EMISSIVITY OF STRAIGHT AND HELICAL FILAMENTS OF TUNGSTEN

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I. INTRODUCTION

The emissive properties of incandescent tungsten have been the subject of numerous investigations by various observers, the object being to find some law connecting the partition of spectral energy with wave length, similar to the Wien-Planck law of spectral radiation of a black body.

The present investigation was begun in January, 1914, but was interrupted, and not until during the past year was it possible to resume this work.

In a previous paper [1] on the radiation constants of metals the Wien equation, $E_\lambda = c_1\lambda^{-\alpha}e^{-c_2/\lambda T}$, was tentatively assumed for a working basis. The results obtained indicated quite conclusively that the distribution of energy in the emission spectrum of a metal can not be represented by an equation which is as simple as the Wien formula.[2]

In a subsequent investigation of the reflecting power of tungsten and other metals [3] it was shown that a spectral-radiation formula

[1] This Bulletin, 5, p. 339; 1908.

[2] In spite of the specific statement that the assumption of the Wien equation was tentative and in spite of the conclusions that this equation is unsatisfactory, subsequent writers (e. g., Stubbs and Prideaux, Proc. Roy. Soc., A 87, p. 451, 1912) quoting this paper say that the Wien equation was "assumed to hold for metallic radiation."

[3] This Bulletin, 7, p. 224; 1910. A recent investigation of the reflecting power of tungsten shows a band of selective reflection in the region of 0.7 μ with a conspicuous minimum at 0.8 μ. This depression in the reflection curve corresponds with a well-defined elevation in the emission spectrum, at 0.8 μ. These data will be published in a forthcoming paper.

of metals must contain factors which take into consideration the the variation in emissivity (1—reflecting power) which is a function of the wave length and the temperature. For it is well established that in the infra-red the variation (decrease) in reflecting power [4] with rise in temperature becomes perceptible at a wave length of about 2μ and is very marked for the region of the spectrum beyond 4μ. On the other hand, in the visible and ultraviolet region the most recent work [5] seems to indicate that the emissivity decreases (reflecting power increases) with rise in temperature and decrease in wave length.

The reflecting-power curve obtained by the writer (loc. cit.) does not show elevations in the infra-red at 1.5μ and 2μ. Hence, it is highly improbable that the depressions in the spectral-energy curves, at these two points in the spectrum, observed by Nyswander,[6] are due to selective emission, but are to be attributed to atmospheric absorption bands and to improper factors for reduction to the normal spectrum. Similarly, the unusual results of McCauley [7] are open to question. For example, he found that at high temperatures the maximum emissivity of tantalum occurs "at a longer wave length than does a black body" (at the same temperature), which from a consideration of the reflecting-power data does not appear to be possible. He found that the metals investigated (tantalum, platinum, and palladium) acquired a minimum reflecting power in the region of 1.2μ, which become more marked with rise in temperature. In view of the fact that these data were obtained indirectly by computation, it seems more probable that the reflection minimum at 1.2μ is to be attributed to incomplete knowledge of the radiation constants used in the calculations. Such reflection minima would give rise to emission maxima in the spectral-energy curve, but no maxima have yet been observed. The point of interest in this investigation was the verification of the previous work just mentioned indicating that the Wien equation can not be applied to the spectral radiation from metals.

In a paper on the reflecting power of tungsten [8] physical data were given showing why tungsten (and in fact all metals which have a lower reflecting power in the blue than in the red) radiates

[4] Hagen and Rubens, Sitzber. Akad. Wiss., XVI, p. 478, 1909; XXIII, p. 467, 1910.

[5] Worthing, Phys. Rev., 7, p. 497, 1916; Hulburt, Jour. Franklin Inst., 182, p. 695, 1916; Weniger and Pfund, Jour. Franklin Inst., 183, p. 354, 1917.

[6] Nyswander, Phys. Rev., 28, p. 438; 1909.

[7] McCauley, Astrophys. Jour., 37, p. 164; 1913.

[8] This Bulletin, 7, p. 197; 1910. See Fig. 2, which, unfortunately, is drawn upon such a small scale that a small indentation at 0.8μ is not shown. In a recent investigation the slope of the reflecting-power curve in the region from 0.7μ to 1.5μ was found to vary for different samples of tungsten.

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.

II. RADIATION CONSTANTS OF A NITROGEN-FILLED TUNGSTEN LAMP

The appearance upon the market about three years ago of the gas-filled tungsten lamp afforded an opportunity for further investigation of the radiation constants of metals at much higher temperatures than were heretofore attainable.

The first measurements on a spiraled tungsten filament (20-mil wire) were made in January, 1914. The lamp was set to the same emissivity (color match) as a vacuum tungsten lamp operated at 1.2 w. p. m. h. c. The spectral-energy curves of these two types of lamps were observed with a vacuum spectrobolometer and fluorite prism, and the radiation constants were computed by the methods previously described.[9]

The spectral-energy curve of the helical filament superposed so closely upon the energy curve of the vacuum tungsten lamp that the lack of coincidence was then attributed to a difference in absorption of the glass bulbs,[10] which is very marked for wave lengths greater than 2μ. However, from the recent work it appears that a more probable explanation is that the spirals, which were suspended in V-shaped loops, were so situated as to prevent much radiation, emitted from within the loop, from entering the spectrometer slit. For this reason the wave length of maximum emission ($\lambda = 1.18\mu$) of the helical filament was the same as that ($\lambda_m = 1.2\mu$) of the vacuum tungsten lamp when operated at a color match with the latter, and the radiation constant, α, mentioned below, was the same as that of the straight filament.

