THE QUANTITATIVE DETERMINATION OF RADIANT HEAT BY THE METHOD OF ELECTRICAL COMPENSATION.[1]

By Knut Ångström.[2]

I.

THE older methods for the absolute determination of radiant heat, the methods of the pyrheliometer and actinometer, had two principal faults: they were neither accurate nor sensitive enough. They were, moreover, almost exclusively intended for the measurement of the radiation from the sun, and were not well adapted for the precise determinations frequently demanded at the present day in the physical laboratory. The great progress which has been made within the last fifteen years in the construction of instruments for relative measurement, such as the thermopile, bolometer, and the radiomicrometer, have been followed by very important investigations upon radiant energy. It is necessary to recall only the fundamental labors of Langley and the brilliant series of memoirs by Julius, Robert von Helmholtz, Rubens, Snow, and others. The investigation of radiant heat has taken an important place in the physical progress of the present day, and for that reason the need of a good method of quantitative measurement is strongly felt.

Such a method, by means of which relative measurements may be converted into quantitative ones by simultaneous observations of a given source of heat with two instruments, I described in 1885.[3] I have made use of the same continually since that time in my bolometric work, and can but emphasize its exactitude and reliability. In the comparative studies of different actinometric

[1] From the Transactions of the Royal Society of Sciences, Upsala, 1893.

[2] Translated for the Review by E. L. N.

[3] K. Ångström, Acta Reg. Soc. Ups., 1886. See also Bihang till K. Vet-Akad. Handlingar, 15, No. 10, 1889, and Wiedemann's Annalen, 39, p. 294, 1890.

methods carried on by Mr. Chwolson,[1] the advantages of this method have been clearly demonstrated. While, on the one hand, I regard, therefore, the problem of the quantitative measurement of radiation as solved, it must be said, on the other, that differential pyrheliometers leave something to be desired as regards simplicity and convenience of operation. In order to compare this, my older method, with the one to be described below, permit me to refer briefly to the former.

Two circular plates of massive copper serve as calorimeters; the blackened faces of the same are exposed alternately to radiation, and one observes the time at which the difference of temperature (θ) changes sign. This difference of temperature is determined by means of a thermo-element and a mirror galvanometer. If W is the water equivalent and A the absorbing surface of the calorimeter plates, then it is plain that the quantity of heat which is absorbed by a unit of surface is expressed by the equation

$$Q=\frac{2\,\theta W}{AT},$$

and that by this arrangement of observations the consideration of rate of cooling is eliminated.

II.

The principle of the new method is briefly as follows: Given two thin strips of metal, A and B, Fig. 1, which are as nearly as possible identical. The sides of these, which are exposed to the source of heat, are blackened, and the strips are arranged in such a way that it is possible to determine accu-

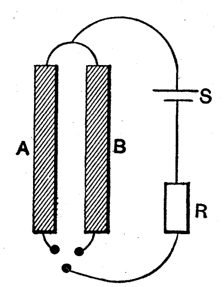

Fig. 1.

[1] O. Chwolson, Rep. für Meteorologie, 15, pp. 1–166; also 16, pp. 1–150. The former treatise contains a theoretical and critical discussion of actinometric procedure; the latter, a full account of my own method, including some attempts to devise a convenient apparatus, making use of the same, for meteorological purposes. Although both researches have as their chief aim the measurement of the radiation of the sun, they are of great interest from the point of view of general study of radiant energy. The success of the author's modifications of the method need not concern us here. Upon another occasion I hope to discuss both of these important papers in detail.

rately when they are of the same temperature. These strips are so placed that a current of any desired strength can be sent through them. If one of them, for example, A, is exposed to the source of heat, while B is protected by a screen, we may restore the balance of temperature which has been disturbed by the absorption of heat on the part of A, by sending a current of proper intensity through B. When the temperatures are the same, then the amounts of energy which A and B have received are equal to one another. Let l and b be the length and width of the strips, r the resistance of the same, and i the current. Then since the heat absorbed by A is the equivalent of that produced by the electric current in b, we may write

$$qlb = \frac{ri^2}{4 \cdot 2}, \text{ or } q = \frac{ri^2}{4 \cdot 2\, lb},$$

where q is the radiant energy received by a unit of surface. In order to counteract the inequality of the strips, they are interchangeable, B being illuminated and the current sent through A. In order to compare the two methods, the operations necessary in each to a complete measurement of radiation are tabulated below.

A. Constants to be determined once for all.

THE OLD METHOD. (*The Differential Pyrheliometer.*)	THE NEW METHOD. (*Method of Compensation.*)
1. Determination of the water equivalent of the calorimeter plates.	1. Determination of the electrical resistance of the strips.
2. Determination of the absorbing surface.	2. Determination of the absorbing surface.

B. Observations to be made during each experiment.

1. Determination of the time within which the temperature differences of the calorimeters change sign.	1. Adjustment of the two strips to equal temperature.
2. Calibration of the thermo-element in degrees.	2. Measurement of the current.

