

ART. VII.—*Upon an Optical Method for the Measurement of High Temperatures*; by E. L. NICHOLS, Ph.D. (Göttingen).

IN a previous paper\* a series of experiments upon the nature and intensity of the light emitted by glowing platinum were described. It is proposed in this article to discuss more fully the results then obtained, and to develop from them, so far as is at present possible, an optical method for the measurement of

\* On the Character and Intensity of the Rays emitted by Glowing Platinum, vol. xviii, Dec., 1879.

high temperatures. This method depends upon our ability to obtain, from results such as are recorded in Table IX of that paper, a general expression for the radiating power of any given body as a function of the temperature, or, what amounts to the same thing, to find the values of the quantities,  $A$ ,  $E$  and  $I$ , in Kirchhoff's equation

$$e = \frac{E}{A} = I \frac{w_1 w_2}{s^2} \quad (1)$$

These quantities being given, the temperature of a source of light could be determined by comparing the intensity of portions of its spectrum—as for instance those lying between  $\lambda$  and  $\lambda + d\lambda$ ,  $\lambda'$  and  $\lambda' + d\lambda'$ ,  $\lambda''$ , and  $\lambda'' + d\lambda''$ , &c.—with the corresponding wave lengths of the spectrum of a body of known temperature and of known emissive and absorptive capacity. Here, as in my former paper, are to be understood by the terms “absorptive and emissive capacity,” the qualities  $A$  and  $E$ , as defined by Kirchhoff.\* Such a method, even though its accuracy be limited to that attainable in other spectrophotometric determinations, would bring into the field of quantitative research, a domain in which, so far as temperature is concerned, accurate measurements have been hitherto unattainable.

M. Crova, in *Comptes Rendus*, has suggested a similar method. He gave, however, no measurements of glowing temperatures upon which to base his method, and ignored entirely the very serious difficulties to be overcome before it can be made practically available. M. Crova proposes the following three modes of procedure :

1. “Au moyen de la longueur d'onde de la radiation qui limite le spectre vers le violet.”†

2. “Par la position du maximum calorifique du spectre qui se rapproche d'autant plus du violet que la température d'émission est plus haute.”

3. “Au moyen du rapport de l'intensité lumineuse d'une radiation déterminée  $\lambda$ , pris dans le spectre de la source, à l'intensité de cette même radiation du spectre d'une source de température connue, comparée au rapport des intensités lumineuses d'une autre radiation  $\lambda'$  dans ces deux mêmes spectres.”

“ . . . . La mesure vigoureuse des températures pourra être faite par voie spectrométrique dès que l'on connaîtra la loi exacte de l'émission pour toutes les radiations et des constantes numériques pour chaque longueur d'onde. . . . ”

In the first method, the visible spectrum is falsely assumed to have a clearly defined boundary at its end nearest the violet.

\* Kirchhoff, Untersuchungen über das Sonnenspectrum, Anhang, § 2.

† Crova, Etude spectrométrique de quelques sources lumineuses; *Comptes Rendus*, lxxxvii, 322.

In point of fact the "*limit of the spectrum*" admits (see vol. xviii, p. 400) of no sharp determination, depending as it does upon the constantly varying condition of the observer's eye.

If, as is commonly supposed, the position in the spectrum of the thermal maximum were a function of the temperature, the second method would be at best practically applicable to but a few of the most intense sources of light. Some recent discoveries of Dr. Jacques in Baltimore,\* seem to show that the position of the thermal maximum depends upon the molecular weight of the glowing body, and that, for a given source of light, its position is in no way affected by a change of temperature. This newly discovered fact renders Crova's second method useless. I shall show presently that aside from Jacques' experimental evidence there are good reasons for supposing the position of the thermal maximum to depend upon the nature of the glowing body rather than upon its temperature.

The third method coincides with that which I have proposed. The chief difficulty in the development of it lies in the varying values of the emissive and absorptive capacity of different bodies.