The data obtained in this test indicated, as in previous work, that no simple formula like the Wien equation can apply to the spectral radiation from metals. The wave length of maximum emission of the helical filament under normal energy input (968 watts; 110 volts) was $\lambda_m = 1.06\mu$.

The constant α ($\alpha - 1 = 4$ for a black body) was computed as in previous communications. The values of α for different points on the energy curve did not fluctuate so much as in previous work, varying from $\alpha = 6.56$ to 6.92. The predominating values were of the order of $\alpha = 6.8$, which means that the emissivity of tung-

[9] This Bulletin, 5, p. 339; 1908. In a future paper it is intended to give these constants of radiation at the true temperatures of tungsten, which from the recent work of Worthing appear to be determinable with a reasonable degree of accuracy.

[10] Coblentz, Lighting Journal, 2, p. 35; February, 1914.

sten is proportional to about the 5.8 power ($\alpha - 1$) of the temperature. This value is closely the same as previously observed[11] by the writer on a straight filament, which may not have been made of as pure material as the present filament. In addition to the value ($\alpha = 6.8$) obtained on the commercial lamp, further data were computed from observations on the special lamps described in the present paper. Of these special lamps the one (No. 61) with the hairpin filament gave values varying from $\alpha = 6.9$ to 7.2 with an average value of about $\alpha = 7$. The lamp (No. 59) having the same kind of wire, but wound into a helix, gave values ranging from $\alpha = 6.7$ to 7.2 with an average value of about $\alpha = 6.8$. Lamp No. 53, having a spiraled filament, was operated on a 15 per cent overload ($\lambda_m = 1.01 \mu$). It gave an average value of $\alpha = 6.5$. This is distinctly lower than the values obtained at the lower temperatures ($\lambda_m = 1.06 \mu$), but it is in agreement with the previous investigation, and it is entirely in agreement with theory, which indicates that with rise in temperature the value of α should decrease and approach that of a black body, viz, $\alpha = 5$. It is to be understood, of course, that these computed data are qualitative in character and that the actual change in value with temperature is probably not so rapid as indicated by the computations. In fact, the experiments of Worthing[12] show but little variation in α for the temperature range between 1500° and 2500° abs. His value is $\alpha = 6.35$ (i. e., $\beta = 5.35$ as compared with $\beta = 4$ for a black body in the equation $E = \sigma T^{\beta}$), which is in remarkably close agreement with the values computed upon the basis of a spectral-energy (distribution) equation, the constants of which had to be assumed. In view of these facts, it is hoped to obtain more complete infra-red spectral-energy curves of tungsten, which will make it possible to compare the experimental with the theoretical spectral-energy distribution.

III. APPEARANCE OF AN INCANDESCENT HELIX OF TUNGSTEN WIRE

The appearance of an incandescent spiraled filament of tungsten (in a nitrogen-filled lamp) is very interesting and illustrates several novel problems in radiation. As shown in the photograph, Fig. 1, the inside of the turn of the helix is much brighter than the outside of the turn of the wire. In the present case measurements were made with a physical photometer[13] on the same areas (indicated by the rectangular black spots in Fig. 2, *A*) on the inside and the outside of the turn of the wire.

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[11] This Bulletin, 5, p. 372; 1908.

[12] Worthing, Phys. Rev., (2), 4, p. 535; 1914.

