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TEMPERATURE AND BLACKENING EFFECTS IN HELICAL TUNGSTEN FILAMENTS

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BY

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TEMPERATURE AND BLACKENING EFFECTS IN HELICAL TUNGSTEN FILAMENTS.[1]

BY B. E. SHACKELFORD.

IT has frequently been noticed by those working with helical tungsten filaments that the inside of the helix is very much brighter than the outside. A photograph of the projected image of such a filament, that of a commercial Type C Mazda lamp, is shown in Plate I., Fig. 1. It will be noticed that the inside sections, sloping downward toward the right, are much brighter than the outside sections, sloping downward toward the left. The edge of the outside also displays a greatly increased brightness and the very center of the inside of the turns is noticeably darker than the rest of the inside. Some few bright streaks appear on the surface but these are due to scratches and will not be considered in the discussion.

Pyrometer measurements on the outside and on the brightest portions of the inside of the same turns of such filaments show the brightness[2] of the latter to be, in some cases, more than twice that of the former.

The object of the present investigation is to determine the causes of the observed differences. Two possible explanations have been suggested; the interior may be at a temperature sufficiently higher than the exterior, or the increased brightness may be due to the radiation added by reflections within the helix. The two are not mutually exclusive. The only previously published work on the subject is that of Coblentz.[3]

Coblentz, using a " microscope " pyrometer, found the appearance of the edges changing so markedly with focus that he doubted whether the inside were really much brighter. He found " that some parts of the inner surface of the turn had a higher apparent temperature than the outside surface of a turn of the spiral." From these observations and from others made with a spectrobolometer he concluded that " the light coming from within the helix was not appreciably modified or blackened."

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[1] Preliminary notice published in Journal Franklin Institute, 180, p. 619, 1915. Some sections have since been checked by Langmuir, PHYS. REV., 7, p. 302, 1916.

[2] Luminous intensity/area.

[3] Elec. World, 64, p. 1048, 1914.

Physical Review, Vol. VIII., Second Series.
November, 1916.

Photographs showing brightness distribution.

Fig. 1. Commercial filament.

Fig. 2. Special polished filament.

B. E. SHACKELFORD.

Matching the pyrometer filament first against the outside and then against the inside of the helix he found that the same increase of potential difference across the pyrometer lamp was necessary for a match through both red and blue filters. From this he concluded that the increase in brightness was the same as that due solely to increased temperature. The outside matches for red and blue corresponded, however, to different potential differences across the pyrometer lamp, and equal increments of these at different original temperatures do not correspond to equal temperature increments. This is a well-known fact and easily observable experimentally.

Coblentz adds, however, that the phenomenon " is to be considered due in part to black body radiation from the interior," and so arrives at no very definite conclusion as to the relative magnitude of the effects of the two causes of brightness difference. It was thought advisable, therefore, to investigate the question more thoroughly.

Temperature-Brightness Relations.

If we differentiate the Wien equation,

$$J_\lambda = c_1 \lambda^{-5} e^{-\frac{C_2}{\lambda T}}, \tag{1}$$

we obtain,

$$\frac{dJ_\lambda}{J_\lambda} = \frac{c_2 dT}{\lambda T^2}. \tag{2}$$

Substituting in equation (2) the values $\lambda = 0.66\mu$, $C_2 = 14{,}500$, we find that at a red black body temperature of 2250° K.[1] a 1 per cent. change in brightness is equivalent to 1°.8 change in temperature. As stated above, brightness differences of over 100 per cent. are found on going from the outside to the inside of the coil. Assuming that the whole of this increase is due to temperature, this difference must be of the order of 200°.

Angell[2] gives the following formula for the difference in temperature between the inner and outer surfaces of a hollow cylinder (the limiting case of a helix) heated by the passage of an electric current,

$$T_2 - T_1 = -\frac{EI}{2k}\left[\frac{r_2^2 - r_1^2}{2} - r_1^2 ln \frac{r_2}{r_1}\right] \tag{3}$$

where E = potential difference per unit length,
I = current density,
k = thermal conductivity,
r_2 = external diameter,
r_1 = internal diameter.

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[1] This temperature notation is used throughout the present paper.

[2] Phys. Rev., 33, p. 421, 1911.

At a temperature of 2250° K., using Worthing's[1] values, $k = 1.35$ watts/cm. deg., and

$$\frac{EI}{2r_2}(r_2^2 - r_1^2) = 62 \text{ watts/cm.,}$$

we find for one of the lamps used ($r_2 = 0.165$ cm., $r_1 = 0.135$ cm.) a temperature difference of 0°.7. This would give the inside an added brightness of less than 0.5 per cent., an amount infinitesimal in comparison with the observed effects. These theoretical considerations seem opposed to the explanation that the difference in brightness is due to difference in temperature.