In Equation (1) the fraction  $\frac{E}{A}$  is to be sure independent of the nature of the body in question; not so, however, the quantities  $E$  and  $A$ , considered separately. That  $A$ , possesses for different substances widely different values we know from former researches. Hitherto, however, these experiments have been confined to ordinary temperatures, and the question of the dependence of this quantity upon the temperature has been for the most part neglected.

For the purposes of general discussion it is convenient to divide all bodies into four classes.

I. Bodies for which  $A = \text{Constant}$ , for all wave lengths and for all temperatures.

II. Bodies for which  $A$  varies with the temperature, but has the same value for all wave lengths.

III. Bodies for which  $A$  varies with the temperature and possesses different values for different wavelengths, but for which the ratio of these values in any two spectral-regions  $\lambda$  to  $\lambda + d\lambda$  and  $\lambda'$  to  $\lambda' + d\lambda'$  is independent of the temperature.

IV. Bodies for which  $A$  varies with the temperature and wave length and for which the above-mentioned ratio is also a function of the temperature.

Black bodies are, by definition, of the first class. Whether bodies exist for which  $A = \text{Constant} < 1$ , can only be determined by special experiment. To the second class belong

\* Distribution of Heat in the Spectra of various sources of Radiation. Cambridge, 1879.

bodies which absorb all colors in equal proportion. They appear colorless when nearly transparent, white or gray when opaque, according to the intensity of the light falling upon them and to their reflecting power. That many transparent bodies belong to this class and not to class I, is evident from the fact that although they remain transparent and colorless at temperatures above that at which metals are red hot, it is possible by heating them still further to cause them to glow brightly. Such a change in the power of emission corresponds to an increase in absorptive capacity.

That in general the absorptive capacity of other than black bodies cannot be a constant quantity may be inferred from the usual equations for the intensity of the reflected ray. Let the body in question be opaque. Of all rays falling upon it one portion will be reflected, the remainder absorbed. It has however been proved that such bodies are in general transparent when taken in sufficiently thin layers. The rays must therefore instead of being converted into heat at the surface, force their way to a certain depth into the interior of the body, and we are justified in assuming that refraction occurs. Let  $r$  be the angle of refraction, and  $i$  the angle of incidence of a certain pencil of light falling upon the substance. Let the intensity of the incident ray = 1. Whatever the character of its vibrations—provided only that in accordance with the accepted theory they be transversal—the ray can be resolved into two components, the one polarized in the plane of incidence, the other perpendicularly to it. Let  $e_p$  and  $e_s$  be the amplitudes of these components the intensities of which are denoted by  $f_p$  and  $f_s$ . Then

$$f_p = e_p^2, \quad f_s = e_s^2;$$

The amplitudes of the reflected portion of the component  $e_p$  will be

$$B_p = e_p \frac{\sin(i-r)}{\sin(i+r)} \quad (2)$$

and its intensity,

$$R_p = f_p \frac{\sin^2(i-r)}{\sin^2(i+r)} \quad (3)$$

The amplitude of the other part of the reflected ray will be

$$B_s = e_s \frac{\tan(i-r)}{\tan(i+r)} \quad (4)$$

and its intensity

$$R_s = f_s \frac{\tan^2(i-r)}{\tan^2(i+r)}. \quad (5)$$

The expressions (3) and (5) approach 0 as a limit when the values of  $r$  and  $i$  are made to approach each other. In other words, when the optically denser medium becomes less dense

the intensity of the reflected ray diminishes, and a larger portion of the incident ray is absorbed.

We know that in the case of liquids their refractive index increases with their physical density, and that generally it changes for other bodies with change of temperature. The change in the index of refraction is however equivalent to a change of optical density and of the quantity  $(r-i)$ ; so that we may expect, for all bodies for which Fresnel's formula holds, a change in the intensity of the reflected ray and consequently of the absorptive capacity for every change of temperature.

Those substances, at the surfaces of which so-called "metall reflexion" occurs, are not included in his argument, since the formulæ do not apply to them. They would have to be considered in the lack of further knowledge as possible exceptions to the law.