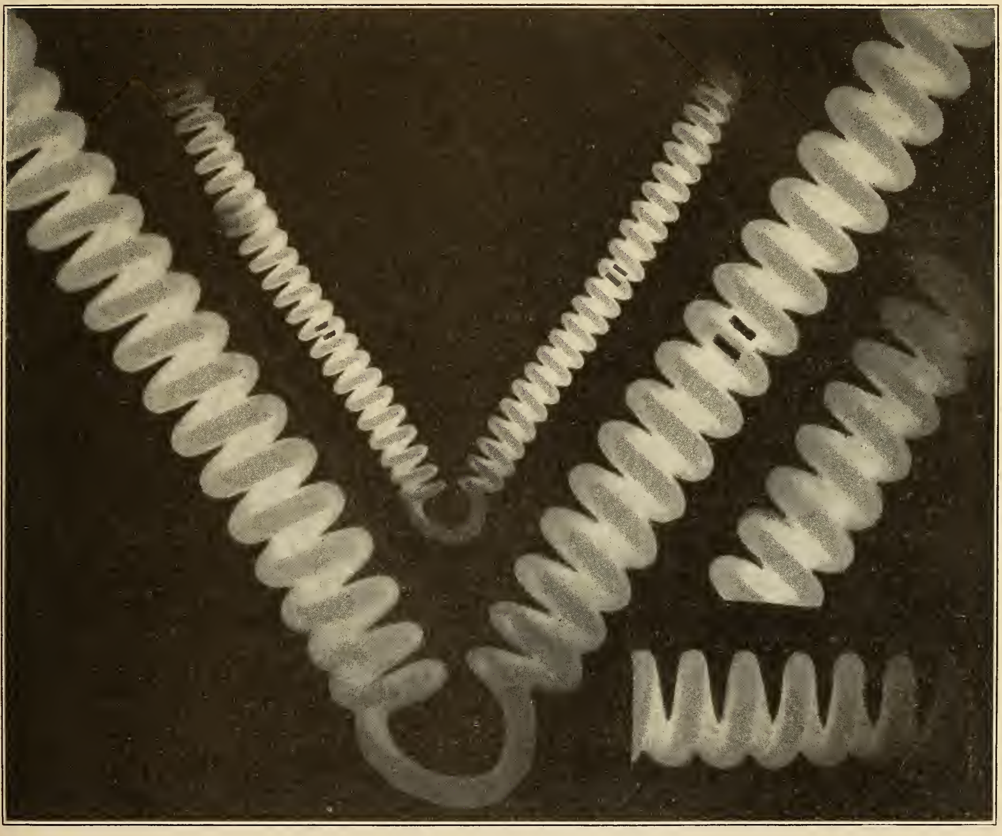

FIG. 1.—*Photograph of an incandescent helical filament of tungsten in a gas-filled lamp*

1. RATIO OF BRIGHTNESS

Using a mirror of 50 cm focal length, an enlarged image of the inside and the outside of the turn was focused upon a slit, 1 by 0.5 mm, placed so as to have the edges parallel with the turn of wire. Back of the slit was placed the physical photometer. Several series of measurements on the inside and the outside of the turn indicated that the light from within the helix was 1.87 times as bright as from the outside of the wire.

This increased brightness is produced no doubt by the emission and multiple reflection of light from adjacent turns of wire. For

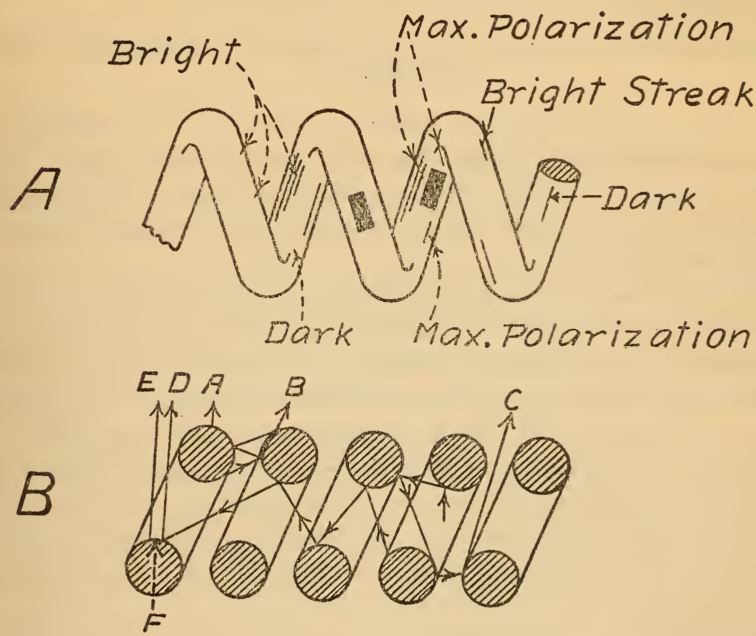

FIG. 2.—*Illustrating the manner in which multiple reflection may occur within an incandescent helical filament*

example, if the intensity of the light emitted directly by the inside of the turn (E in Fig. 2) be taken as unity (the same as the outside of the turn, A in Fig. 2), then the intensity of the image D would be $1+R$ for the light emitted by the adjacent turn, $+R^2$ for the light emitted by the second turn, etc. Hence, the increased brilliancy may arise from reflections, $D=1+R+R^2+R^3+$, as shown at C and D in Fig. 2. The increased brightness along the edge of the helical filament as compared with the appearance of the edge of a straight filament is no doubt due to multiple

[13] Ives and Kingsbury, Phys. Rev., **6**, p. 319; 1915. Coblentz, Jour. Franklin Inst., **180**, p. 335, 1915; **181**, p. 233, 1916.

reflections as indicated at B in Fig. 2. Along the highest part of the inside of the turn F, in Fig. 2 (see also Fig. 1) and the regions marked "Dark" in Fig. 2 (multiple), reflections can not occur in the direction viewed, and the intensity of the light is quite as low as on the outside of the turn.[14]

On the assumption that the reflecting power of tungsten is $R=0.51$ at $\lambda=0.55\mu$, the increased brightness for three reflections is $(1+R+R^2+R^3)=1.90$ as compared with the observed value of 1.87. As will be noticed presently, making similar computations for the infra-red, the observed and calculated energy curves are found to be in remarkably close agreement.

2. TEMPERATURE RISE VERSUS BLACKENING OF RADIATION WITHIN THE HELIX[15]

In view of the fact that opinions differed as to whether the increased brightness within the helix was due to a higher temperature or to internal reflection, it is relevant to discuss this question and give some criteria to distinguish between these two possible explanations.

