THE TEMPERATURES AND SPECTRAL ENERGY
CURVES OF LUMINOUS FLAMES.

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IN a communication to the German Physical Society, Messrs. Lummer and Pringsheim¹ suggested a method for the measurement of luminous flame temperatures, based upon the well-known relation between the wave-length of the maximum in the energy curve and the temperature of a black body. This relation is $\lambda_m T = A$, a constant, where λ_m is the wave-length of the maximum and T is the absolute temperature. For a black body they found the constant to be 2940, while experiments with bright platinum gave about 2630. They suggested that the temperatures of luminous flames could be calculated from this formula, and that the temperature would lie between the values obtained by assuming these two values for the constant.

In a recent article² the writer computed the temperature of the acetylene flame according to this suggestion. The value obtained for a cylindrical flame lay between 2890° C. and 2560° C., which this is certainly wrong. I have since found my method of correcting the observed curves to be incorrect, but the temperatures, using the correct curves, are yet much too high.

Kurlbaum,³ in an account of a simple method for the measurement of flame temperatures, remarks that while a luminous flame of very great thickness would radiate as a black body, yet we might expect a candle flame, for example, to radiate as a very thin film of carbon at that temperature. He has already shown⁴ that a thin coat of lampblack is more transparent to long than to short waves, *i. e.*, the absorption and radiation increase with decrease of wave-

¹ Lummer and Pringsheim, *Verh. Deutsch. Phys. Gesell.*, 1899, p. 214.

² *PHYSICAL REVIEW*, XIII., 1901, p. 257.

³ Kurlbaum, *Physik. Zeitschr.*, Feb. 1, 1902, p. 187.

⁴ Kurlbaum, *Annal.*, 67, 1899, p. 846.

length. Hence in the curves showing the distribution of energy in the spectrum of the acetylene flame, for example, the maximum would be found further toward the short wave-lengths than in the case of a black body at the same temperature. One would expect, then, that the results obtained by applying the formula, $\lambda_m T = A$, would give temperatures much too high.

Kurlbaum's method of measuring flame temperatures is as follows : Let a black body at a known temperature be brought before the eye of the observer. It will appear of a certain brightness. If a flame is now inserted between the eye and the black body, the apparent brightness of the body will, in general, change. If the flame has the higher temperature, the body will appear brighter, and if it has a lower temperature, the brightness will be less. But if the body and the flame have the same temperature, the brightness of the body will remain unchanged. One then needs only to vary the temperature of the body until the brightness remains the same when the flame is introduced. By this method, Kurlbaum found the temperature of the candle flame to be 1430°C .

Lummer and Pringsheim,¹ in a later article, criticise Kurlbaum's method. They show that it would be correct only in case the reflection of the flame can be neglected in comparison with the absorption. They made a measurement of the transmission of the candle flame in the red portion of the spectrum and found the value 0.8. Then assuming the reflection of the incandescent carbon particles in the flame to be from 5 to 10 per cent., they computed, by means of a formula and their own previous work on a black body, that Kurlbaum's value of 1430°C . or 1700°abs. is about 40° to 120° too low. When this correction is made, the result 1740°abs. to 1820°abs. compares favorably with their value of 1780°abs. to 1960°abs. found from the spectral energy curve. They conclude that the slight discrepancy hardly justifies the assertion that the incandescent carbon particles in the flame of the candle radiate more selectively than bright platinum. Kurlbaum, however, replies,² and shows by experiment that the reflection of the candle is about 1 per cent. in the red portion of the spectrum. If he now assumes the

¹ Lummer and Pringsheim, *Phys. Zeitschr.*, 3, No. 11, 1902, p. 233.

² Kurlbaum, *Phys. Zeitschr.*, 3, No. 15, p. 332.

value of transmission found by Lummer and Pringsheim, 80 per cent., and applies this correction to his previous value of the temperature, 1430° C., there appears to be an error of only 7° . He therefore concludes that the error to which his attention has been called, is of no importance.

The work which follows in the present paper shows that the value of Lummer and Pringsheim for the transmission of the candle flame is much too small; that, nevertheless, their criticism of Kurlbaum's method is of considerable importance; that Kurlbaum's statement to the effect that the carbon particles in a luminous flame radiate more selectively than bright platinum, is correct; and that the value of Lummer and Pringsheim for the wave-length of the maximum in the energy curve for the candle flame is in error.

It is a well-known fact that the horizontal distribution of light of an ordinary illuminating gas flame varies but a few per cent., showing that the flame is practically transparent for visible radiations. According to Kurlbaum,¹ the transparency in the infra-red is even greater. Although his observations were made with carbon at ordinary temperatures, the shifting of the maximum absorption toward the longer waves with increasing temperature, as shown by Koenigsberger,² would probably not be sufficient to make the transparency in the visible greater than that in the infra-red.