This comparison appears to me to be favorable to the new method. The measurement of resistance is more rapidly and conveniently carried out than the determination of the specific heat of the plates of the calorimeters, and as regards the determinations which are to be made during each experiment, it is much easier to make the adjustment to equal temperatures than to carry out the tedious determination of the time. The last operation requires a more skilled observer. The determination of current strength is doubtless of about the same difficulty as the calibration of the thermo-element in degrees. Since both of these measurements are ultimately dependent upon the constant of the instrument for the measurement of current, it seems to me that here also the new method is to be preferred, because that instrument does not need to be of so high a degree of delicacy, and consequently its figure of merit is more easily determined.

III.

In the practical application of this principle of compensation, one may follow various methods. The equality of temperature may be determined in a variety of ways. If thermo-elements

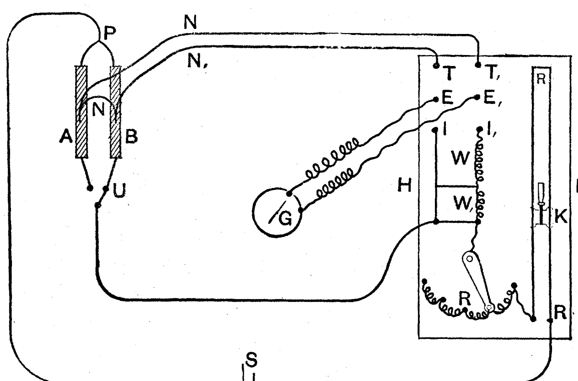

Fig. 2.

are used for this purpose, one needs a sensitive galvanoscope, and the measurement of the current can be made upon an instrument of ordinary delicacy. It is possible, however, to carry on the investigation without any difficulty, using only one galvanometer, a plan which I pursued in the case of the first apparatus which I constructed. Fig. 2 gives a diagram of the connections, while Figs. 3, 4, 5, and 6 show more in detail the arrangement of the apparatus. The metallic strips, A and B, cut simultaneously from two thin sheets of platinum laid one upon another, are 0.154 cm. wide and 1.80 cm. in length. They are blackened in the usual way upon the side exposed to radiation, and are mounted

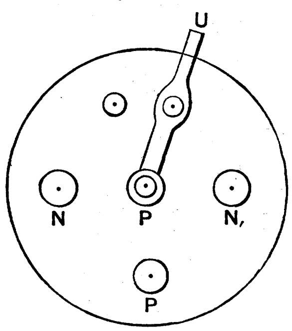

Fig. 3.

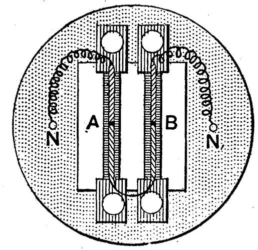

Fig. 4.

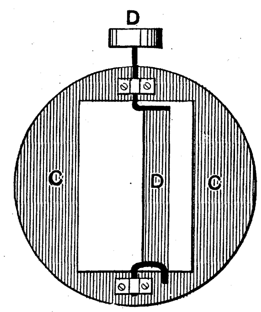

Fig. 5.

side by side in a frame of ebonite (Fig. 4). This frame is inserted in a tube, as is shown in Fig. 6. Upon the back of the strips are laid two exceedingly thin leaves of mica, upon which the very minute junctions of copper and German silver, NN_1, are inserted (see Fig. 4). To hold the mica and the thermo-junctions together, I used marine glue in as thin a layer as possible. Mounted upon

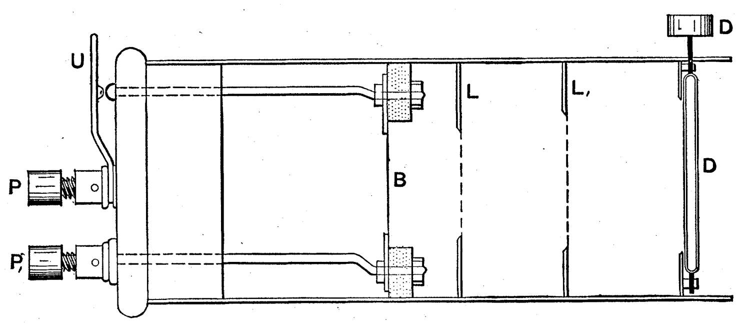

Fig. 6.

the block, Fig. 2, is a rheostat, a resistance WW_1, which serves as a shunt for the galvanometer G, and the commutator TEI. The rheostat has a sliding contact, K, by means of which the resistance can be varied at will. In this way the current from the battery, S, usually a Daniell's cell, is indirectly controlled.