When this work was first undertaken the preliminary data on the heat conductivity of tungsten at high temperatures, by Worthing,[16] had just been published, and from his data it seemed quite evident that the increased brightness could not be explained solely on the basis of a higher temperature within the helix. On the basis of these data the difference in temperature between the inside and outside of the turn would be less than 1° for a 0.5 mm filament, while under the most unfavorable condition Langmuir [17] estimates that the temperature difference can not exceed 5° at 2900° Abs.

Furthermore, by differentiating the Wien equation we have $\frac{dE}{dT}=\frac{C_2E}{\lambda T^2}$. Using $C_2=14\ 350$, $\lambda=0.6\mu$ and temperature $T=2300°$ Abs., it can easily be shown that $\frac{dE}{dT}=\left(\frac{14\ 350\ E}{0.6 \times 2300^2}=\right)$ $0.0045\ E$, or a change of 1° corresponds to only 0.45 per cent in brightness. It would therefore require an increase in temperature of almost 200° in order to account for the observed increased

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[14] See also Langmuir, Phys. Rev., 6, p. 138, 1915, and Coblentz, Elect. World, 64, p. 1048, 1914, for further illustrations and similar conclusions.

[15] By "blackening" of radiation is meant a modification of the quality of the radiation from an incandescent substance, so that it has more nearly the properties of the radiation from a uniformly heated inclosure, or so-called "black body."

[16] Worthing, Phys. Rev., 3, p. 67; Jan., 1914. Since then more complete data have been published, Phys. Rev., 4, p. 535; 1914.

[17] Langmuir, Phys. Rev., 6, p. 150; 1915.

brightness of about 90 per cent within the helix. This would shift the maximum emission by the amount of 0.06μ to 0.09μ toward the short wave lengths as compared with the maximum of the radiation from the outside of the turn. Such a large shift has not been observed.

In view of the fact that the reflecting power of tungsten[18] is lower in the blue than in the red, the intensity of the light emitted by one turn of the helix and reflected from another turn is more depleted in the blue than in the red. Hence, if the increased intensity of the light from within the helix is caused by multiple reflections, then its color should be redder; that is to say, the light from the outside of the turn should be relatively more intense in the blue than the radiation from within the helix. The difference is so small, however, that it requires special care in observing this effect.[19]

If the increased brightness observed within the helix is due to blackening of the radiation, caused by reflections, then the spectral-energy curve should be much higher and unsymmetrical on the long wave-length side of the maximum emission, as compared with the spectral radiation from the outside of the turn of the helical filament, for it is well established (both experimentally and theoretically) that in metals the spectral-energy curve in the infra-red falls very much below the spectral-energy curve of a black body at the same temperature.

On the other hand, as already stated, if the increased brightness, to be observed within the helix, is due to a higher temperature, then the wave length of maximum emission should be shorter than that of the radiation from the outside of the turn; and the energy curves, reduced to equal ordinates at a given wave length, say 0.6μ, should intersect unsymmetrically. If the temperature within the helix is but a few degrees higher than the outside of the turn, then the energy curves will superpose and intersect quite symmetrically.

The probable reason why, in the earlier part of this work on nitrogen-filled tungsten lamps containing helical filaments, it was

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[18] This bulletin, **7**, p. 197; 1910.

[19] For this reason the writer feels justified in adhering to the statement in the preliminary report (Electrical World, **64**, p. 1048, 1914), viz, that "the quality of the light coming from within the helix is not appreciably modified." For, if the quality of the light was very markedly changed, it would not require great efforts in order to establish the fact. In a recent paper Shackelford (Phys. Rev., **8**, p. 470, November, 1916), by means of a special color-match test, was able to show that the light from within the helix is redder than that emitted from the outside of the turn. His ratio of diameter of helix to diameter of wire was much greater (five times greater) than that of the sample examined by the writer. This would reduce the crimping within the turn and lessen the blackening of the radiation from this cause.

not possible to settle the questions just enumerated is attributable in part to the fact that all the measurements were not made on the same lamp, as was done in the later work. However, to make the infra-red measurements upon the inside and outside of a single turn of the helix involves considerable difficulties which it was hoped could be avoided.

In the lower part of the V-shaped loop, Fig. 1, it may be noticed that the outside of several of the turns of the helix show bright spots indicating reflection of light emitted by the turns of wire which are on the opposite sides of the loop.

IV. COMPARISON OF THE RELATIVE EMISSIVITIES OF STRAIGHT AND HELICAL FILAMENTS

In order to carry out more fully the investigations just described, an opportunity was presented through the courtesy of the General Electric Research Laboratory, Schenectady, N. Y. (in February, 1914), to determine the relative energy distribution in the spectrum of straight ("hairpin") and helical filaments of tungsten in nitrogen-filled bulbs of the same kind and closely the same thickness of glass.

The tungsten wire used was 0.5 mm (20 mils) in diameter. In the helical filament the pitch was twice the diameter of the wire, while the inside diameter of the helix was two times the diameter of the wire. This was a rather small diameter and caused a noticeable crimping on the inside of the turn which might cause a blackening of the radiation.

One series of spectral-radiation measurements was made (with a vacuum spectrobolometer and fluorite prism) upon the helically wound filament and upon the hairpin filament set to the same emissivity, in the visible spectrum, as the outside of the turn of the helical filament. For this purpose the lamps were calibrated by operating the hairpin filament at its normal temperature ($\lambda_m = 1.06\mu$) and adjusting the current through the spiraled filament so that the outside of the surface of the turn had the same emissivity (the same intrinsic brilliancy) in the visible spectrum as the straight wire.

