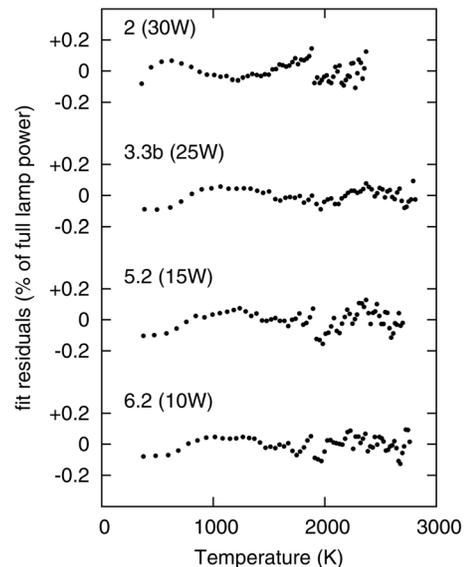

Fig. 3. Residuals after the fit on the four curves shown as examples in Fig. 2.

IV. DISCUSSION

The data in Table III show that in most cases the radiation from the tungsten filament of a light bulb closely follows the Stefan–Boltzmann T^4 law, with an additional linear heat loss consistent with Fourier thermal conduction.

Measurements 3.1a, 3.2a, and 3.3a show odd behavior, with an exponent $a < 4$. All three of these lamps were brand new and produced a slightly different $I(V)$ curve on the very first voltage scan (3.1a, 3.2a, 3.3a), and thereafter they all followed curves (3.1b, 3.2b, 3.3b) that were accurately coincident, as shown by the ϵ_2 values in the table. This suggests that some kind of metal annealing or surface rearrangement with first filament heating must take place, as has already been argued in Ref. 2, where clear surface differences were reported in a dual filament bulb between the used and unused filament. Apart from this observation, though, this effect is of no further relevance for this work.

Four of the eight lamp models, namely 3–6, strictly followed the Stefan–Boltzmann law with an exponent only slightly greater than 4. This is a rather surprising result because at a first glance all filaments appear to be bright metal, so that a significant dependence of emissivity on temperature should be expected.

A possible (partial) explanation of this finding is suggested by a comparison of the shapes of the filaments of these lamp models. Lamps 1 and 2 have a similar filament type shown in Fig. 4 (top). It is a flat, large, and thin rectangular coil with a wide spacing between the loops. Lamp models 3, 4, 5, and 6, instead, have the more common filament shape of a long, slim, tightly wound spiral, as shown in Fig. 4 (bottom). As already shown by Langmuir,[18] a coiled filament behaves differently from an open surface; it partially traps radiation, effectively increasing the "blackness" of the emitting surface as in a very primitive black body cavity. Filaments of the second type are much more tightly coiled, and hence should be more effective in this respect.
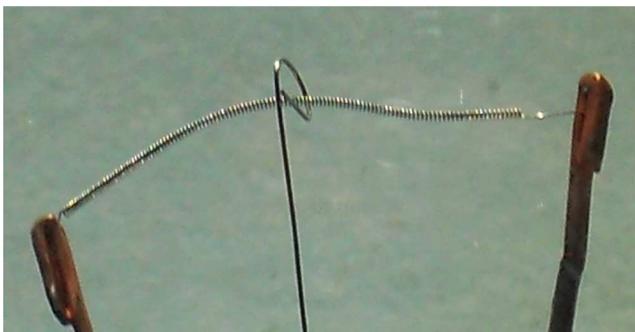

Fig. 4. Photographs of the filaments of lamp types 2 (top) and 3 (bottom).
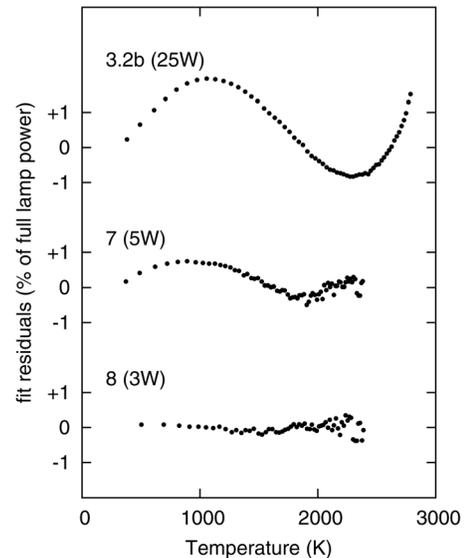

Fig. 5. Residuals after the fit with the reduced equation $P = A(T^a - T_0^a)$ for low-power lamp types 7 and 8 and, for comparison, with the 2 W type 3.

A data fit for lamps 7 and 8 could not be made with the same procedure used for the other lamps. These two very-low-power bulbs show a $P(T)$ curve already well described by the first term of Eq. (2), as can be seen in Fig. 5, which shows the residuals of the fit with only the first power term for bulbs 7 and 8 and, for comparison, for bulb 3.2. The 3 W bulb is completely described by the Stefan–Boltzmann term alone with an exponent $a = 4.43$. The 5 W bulb shows a small deviation at low temperatures, but if a fit is attempted with the full Eq. (2), a negative, unphysical B coefficient results for the conduction/convection term. The fit of the lamp 3.2 data shows that in this case the single term equation is unsuitable.

Bulbs 7 and 8 are similar to bulb 6 in shape and dimensions, and the power difference is not very large; there is a bigger difference, both in ratio and absolute value, between lamps of types 6 and 3. The different behavior of lamp types 7 and 8 is probably due to the fact that these two bulbs are evacuated, as is usual for low-power bulbs, instead of being filled with an inert gas, so that convection losses are negligible.[19]

The filaments of these two small bulbs are of the same type as that of bulb 3 (Fig. 4, bottom), so that an a exponent closer to 4 was expected, as with bulbs 3 to 6. Currently, I have no explanation for the difference in behavior. There are, however, two points to consider. First, the data on tungsten emissivity are mostly for the metal in vacuum; a small effect of the filling gas might be significant. And second, the filament coiling alone can hardly explain the a exponent of lamps 3–6. It is very likely some other effect contributes either the filling gas or some kind of surface blackening that is not apparent under simple naked-eye inspection.

V. CONCLUSIONS

Accurate measurements show that in many cases the tungsten filaments of common light bulbs emit radiation as a function of temperature according to a power-law with exponent very close to 4, as described by the Stefan–Boltzmann law, regardless of the temperature dependence of surface emissivity. This result can partially be explained by the shape of the filament, which when tightly coiled partially traps radiation as in a black body cavity, resulting in an enhanced effective emissivity.

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Slated Globe

The slated globe was developed in the mid-19th century to teach geography and astronomy. For example, the Tropics of Cancer and Capricorn can easily be drawn on the surface of the globe. Some examples have lines of latitude and longitude on the surface. A rough black paint, often called blackboard paint, is applied to the surface of the globe to allow the application of chalk. This globe is at Cornell University. (Notes and photograph by Thomas B. Greenslade, Jr., Kenyon College)