BRIGHTNESS MEASUREMENTS.

A Holborn-Kurlbaum optical pyrometer employed in this part of the experiment was set up in the manner indicated in Fig. 3, the precautions mentioned by Worthing and Forsythe[2] being observed. A Zeiss-Tessar lens used for the objective projected the image of the spirals on the 0.05 mm. filament of the vacuum-type tungsten pyrometer lamp. Red and blue filters of effective wave-lengths approximately 0.656μ and 0.493μ were mounted on the eyepiece of the observing telescope, and when necessary the intensity of the background image was reduced by means of sectored discs or neutral tint screens. The currents through the background were maintained at constant values by means of a simple potentiometer arrangement and the currents through the pyrometer lamp were measured with a millivoltmeter across a constant low resistance.

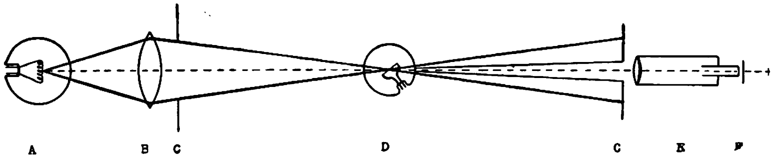

Fig. 3.

Diagram of apparatus. *a*, background lamp; *b*, objective lens; *cc*, diaphragms; *d*, pyrometer lamp; *e*, eyepiece; *f*, monochromatic filter.

Five gas-filled helical filament tungsten lamps were used, all made from the same wire and wound on the same mandril, the filaments differing from each other only in pitch, which ranged from 1.35 to 2.96 times the diameter of the wire.

At two different temperatures brightness measurements were made on the outside and on the inside of the coils with both red and blue

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[1] PHYS. REV., 4, p. 535, 1914.

[2] PHYS. REV., Vol. IV., p. 163, 1914.

filters. The brightest large portions of the inside were utilized, the edges being excluded because of the difficulties attendant upon focusing, and because of the deviations from the cosine law.[1] No difficulties were experienced in this except with the most closely wound filament, and even in this case good readings were possible when a little extra care was exercised in the adjustment.

Table I. gives the average results of many such measurements. In each case the outside-inside brightness ratio is greater for the blue than for the red, *i. e.*, the radiation from the interior of the helix is relatively stronger in the red. If tungsten radiated as a grey body, *i. e.*, if the ordinates of the energy distribution curve bore a constant fractional ratio to those of the energy distribution curve for a black body at the same temperature, this result would mean that the inside is actually cooler, for the curve is shifted toward the long wave-lengths. As this is obviously contrary to fact, tungsten must radiate more strongly, proportionally, in the blue than in the red, as has been observed previously, and the radiation from the inside must be blackened by repeated reflections. Due to a higher temperature inside of the spiral the distribution should show a shift toward the short wave-lengths and as the opposite is found to be the case, at least the greater part of the increased brightness must be due to reflections rather than to a temperature difference.

Table I.

Variation of Brightness Ratio with Pitch.

Pitch.	Outside-Inside Brightness Ratios.					
	2300° K.			1900° K.		
	R_1 $\lambda = 0.656\ \mu$.	R_2 $\lambda = 0.493\ \mu$.	$\frac{R_2}{R_1}$	R_1 $\lambda = 0.656\ \mu$.	R_2 $\lambda = 0.493\ \mu$.	$\frac{R_2}{R_1}$
2.96	.615	.681	1.11	.656	.682	1.04
2.28	.555	.598	1.08	.581	.604	1.04
1.78	.515	.551	1.07			
1.47	.487	.516	1.06			
1.35	.473	.500	1.055	.498	.515	1.035
1.00	.445	.465	1.045	.456	.470	1.03

In justification of these conclusions it was found that when the brightness ratios were plotted against pitch (Figs. 4 and 5) straight lines were obtained, which when extrapolated backward to pitch unity, corresponding to a closed cylinder or black body, gave limiting values, at a red black body temperature of 2300° K., of 0.445 for $\lambda = 0.656\mu$ and

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[1] A. G. Worthing, Astrophysical Journal, 36, p. 345, 1912.

0.465 for $\lambda = 0.493\mu$. At 1900° K. the ratios became for the former, 0.456 and for the latter, 0.470. These values correspond very closely with those of Worthing[1] for the emissivity[2] of tungsten, found by an entirely different method.

Brightness ratios plotted against pitch, in order to determine the emissivity.

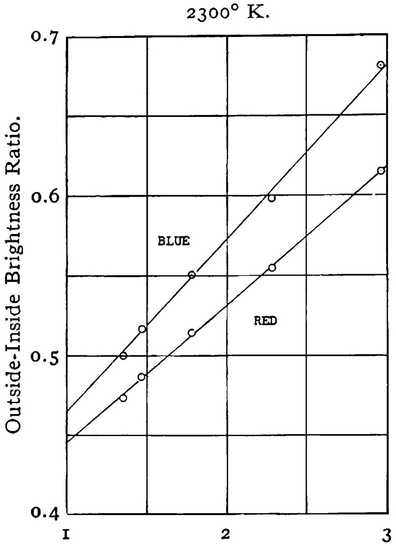

Fig. 4.