1. CALIBRATION OF LAMPS

The apparatus for calibrating the lamps is shown in Fig. 3. The nitrogen-filled lamps were placed (one at a time) at *L* and the image of the filament was viewed by means of a microscope, *O*, consisting of a 48 mm focal length objective and a low-power

(Zeiss No. 2) eyepiece, *E*, the combination having a magnification of about 20. A higher power gave poor definition owing to imperfections in the lamp bulbs. An iris diaphragm, at *I*, was useful in adjusting the focus on and within the spiral, and, when using the device as a pyrometer, for limiting the cone of rays in the field of view. A water-cooled screen was placed at *W*. An image of the filament *L* was brought to focus at *M* by means of two Zeiss achromatic telescope objectives *T*, having a high aperture (18 cm focal length, 6 cm diameter). These lenses give the best definition when used in pairs, with the source placed at the principal focus so that the light is parallel on leaving the first objective and on entering the second objective. An absorption screen of Schott's black glass was placed at *A* to reduce the

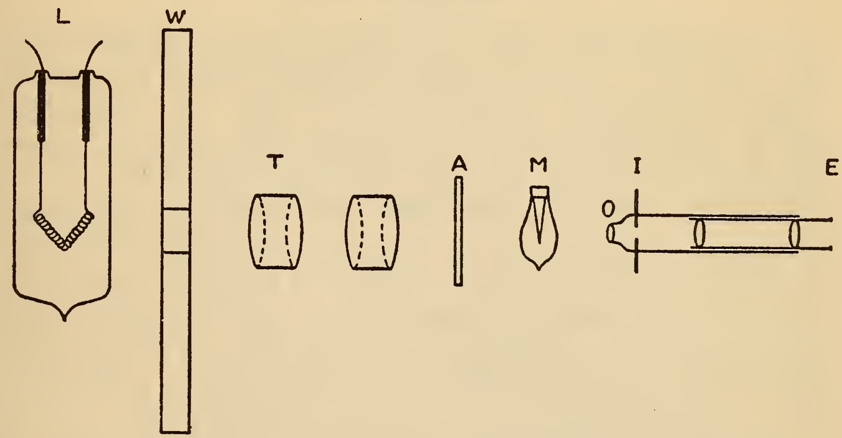

FIG. 3.—*Arrangement of apparatus for calibrating the gas-filled lamps*

intensity to that of the comparison lamp *M*, which was a 40-watt vacuum tungsten lamp.

The intensity of the light from *L* might have been reduced by means of a rotating sector or a nitrogen-filled lamp with hairpin filament might have been used at *M*, if one having homogeneous glass walls had been available. The lamp at *M* served, of course, merely as an intermediary in the substitution method of calibrating the lamps placed at *L*. The glass screen *A* is, of course, slightly selective in its transmission, so that when the image of the filament is viewed through red, green, and blue glass at *E* one experiences the same difficulties that are found in any optical pyrometer. This, however, does not interfere with the calibration so long as use is made of the same kind of wire in all the lamps.

2. POLARIZATION TESTS

An examination was made of the light from within the helix by using a Nicol prism in the eyepiece *E*, Fig. 3. As shown in Fig. 2 (section *A*), the regions of greatest brightness show marked polarization of the emergent light. The outside of the turn shows but little polarization. Hence, while some of the polarized light from within the filament might be due to emission, there is strong evidence that it is due primarily to reflection of light coming from adjacent filaments.

The highly polarized condition of the light is a further test, showing that the quality of the radiation from within the helix is quite different from that of a black body.

3. PYROMETRIC TESTS

It was found that when the hairpin filament (nitrogen-filled lamp No. 61) at *L* was operated at a predetermined temperature (giving a maximum emission at $\lambda_m = 1.06\mu$) the comparison lamp *M* disappeared against the image of the hairpin filament when operated on 41.3 (to 41.4) volts when viewed through red glass, on 43.6 (to 43.7) volts when viewed through green glass, and on 45.1 (to 45.2) volts for blue glass. The spiraled filament was substituted for the hairpin filament at *L* and its temperature raised until the comparison lamp on 41.3 volts (red glass) disappeared against the image of the outside surface of a turn of the spiraled filament. It was then found that there was a disappearance of the filament on 43.6 volts for green glass and 45.1 volts for blue glass, as in the case of the hairpin filament. Making similar settings on the brightest part of the inside surface of a turn of the helical filament, the current being held constant, the voltage of the comparison lamp *M* had to be raised to 48.6 volts for disappearance in the red light and to 52.4 volts in blue light. In both sets of measurements, on the inside and on the outside surface of the turn, the difference in voltage for disappearance when viewed through red and blue glass happens to be close to 3.8 volts.[20] By actual test the candlepower (data kindly furnished by the photometric division of this Bureau) of the comparison lamp was found to have doubled (1.6 to 3.2 cp) by this increase in voltage (7.3 volts) in setting on the inside and outside of the turn, using red glass. In increasing the voltage when com-

[20] In a preliminary report in the Electrical World, **64**, p. 1048, 1914, these tests were discussed in the terminology appropriate to pyrometers, viz, "apparent temperature," but it was not intended to convey the idea that the increased brightness is due "solely to increased temperature." See further discussion in Electrical World, **69**, p. 328, 1917.

paring the radiation from the inside of the filament, the spectral-energy distribution in the lamp *M* becomes relatively stronger in the blue. This method of attacking the problem was useful only in showing the difference in selective emission of different samples of tungsten wire, when the comparison was made in red and in blue light.