We know, too, from Kirchoff's Law, — the ratio of the emissive to the absorbing power for any wave-length of a body at any temperature is equal to the emissive power of a black body at the same temperature and wave-length — that the maximum absorption for carbon at the temperature of the acetylene flame is at least less than 1.05μ ; for this wave-length, at which I have found (see below) the energy of the acetylene flame to be a maximum, should lie between the wave-length of the maximum absorption of the flame and the wave-length of the maximum emission of a black body at that temperature. And, assuming as correct the temperature determined by Nichols,³ 1900° C., this latter wave-length is about 1.35μ .

From these two facts, viz., that the maximum absorption of these luminous particles is probably not beyond the visible and certainly

¹ Kurlbaum, *Annal.*, 67, 1899, p. 846.

² Koenigsberger, *Annal.*, 4, 1901, p. 796.

³ Nichols, *Phys. Rev.*, X., 1900, p. 234.

at a much less wave-length than 1.05μ , and that an ordinary gas flame absorbs very little visible radiation, we can conclude that the absorption of any wave-length (the ultra-violet excepted) by the luminous particles of a flame is quite small. This would indicate that the movement of the maximum in the spectral energy curves of different luminous flames would depend almost entirely upon the temperature, for the amount of carbon present in any ordinary flame is too small to affect appreciably this maximum by its selective absorption. If this is true, the formula, $\lambda_m T = A$, should also apply to luminous flames, provided the constant A is determined for some flame of which the temperature is known.

Before taking up this application of the formula, I shall give an account of some experiments undertaken to give a more definite knowledge of the absorption of the acetylene flame.

THE ABSORPTION OF THE ACETYLENE FLAME.

At one end of a photometer bar about 6 meters in length, I mounted two burners, giving cylindrical flames 3.5 cm. in height and about 3.5 mm. in maximum diameter, upon a support which could be revolved about an axis midway between the two flames. These burners were 3 cm. apart. At the other end of the bar was placed a flat jet Naphey burner, its flame being about equal in intensity to the sum of the other two. The readings were made with a Bunsen photometer. By revolving the upright holding the two burners, the intensity of the two cylindrical flames, as compared with the flat flame, was observed in three cases: First, one cylindrical flame behind the other; second, the two side by side; third, the reverse of the first. The adjustments had to be made with great care as a very slight error in setting would produce a large error in the result. Representing the intensity of the light, relative to that of the flat flame, by I , and indicating the observation, as numbered above, by the subscript, the percentage absorption of such a cylindrical flame would be

$$\frac{I_2 - \frac{I_1 + I_3}{2}}{\frac{I_2}{2}}.$$

The results obtained from one series of observations were 4.5 per cent., 2.4 per cent., 2.7 per cent., and 4.7 per cent., and the average 3.6 per cent. Two days later with a new adjustment, and by computing after averaging all the readings obtained, the result was again 3.6 per cent. Several errors enter into this determination, but all tend to increase the apparent absorption. There is a reflection of the light of one flame from the carbon particles and also from the hot gases in the other, and the latter flame also acts as a diverging lens. It is sufficient for our purpose to know that the actual absorption does not exceed, at the most, 3 or 4 per cent.

As the acetylene flame is quite rich in carbon, the small percentage here obtained, viewed in the light of the remarks made above, assures one that the formula, $\lambda_m T = A$, should apply to flames in which the source of radiation is incandescent carbon. Of course there are present emission bands due to H_2O and CO_2 . But, fortunately, all these bands are at wave-lengths greater than 1.4μ , and hence have no influence on the position of the maximum in the energy curves, excepting with flames whose temperature is considerably lower than the gas flame, *e. g.*, the candle flame.

THE APPLICATION OF $\lambda_m T = A$ TO LUMINOUS FLAMES.

In order to test the correctness of applying $\lambda_m T = A$ to luminous flames, I shall consider the energy curves for the candle and illuminating gas flames, finding the value of A from previous work on the acetylene flame. These energy curves were found with the same apparatus, mirror spectrometer, radiometer and fluorite prism, as in the case of the acetylene flame.¹ The adjustment was tested by means of the CO_2 band at 4.4μ , and no error was found in the measurement of wave-lengths.

The Acetylene Flame. — In Fig. 1, a portion of the observed curve of a cylindrical acetylene flame is reproduced from my previous article. Curve 1 is the observed curve, and Curve 2, the correct one, is obtained by applying Paschen's equation,

$$af(x) = F(x) - \frac{1}{6} F_1(x),$$

where a is the slit width of spectrometer and radiometer in wave-lengths.

¹ PHYSICAL REVIEW, XIII., 1901, p. 257.

$f(x)$ is the intensity of the wave-length x on the corrected curve.

$F(x)$ is the intensity of the wave-length x on the uncorrected curve.

and
$$F_2(x) = \frac{F(x+a) - F(x-a)}{2} - F(x).$$

In a later article I hope to give experimental justification of the correctness of Paschen's method as opposed to the one I used in my previous article.

The maximum point on the corrected curve is 1.05μ .

Fig. 1.

The Gas Flame. — In Fig. 2, Curve 2, is shown the spectral energy curve of a cylindrical flame of illuminating gas. Curve 1 is the observed distribution of energy. That the observations were made with a fair degree of accuracy, is readily seen by the appearance, in proper proportion, of the emission bands of H_2O at 1.46μ and 1.90μ in the corrected curve.