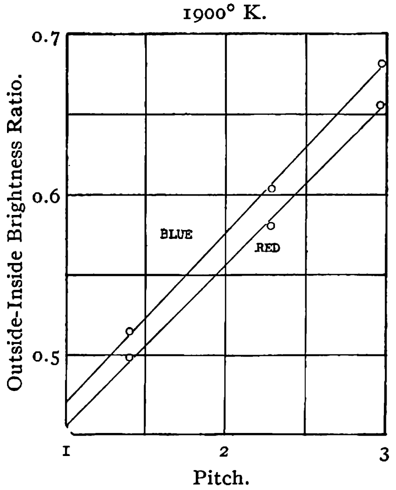

Fig. 5.

The Polished Flattened Filament.

A piece of 0.5 mm. tungsten wire was flattened to about half its original thickness, after which it was polished, coiled with a pitch equal approximately to twice the width of the ribbon and mounted as a lamp. The characteristics of this filament are in general the same as those of the commercial ones, the differences being those of degree (Plate I., Fig. 2). The middle dark portion of the inside is much broader and more pronounced, as are also the two adjacent bright portions. In addition to these there may be seen on the rounded edges other light and dark bands. This photograph alone is almost conclusive evidence that the phenomenon is one of reflection. The central sections of the turns appear dark since they are viewed normally and there is no opportunity for light to be added by specular reflection. Despite the fact that the surface is not an optical one there is very little diffuse reflection, as evidenced by the fact that the brightness of this part is only slightly greater than that of

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[1] Phys. Rev., VII., p. 497, 1916.

[2] Relative to that of a black body.

the outside. The two central bright bands are seen to be images of the adjacent filaments, which fact accounts for the added brightness. The other bright bands are the images of the next succeeding turns of the helix, and the dark bands correspond to the spaces between the turns.

Quantitative support of these conclusions is obtained from measurements made at 2000° K. as above. For this lamp also the maximum brightness of the inside was found to be of the order of twice that of the outside. The broad dark bands in the center of the interior, however, showed a brightness only slightly greater than that of the exterior (Table II.).

Table II.

Polished Filament, Red Black Body Temperature 2000° K.

Number of Turn.	Outside-Inside Brightness Ratio.		$\frac{R_2}{R_1}$
	R_1 $\lambda = 0.656\mu$	R_2 $\lambda = 0.493\mu$	
1	.942	.977	1.04
2	.970	.980	1.01
3	.918	.917	1.00
4	.973	.967	0.99
Average..........	....	....	1.01

Although some of the four turns measured exhibited a more perfect polish than did others, still in every case the brightness of the outside approached very closely to that of the central portion of the inside, and on the average even this portion of the inside was redder, as in the cases mentioned above. For the second turn, assuming the whole brightness difference to be a temperature effect, we obtain in the manner indicated above a maximum allowable temperature difference of about 5 degrees between the outside and the dark band of the inside. For the brighter portions of the inside of the coil this difference would amount to approximately 175 degrees. It would be impossible for these to have a temperature 170 degrees higher than the middle of the same turn. The brightness difference has been practically entirely localized, simply by the polishing of the filament. This obviously could not be true of a temperature effect, and reflections within the helix must be at least the principal cause of the brightness difference.

Color Matching.

Photographs of the helical filaments were made and cut as templates to transmit only the radiation from the interior and exterior respectively. These were placed in turn against a ground glass diffusing screen, upon which the image of the helix was then projected. By means of a Lummer-

Brodhun photometer these filaments, operated at 2000° K., were color matched against a comparison lamp. When the comparison lamp was adjusted to match the radiation from one of the surfaces, and then that from the other was permitted to pass into the photometer, the difference in color was very evident.

As will be seen from Table III., in order to match the outside, 0.5 per cent. greater current was necessary through the comparison lamp than to match the total radiation. Two per cent. less current was required to match the interior radiation, the lamp distances being adjusted in each case so as to give equal brightness contrast on the photometer screen. Again it is shown that the interior is redder than the exterior, so that the major portion of the increased brightness must be due to reflected light.

TABLE III.

Color Matching. Temperature 2000° K.

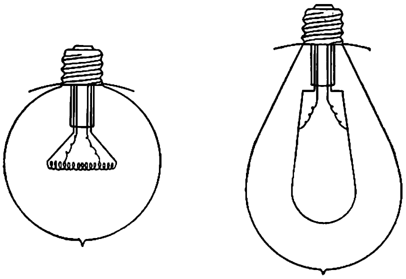
Current, in amperes, through the comparison lamp necessary to match the helix.