4. COMPARISON OF SPECTRAL-ENERGY CURVES (DATA OF 1914)

In spite of the care taken in the calibration of the lamps the results obtained with the spectral-energy curves did not prove to be very satisfactory. The shape of the spectral-energy curve of the hairpin filament differed but little from that of the composite radiation coming from within and from the outside of the spiraled filament. After reducing the energy curves to a common ordinate in the visible spectrum it was found that the area of the energy curve of the spiraled filament was only 7 per cent larger than that of the energy curve of the hairpin filament, due to "blackening" of the radiation in the region from 1 to 3μ, as already explained. While this proved, of course, the presence of some reflected light from within the helix, it did not account for the 90 per cent increase in the visible spectrum.

It was evident that in order to reach definite conclusions in this matter it would be necessary to determine the spectral-energy curves of a small area on the inside and outside of the turn of the helix. This is a much more difficult problem than the one in which observations are made on the radiation from a long filament because of the reduction in energy and difficulty of projecting a satisfactory image of the spiral upon the spectrometer slit. However, during the past year the work was undertaken anew, using a mirror spectrometer, fluorite prism, and bismuth-silver thermopile.[21] The helical filament stood at a distance of about 2 m from the spectrometer slit, and for the investigation of the visible spectrum an enlarged image of the spiral was projected upon the spectrometer slit by means of the lens *T*, as shown in Fig. 3. For determining the infra-red energy curves the lens *T* was replaced by a concave silvered mirror of 50 cm focal length and a silvered plane mirror. This combination permitted the projection of an image of the spiraled filament upon the spectrometer slit (at *E* in Fig. 3) without distortion of the image. The spectrometer slit was 0.55 mm wide and its length was reduced to 1 mm by covering the upper and lower portions

[21] This Bulletin, **9**, p. 7, 1912; **11**, p. 131, 1914.

with pieces of thick white cardboard, which were adjustable and which had sharp beveled edges. By means of an adjusting screw a uniformly illuminated image of a small portion of the inside or outside of the turn (shown diagrammatically by the dark rectangles in Fig. 2 (section *A;* also Fig. 1) could be projected upon the spectrometer slit.

5. ENERGY MEASUREMENTS IN THE VISIBLE SPECTRUM (DATA OF 1916)

The data for the visible spectrum are given in Fig. 4. Curve *I* gives the distribution of energy radiated from the inside of the

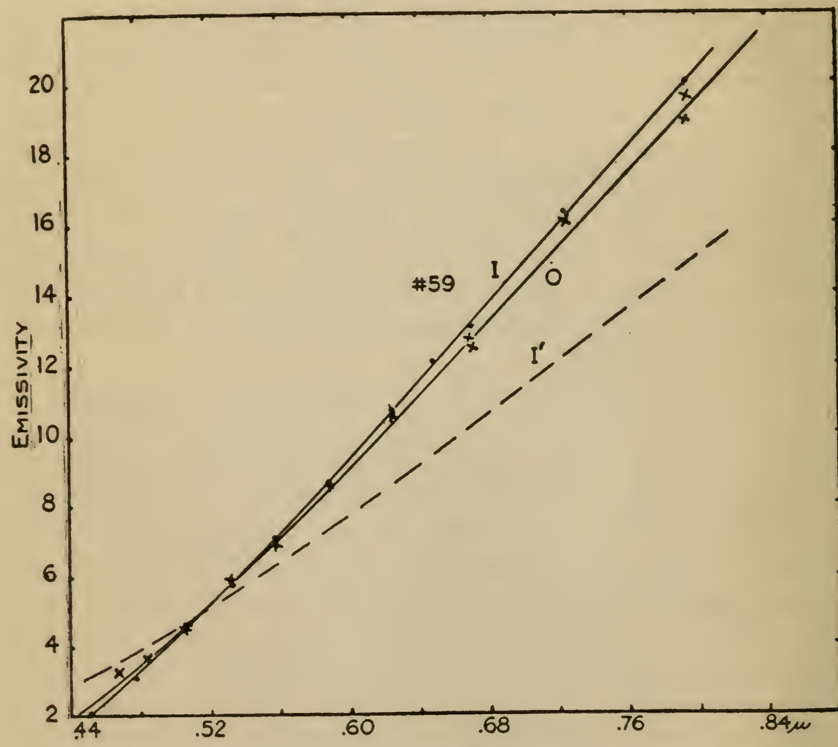

FIG. 4.—*Distribution of energy radiated from the inside, I, and outside, O, of an incandescent helical filament of tungsten*

turn. Similarly, curve *O* gives the energy distribution of the radiation from the outside of the turn of the helical filament of the tungsten. In the latter the ordinates were magnified 2.2 times in order to superpose the curves, and hence the errors are magnified as compared with curve *I*. In each curve the data represent two distinct series of measurements. It is to be noticed that the two curves intersect at a very acute angle, which is so small that, in the earlier tests, the difference in the slope of the two curves was attributed to experimental errors.