For such bodies MacCullagh,\* making use of the hypothesis of an imaginary angle of refraction, assumed for  $r$  the following expression :

$$\begin{aligned}\sin r &= \frac{\sin i}{m} \cos \chi + \sqrt{-1} \sin \chi. \\ &= \frac{\sin i}{n} (\cos^2 \chi + \sin^2 \chi)\end{aligned}\quad (6)$$

which admits of the common definition of  $n$

$$n = \frac{\sin i}{\sin r},$$

since even for an imaginary angle,

$$\cos^2 r + \sin^2 r = 1.$$

In a similar manner MacCullagh assumes

$$\cos r = \frac{\cos i}{m'} (\cos \chi' + \sqrt{-1} \sin \chi'), \quad (7)$$

where  $m'$  and  $\chi'$  are functions of  $m$  and  $\chi$ .

Substituting these values in equation (3) we obtain,

$$R_p = r^2 \frac{(m'^2 - m^2)^2 + 4m'^2 m^2 \sin^2 (\chi - \chi')}{(m^2 + m'^2 + 2m' m \cos (\chi - \chi'))^2}$$

To cause  $R_p$  to disappear we must set  $m = m'$  and  $\chi = \chi'$ . MacCullagh determined experimentally the values of  $m$  and  $\chi$ , but I know of no researches from which to draw any conclusions concerning the influence of temperature upon these quantities.

Cauchy† gives for  $R_p$  the following expression,

$$R_p = f_p \frac{\sin^2 (i - r) + \gamma^2 \sin^2 r}{\sin^2 (i + r) + \gamma^2 \sin^2 r}, \quad (9)$$

\* MacCullagh, Proceedings of the Irish Academy, i, 2, 159; ii, 375.

† Cauchy; Comptes Rendus, ii, 427; viii, 553-558; ix, 727; xxvi, 86.

making use of the hypothesis that the intensity of the refracted ray within the metal, diminishes in geometrical progression from the surface inward. Here as in the equations for ordinary reflected light,  $R_p$  depends upon the quantity  $\sin(i-r)$ . In what manner  $r$  is influenced by change of temperature has never been experimentally determined.

I have found, experimentally, the value of  $A$  for platinum at  $1650^\circ\text{C}$  (of the Pt. thermometer). At this temperature the spectrum afforded by glowing platinum is similar as regards the relative intensity of its various wave lengths to that of the flame of a petroleum lamp. Such a lamp-flame, the luminous rays being emitted by hot particles of carbon, answers most nearly of any available source of light the definition of a black body glowing at a constant temperature.

A flame of this kind is far from being opaque. It is quite possible under proper conditions to read fine print through it, so that in this respect the flame differs from a perfect, "*black body*." I measured in the following way the transparency of the petroleum flame which I wished to use in the experiments about to be described.

Suppose such a flame to be brought into position before the spectrophotometer so that a certain pencil of rays would fall upon the slit. Were the flame perfectly transparent, a second precisely similar one and equally bright would, if placed behind the first flame, double the intensity of the above mentioned pencil of rays. Were on the other hand the first flame perfectly opaque, all rays reaching it from the second flame would be cut off, and the light arriving at the slit would suffer no increase in brightness.

The nearest approach to a second precisely similar flame is the real image of the first one. This image would be, when of the same size, of weaker intensity than the flame itself; but its other properties should, provided the mirror absorb all wave lengths of light in equal proportion, coincide perfectly with those of the flame.

I illuminated both halves of the slit of the spectrophotometer with two common petroleum lamps with *flat* burners. Before the lower flame, was adjusted a system of cross-wires, of which the horizontal ones appeared as dark lines in the polarized spectrum. By means of these it was easy to tell which portion of the flame came into the field of vision. Behind this lamp I placed a concave mirror, so that a real image of the flame was cast upon the flame itself. This image was of the same size but weaker than the flame. Since the horizontal wires appeared in the spectrum of the image as well as in that of the flame, forming another set of black lines, it was possible to adjust the mirror so that corresponding portions of flame and

image coincided. The spectrum formed by the two combined was much brighter than that of the flame alone, and it was easy, having measured the increase of intensity due to the image, to calculate how much of light reflected by the mirror and falling upon the flame, was absorbed, and how much allowed to pass through it. In making this calculation it was necessary to know: the reflecting power of the mirror, the transmitting power of the lamp chimney, and the relative intensity of the spectrum of the flame to that of the flame and image combined.