Setting.	Total Radiation.	Outside of Helix.	Inside of Helix.
1	2.243	2.247	2.222
2	2.232	2.240	2.182
3	2.227	2.227	2.200
Average...........	2.23	2.24	2.20

The various settings were made on different days and with slightly different currents through the helix.

RESISTANCE MEASUREMENTS.

Two filaments, one a hairpin, the other a helix, were made from the same piece of wire, provided with potential leads approximately a quarter of the way from the ends, and mounted in lamp bulbs (Fig. 6). Owing to the size (0.05 mm.) of these leads it was found inadvisable to weld them on, and they were tied tightly around the filament. The temperatures



Coiled and hairpin filament lamps used for the temperature-resistance measurements.

Fig. 6.

of the hairpin filament and of the outside of the helical filament were found to be very uniform over the lengths used. These temperatures were measured with the optical pyrometer and the resistances were measured by comparing the fall of potential across the lamps with that across a known resistance. The results are given in Table IV. and shown diagrammatically in Fig. 7, the line *A* representing the helical and the line *B* the hairpin filament. When the ordinates of *B* are multiplied by the ratio of the two ordinates at 1400° K., in order to bring the filaments to equivalent lengths, the new curve for *B* coincides exactly with *A* as drawn. Therefore, within the limits of experimental error the two filaments have the same temperature coefficient of resistance. This would not be the case if the helix heated unduly on the inside, for then the average temperature would be greater than that measured by the pyrometer, the effective resistance would be greater, and the curve for the helix would be steeper. From resistance measurements, therefore, the temperature throughout the helical filament is sensibly that of the outside.

TABLE IV.

Values of the Resistances of the Helical and Hairpin Filaments at Various Temperatures.

A—Helical Filament.		*B*—Hairpin Filament.	
Temperature.	Resistance.	Temperature.	Resistance.
1360	49.6	1390	48.9
1372	49.4	1413	48.5
1473	55.4	1519	55.3
1510	57.5	1524	55.4
1558	60.1	1650	61.2
1586	60.8	1695	63.0
1589	60.9	1793	67.9
1605	62.5	1795	68.2
1635	64.2	1885	72.5
1732	68.9	1948	75.8
1778	70.5		
1795	71.7		
1798	72.3		
1908	77.4		
1987	81.8		

SUMMARY.

To summarize: The data show:

1. That the interior of the helical tungsten filament has a maximum brightness of the order of twice that of the exterior.

2. That the inside is redder, and that the increased brightness is, in the main, due to internal reflections.

Resistance-Temperature curves.

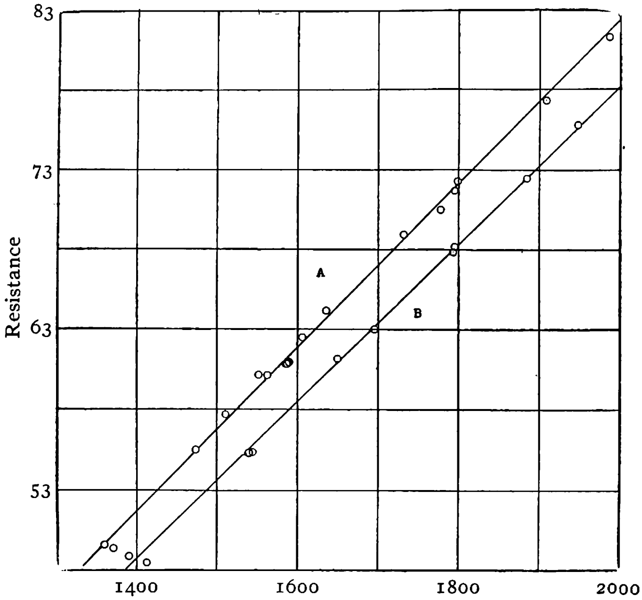


Fig. 7.

3. That the temperature difference between the inside and the outside of an unusually heavy filament operated at 2000° K. is not greater than 5°, as the maximum difference allowable from resistance and pyrometer measurements.

4. That for all ordinary lamps the calculated difference is of the order of 1°.

5. Values of the emissivity of tungsten have been obtained for two wave-lengths at two temperatures.

6. That tungsten radiates selectively in the visible portion of the spectrum in such a way as to make the amount of radiation, relative to that of a black body, greater in the blue than in the red.

I desire to acknowledge my indebtedness to Director E. P. Hyde, of the Nela Research Laboratory, for suggesting the problem and placing the facilities of the laboratory at my disposal while Brush Research Fellow; and to Dr. A. G. Worthing for constant help and criticism.

NELA RESEARCH LABORATORY,
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