The curve *O* indicates that the light emitted from the outside of the turn is relatively stronger in the blue than the light emanating from within the turn of the helix. That is to say, the light from within the helix is redder than that from the outside of the turn. As already explained, this indicates that the increased brightness of the light from within the helix is caused by reflections which deplete the blue as compared with the red.

If the temperature of the interior of the helix were enough higher than the outside of the turn, then the curves *I* and *O* would be interchanged. As already mentioned, the temperature within the helix would have to be 200° higher in order to account for the observed increased brightness of 90 per cent. This would produce a spectral-energy distribution, as shown by the dotted curve *I'* in Fig. 4. The depletion of the blue light by reflection within the helix produces an energy distribution corresponding to an apparently lower temperature (of 1° to 30°) than that of the outside of the turn. The actual difference in temperature, which, under the most unfavorable condition of plotting the curve *I* in Fig. 4, can not be higher than 37°, is not sufficient to account for the increased brightness of 90 per cent observed within the helix.

Using two wave lengths, λ_1 and λ_2, in the visible spectrum the temperature T, of a black body may be computed from the Wien equation in the form

$$T = c_2\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)\log \epsilon \div \log\left[\left(\frac{\lambda_2}{\lambda_1}\right)^5 \frac{E_2}{E_1}\right]$$

in which E_1 and E_2 are the observed emissivities at λ_1 and λ_2, respectively.

This indicates a black-body temperature of 2550° C, using $c_2 = 14\,350$. This is somewhat higher than the observed black-body temperature computed from the value of λ_m, to be discussed presently.

6. INFRA-RED SPECTRAL-ENERGY MEASUREMENTS (DATA OF 1916)

The distribution of the energy radiated from the inside of the turn of the spiral is shown in curve *I* of Fig. 5. Similarly, curve *O* gives the distribution of spectral energy radiated from the outside, *O*, of the turn of the wire. Curve *C* gives the energy distribution of the hairpin filament when set to the same brilliancy as the outside of the turn of the helical filament. The lack of coincidence of curves *O* and *C* may be due to a slightly higher temperature (perhaps 10°) of the hairpin filament.

The wave length of the maximum emission of the radiation from the outside of the turn of the helix is $\lambda_m = 1.06\mu$. The wave

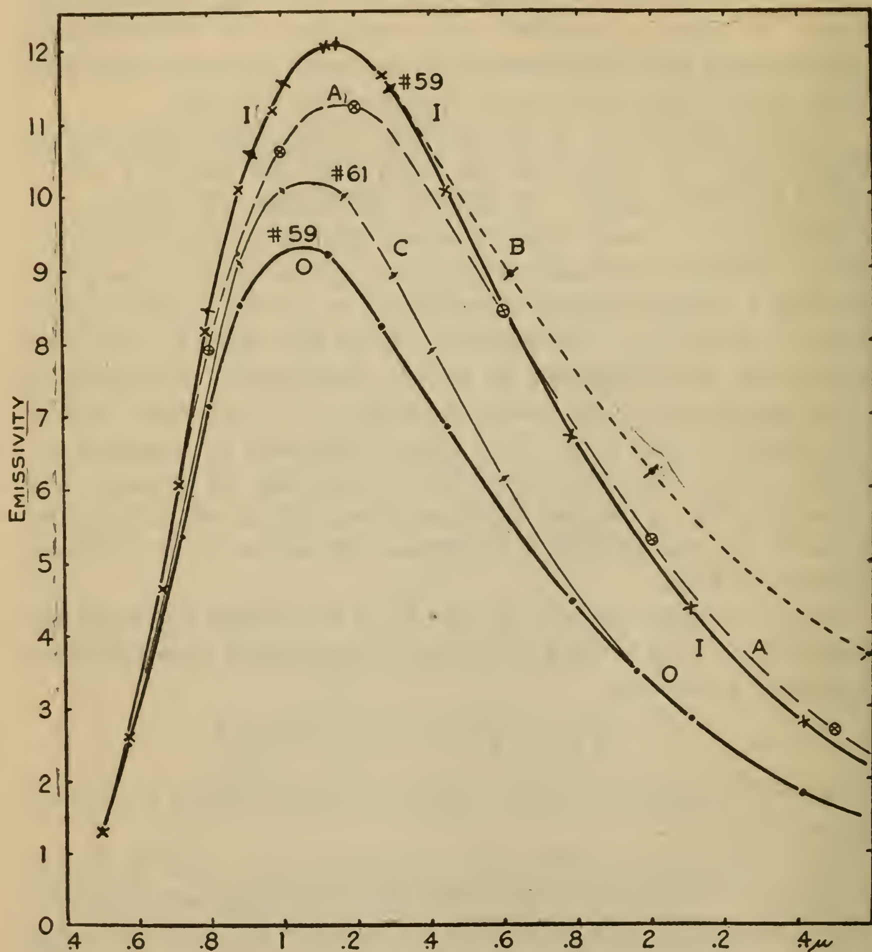

Fig. 5.—*Distribution of energy radiated from the inside I, and outside, O, of the turn of a helical filament of tungsten*

length of the maximum emission of the radiation from within the helix is $\lambda_m = 1.115\mu$. Using $\lambda_m T = 2894$ for a black body, which, of course, is not exactly the condition for curve *I*, Fig. 5, the value of the temperature is about 2596° to 2600° *T* or, roughly, 2325° C, which is close to the estimated black-body temperature.