The maximum value of the intensity occurs at 1.13μ .

The Candle Flame. — The energy curve of the candle flame is

very difficult to obtain with accuracy on account of the great variation in the intensity of the flame itself and the change of its proper

Fig. 2.

Fig. 3.

position in front of the spectrometer slit. In Fig. 3 are shown three observed curves. When these curves are corrected, the aver-

age maximum is about $1.4\ \mu$, and the corrected curves clearly show that the position of this maximum is influenced by the H_2O band at $1.46\ \mu$. If one makes allowance for this band, the average maximum of curves due to the incandescent carbon alone, appears to be about $1.25\ \mu$. So far as I am aware, the only previous work on the energy curve of the candle flame is that of Lummer and Pringsheim in the articles cited at the beginning of this paper. They give no observations whatever, merely stating that the maximum occurs at $1.5\ \mu$. This is about the value found on my uncorrected curves.

Temperatures Computed from $\lambda_m T = A$.—In order to find the value of A in the case of luminous flames, I assume the temperature of the acetylene flame to be 1900°C ., found by Nichols in an article already cited, and the wave-length of the maximum of its energy curve to be $1.05\ \mu$. A becomes 1.05×2170 , or about 2282.

Computing T from the wave-lengths of the maxima for the gas and candle flames, $1.13\ \mu$ and $1.25\ \mu$ respectively, I find that with the former T is 2020°abs. , or about 1750°C ., and with the latter, T is 1825°abs. , or about 1550°C . In the paper already mentioned, Nichols finds the temperature at the center of the luminous sheath of a flat gas flame to be 1780°C ., and the temperature of the surface of the luminous cone of a candle flame to vary from about 1400°C . to 1675°C ., depending upon the height from the rim of the cup of the candle. Judging from his results, the average temperature of the part I had in front of the spectrometer slit is about 1630°C .

The error in the value of 1430°C . found by Kurlbaum is due to his error in neglecting the reflection in comparison with the absorption. He found the reflection to be about 1 per cent., but he makes a mistake in assuming the value of the transmission of the candle flame found by Lummer and Pringsheim, 80 per cent., to be correct. My value of transmission of the acetylene is 96.4 per cent. In comparing the two flames in regard to absorption, it must be remembered that the acetylene flame is very rich in carbon, and that also the luminous portion of the candle flame does not average more than twice the thickness of the acetylene flame I used. In consideration of these facts, it seems quite probable that the transmission of the candle flame is about 95 to 96 per cent. Then,

too, the error due to the absorbing flame acting as a diverging lens, makes the apparent transmission too small. If this should make an error of 1 per cent., which is not unlikely, and if the reflection of the flame is 1 per cent., the transmission would be 96 or 97 per cent., or the actual absorption of the flame would be 2 or 3 per cent. If this estimate is approximately correct, then Kurlbaum's error is as great as stated by Lummer and Pringsheim, *i. e.*, his value is 40° to 120° too low. Even this correction does not satisfactorily account for the disagreement between the values of Nichols and Kurlbaum.

In comparing my results for the temperature obtained from the energy curves with those Nichols obtained by actual measurement, several points must be considered. He measured the temperatures by means of thermo-junctions of varying cross-section, plotted a curve with temperatures as ordinates and relative cross-sections as abscissæ, and by extrapolation found the temperature corresponding to a junction of zero cross-section. Although he does not assume a great degree of accuracy for these values obtained by extrapolation, yet the method should give fairly consistent results for different flames. I find, however, that from his results on the gas flame one can draw a different curve, apparently just as good, which gives a value of 1760° C., or 20° lower.

His temperature of 1900° C. for the acetylene flame is for the center of the luminous sheath of a flat flame, while that of 1780° C. for the illuminating gas and 1630° C. (averaged value) for the candle, are of the edge of the luminous sheath. If he had measured the temperature of the center of the luminous sheath of the gas flame, he would have found it perhaps 15° or 20° lower.

These facts indicate that, if the maxima of my curves were exactly correct, and if the formula $\lambda_m T = A$ applies to luminous flame I should get a value of the gas flame lower than 1780° C. by perhaps 20° or 30° , and for the candle flame, a value lower than 1630° C.

My value of 1750° C. for the gas flame is therefore in very good agreement with the value given by Nichols, which that of the candle flame, 1550° C. is as nearly correct as the accuracy of my observations on the distribution of the energy in its spectrum would lead one to expect.

Summary.—Lummer and Pringsheim criticise Kurlbaum's method of measuring the temperatures of flames in that it neglects the reflection in comparison with the absorption of the flames. This criticism is just.

Kurlbaum's assertion that the carbon particles in a luminous flame radiate more selectively than bright platinum, is correct.

The maxima in the energy curves of luminous flames depend almost entirely upon the temperatures of the flames, and hence the law for a black body, $\lambda_m T = A$, should be applicable to flames. The value of A is determined experimentally in the case of the acetylene flame, and found to be 2282. Then equation $\lambda_m T = 2282$ is applied to the candle and gas flames, and the values for temperatures found to agree satisfactorily with the observed values of Nichols.

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