One of the strips is subjected to radiation; the circuit is then closed through the other one; the thermo-element is brought into circuit with the galvanometer by means of the commutator; the sliding contact is adjusted until the galvanometer stands at zero; the commutator is then reversed, and the strength of the current used in heating the strip is determined. The switch, U (Fig. 3), is then reversed, the shutter is placed in front of the other strip, and the setting and current measurement are repeated. There are two other ways in which one can use this apparatus for the measurement of radiation, viz.:—

First Variation of the Method.—One of the strips, for example, A, is exposed to radiation, while the other is screened. One notes the deflection of the galvanometer, which becomes constant in about fifteen seconds. A is then also screened, and by means of the current is brought to the same temperature to which radiation had previously brought it. The strength of the current producing this rise of temperature is then measured. The advantage of this arrangement is that the same strip is warmed by means of radiation and then through the agency of the current, so that it is not necessary to be so painstaking as regards the identity of the two strips.

Second Variation of the Method.—One of the strips, for example, A, is exposed to radiation, the other, B, is screened; the deflection of the galvanometer is observed after the thermo-current has become constant. The quantity of heat which A has received is calculated from Newton's law of cooling,

$$Q = blq = k\theta,$$

where θ is the difference of temperature indicated by the galvanometer, and k is the constant of cooling of the strip. If we now send a current through A, without making any change of conditions, the difference of temperature will become greater still. This will be indicated by the resulting deflection θ_1. The strength of the current producing this additional heating effect may be measured in the manner already described. The amount of heat added to the strip is

$$Q_1 = blq + \frac{ri^2}{4 \cdot 19} = k\theta_1,$$

from which equations we find

$$q=\frac{i^2r\theta}{4\cdot 19(\theta_1-\theta)bl}.$$

When the experiment is performed in this way, it is not necessary to have an arrangement for the adjustment of the intensity of the current. The greatest advantage is, however, that the use of a screen may be avoided. This is perhaps the only method by means of which the screen, the use of which is always open to suspicion, can be eliminated.

IV.

As an example of the application of the new method, the following determinations of the radiation from an argand lamp may be of interest. In front of the lamp a double screen was set up so that the rays could reach the apparatus only through a hole 2.4 cm. in diameter. The distance between the strips and the middle of the flame was 60 cm. The other constants of the apparatus were as follows: Absorbing surface of each strip, .277 $\overline{\text{cm.}}^2$; resistance of A, 0.172 ohms; resistance of B, 0.176 ohms; reduction factor of the galvanometer (with shunt), 0.00122 amperes.

(*a*) *Experiment using the zero-method.*

Heating current of compensation:

(1) When A was subjected to radiation,	49.8	s.d.
(2) " B " " " "	49.7	"
Mean,	49.75	"

This reading corresponds to 0.0607 amperes, from which the radiation may be computed from the equation

$$q=\frac{\overline{0.0607}^2\times 0.174}{4.19\times 0.277},$$

$$=0.000552 \text{ gram-calories per second per } \overline{\text{cm.}}^2$$

(*b*) *Experiment following the first modification.*

The strip A was subjected to radiation. The deflection of the galvanometer due to the thermo-current was 44.0 s.d. The strength of current necessary to bring about this rise of temperature was 49.5 s.d. = 0.0604 amperes, from which the following value of q was computed, viz.: —

$$q = 0.000541 \text{ gram-calories per second per } \overline{\text{cm.}}^2$$

(*c*) *Experiment following the second modification.*

The strip A was subjected to radiation. The galvanometer gave a deflection, due to the thermo-current, of 45.5 s.d. Upon closing the circuit of the heating current, the deflection rose to 91.5 s.d. The intensity of the current was 50 s.d. = 0.0610. The radiation was computed by means of the equation

$$q = \frac{\overline{0.0610}^2 \times 0.172 \times 45.5}{4.19 \times 0.277 \times 46.0},$$

from which we find $q = 0.000546$ gram-calories per second per $\overline{\text{cm.}}^2$

From what has been said it will be seen that the determination is an extraordinarily simple one. When the constants of the instrument are known and the figure of merit of the galvanometer, the whole measurement can be made with great exactness in a few minutes. If it is desired to take into consideration the change in resistance due to heating, it is only necessary, after an adjustment to zero, to open the circuit with the strip still exposed to radiation. From the deflection then produced, the temperature of the strip can be determined with sufficient exactitude. Thus far we have considered only the heat which is received by the instrument, without taking into account the absorbing power of the surface. In the method just described, as in the case of all other methods, it is necessary for exact measurements to determine the coefficient of absorption. No very good method for estimating this constant exists, but it is possible to obtain surfaces which possess the same absorbing power within the errors of observation; that is to say, within about 98 per cent. In most cases, therefore, the determination of this quantity may be neglected. In conclusion, I hope that the method outlined in this paper will be found to afford a means for the quantitative measurement of radiation, sufficiently simple, rapid, exact, and sensitive. In this brief note I have merely indicated the principle of the method; later, after a more thorough investigation, I purpose to give a fuller description of it.