The most interesting application of the data illustrated in Fig. 5 is in the possibility of accounting for the increased brightness within the helix on the basis of multiple reflection of light. As already stated, the increased intensity in the visible spectrum of the light from within the helix can be accounted for on the assumption of three reflected images, which would increase the brightness by 90 per cent. A similar application of the reflecting-power data,[22] in the infra-red, to the spectral-energy curve *O* gives curve *A*, which is in remarkably close coincidence with the observed curve *I* for the radiation from within the helix. This is especially marked in view of the fact that no correction has been applied to the reflecting-power data, which are for room temperature. Now, it is well known that in the infra-red the reflecting power of metals decreases with rise in temperature. The data of Hagen and Rubens[23] indicate that in the region of 2 to 3μ the temperature coefficient of reflection is already perceptible, while beyond 4μ it is quite large, so that the emissivity (100 reflectivity) of platinum increases about 40 per cent in a temperature range of about 1400° C.

Hence, an application of a temperature correction to the observed reflecting-power data would bring the computed curve closer to the observed curve. For example, at 2.5μ, where a value of $R=0.84$ (20° C) was used, if the reflecting power decreased to $R=0.80$ at 2300° C, which is not improbable (in fact, it seems a very conservative estimate), then the observed curve *I* and the computed curve *A* would coincide within 2 per cent, which is as close as the experimental data are known at this point.

These data appear to furnish conclusive proof that the phenomenon of increased brightness within the helical filament can be accounted for by multiple reflections within the helix. A slight blackening of the radiation may be produced by crimping in case the filament is wound upon a small mandrel, but there is little or no evidence that the temperature within the helix is higher than on the outside of the turn of the wire.

While the increased radiation from within the helix can be accounted for on the basis of multiple reflection, the quality of the radiation in the infra-red is quite different from that of a black body at the same temperature. This is illustrated in Fig. 5, curve

[22] This Bulletin, 7, p. 201; 1911. A redetermination of these reflecting-power data is in progress.

[23] Hagen and Rubens, Sitzber, Akad. Wiss., XXIII, p. 467; 1910. See also a paper by Weniger and Pfund, Jour. Franklin Inst., March, 1917, in which a decrease of 12 per cent in reflecting power, at 2 to 3μ, has been published since the completion of this paper.

B, which gives the distribution of energy in the spectrum of a black body at the temperature ($T = 2600°$) which gives the same λ_m ($= 1.115\mu$) as observed for the radiation from within the helix. The intensity of the radiation at 2.5μ is about 40 per cent higher (allowing 15 per cent for absorption of the glass) than the observed value. In other words, the apparent emissivity of the inside of the helix at 2.5μ is only 60 per cent that of a black body.

The ratio of the areas of the curves $I \div O$ is 1.36, which indicates that "blackening" of the radiation within the helix has reduced the luminous efficiency by 36 per cent. The filament in a gas-filled lamp is wound helically in order to reduce the loss of energy by conduction and convection. To the writer the most striking observation is the increase in light efficiency introduced by actually increasing black-body conditions, when, as is well understood, an increase in light efficiency is to be sought by decreasing the infra-red radiation. In the present case the helical filament acts as a very thick, short filament as regards elimination of convection losses; and in spite of the fact that the luminous efficiency is reduced by blackening of the radiation from within the helix, there is a net gain in light efficiency due to the prevention of dissipation of energy by convection and conduction.

V. SUMMARY

In the present investigation data are given on the radiation from the inside and the outside of the turn of a helically wound tungsten filament in an atmosphere of nitrogen.

The intensity of the radiation from within the turn of the helix is from 90 to 100 per cent greater than from a similar area on the outside of the turn. This is accounted for on the basis of multiple reflection within the helix. This modifies the quality of the light so that it is redder than the light from the outside of the turn.

The observed infra-red measurements on the radiation from within the helix and the computed values (obtained on the basis of multiple reflection and the reflectivity of tungsten) are in close agreement. This is further evidence that the phenomenon is the result of multiple reflection.

Tests were made with a Nicol prism, which showed that the light from some parts of the inside of the filament is highly polarized, indicating that the quality of the light is quite different from that of a black body. The infra-red energy measurements also indicate that the quality of the radiation differs from that of a black body.

Computations of the radiation constant of tungsten indicate, as found in previous investigations, that the Wien equation is not applicable to the radiation from tungsten.

There is no indication that the temperature within the helix is higher than on the outside of the turn. A difference in temperature of 200° would be required to account for the observed difference in brightness of 90 per cent, whereas pyrometric, thermal conductivity and other measurements place this temperature difference at less than 5°.

Although the quality of the radiation has been modified by multiple reflection within the helix, it is not sufficiently similar to that of black-body radiation to permit its use in exact temperature measurements by sighting an optical pyrometer within the turns of the helix.

In conclusion, especial acknowledgment is due to W. B. Emerson for able assistance in this investigation.

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