First of all the transmitting power of the lamp-chimney was investigated. The lamp having been provided with an exactly similar chimney, the spectrophotometer adjusted and the spectrum of this lamp flame having been compared with that of the flame lighting the upper half of the slit, the chimney to be examined was suspended in the path of the rays between the flame and slit, whereupon the spectra were again measured. I found that the chimney permitted the passage of 0.8573 of the light. Then the mirror was taken in hand. The lamp being moved a few centimeters to one side and the mirror turned until the image of the flame occupied the former position of the flame itself; the intensity of the resulting spectrum was measured. This gave as illuminating power of the image, 0.6509 of the flame's intensity. The lamp was then restored to its place before the slit and the mirror readjusted until those portions of the flame and image which appear in the spectral image coincided. The spectrum of this double source of light was then measured, and by repeated intervention and withdrawal of a black screen between the lamp and mirror, compared with the spectrum of the flame above. I found the ratio of flame and image combined to the flame alone, to be 1.2075 : 1. Had both flame and lamp-chimney been perfectly transparent, this ratio would have been 1.6509 : 1. The effect of the lamp-cylinder being eliminated the remaining difference is naturally to be attributed to the absorptive capacity of the flame; and we find  $A = 0.6432$ .

To determine the value of  $A$  for platinum at the temperature in question, it only remained to compare the radiation of a glowing platinum wire with that of the flame. The wire having been given a temperature of 1650° (Pt. thermometer) for which the leucoscope\* showed that the quality of the light emitted corresponded precisely with that from the petroleum-flame, the intensity of its spectrum was measured and found as compared with that of the flame to be as 1.198 : 1.

The value of  $A$  for platinum at this temperature is accordingly,  $A = 0.7597$ .

\* For the method by which the platinum wire was made to glow, and for a description of the leucoscope, see Paper I.

De la Provostaye and Desain\* give as the reflecting power of cold platinum for lamp light (unpolarized), 0.677, so that for this metal when cold,  $A = 0.323$ .

The difference between these values is so large, that making all reasonable allowance for the inaccuracies of both researches it seems certain that *platinum at 1650° has a much greater absorptive power for the rays of the visible spectrum than at ordinary temperatures.*

This experiment shows that platinum at least, of those substances affording metallic reflexion, offers no exception to the general law deduced for other bodies, viz: that  $A$  and  $E$  are functions of the temperature. The nature of this function, and the dependence of  $A$  and  $E$  upon the wave-lengths of the rays in question must be made the subject of special and extended investigation. It is an unexplored domain. Almost the only researches which give substance for a probable surmise, are those of Jacques already mentioned. The fact that the position in the spectrum of the maximum of thermal intensity is a function of the nature of the glowing substance and independent of its temperature, points to the conclusion that *solid bodies belong to the first three classes.*

The effect of temperature upon the spectra of gases has already, thanks to the interest lent to this subject by its importance in Spectrum Analysis, attracted much attention, and the existing researches admit of no doubt that in general *the gases belong to the fourth class.*

The steps necessary to the application of the results of the first article to the proposed method of measuring high temperatures are now evident. A general law for the changes of the quantity  $A$  must be experimentally determined, or failing in this, its values found for the various glowing bodies it is most desired to measure. It will then only remain to subject the results in Table IX (Paper I) to a further reduction so that they may be made to express the effect of temperature upon the rays from an ideal "black body" instead of those emitted by glowing platinum; and finally to obtain a satisfactory comparison of the platinum thermometer with the scale of the Centigrade air thermometer. Experiments to this end are in preparation by the author.

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\* De la Provostaye et Desain, Comptes Rendus, xxxi, p. 512; also, Annales de Chimie et de Physique, III, xxx, 276.

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