vary with the temperature, which fact renders their exact determination for high temperatures a difficult operation. Determinations of $E$ at high temperatures have been made for liquid copper, 0.14; iron, 0.29; cuprous oxide, 0.60.

There is room for a great deal of experimental work in determining satisfactorily the emissive properties at high temperatures of those substances met with in pyrometric practice.

# CHAPTER VII.

## RADIATION PYROMETER.

**Principle.** — The quantity of heat a body receives by radiation from another body depends on certain conditions relative to each of the two bodies, which are:

1. Temperature;
2. Area of surface;
3. Distance apart;
4. Emissive and absorbing power.

In order to utilize heat radiation for the determination of temperatures, one measures a heat change produced on the object used as an instrument by the object to be studied; this heat change is either a rise of temperature or a resulting phenomenon, such as a change of electrical resistance, thermoelectromotive force, expansion, etc.

The quantity of heat given off is proportional to the area of the radiating surface $S$, and varies inversely as the square of the distance $l$.

$$q = k\frac{S}{l^2} = k'\frac{d^2}{l^2} = k''E\cdot\frac{d^2}{l^2},$$

$d$ being the diameter of the radiating surface and $E$ its emissive power.

Now, $\frac{d}{l}$ is the apparent diameter of the object; the quantity of heat radiated depends, then, upon the solid angle under which the object is seen. Any instrument making use of the intensity of radiation must, therefore, have a receiving device of sufficiently small area so that it may be completely covered by the desired radiation.

The emissive power $E$ is very variable from one substance to another, as we have seen, and for the same substance variable with the temperature. It would be desirable to determine this, but that is difficult and often impossible, especially at high temperatures, although some small advance has been made in this direction for a few substances, as we have seen in the preceding chapter.

The coefficient $k''$ is a function of the temperature alone, which expresses the law of variation of the radiation with the temperature. This law should be determined in the first place. It is on the more or less exact knowledge of this law that the entire accuracy of the results depends. We have seen that Stefan's law (page 245) satisfies all requirements, at least in the case of black bodies, for the measurement of total radiation, although the early experimenters, working before the establishment of this law, were obliged to express their results empirically, and great confusion resulted from the different assumptions made.

**Early Investigators: Temperature of the Sun.** — Let us see now what are the experimental arrangements which have been used to measure the intensity of heat radiation; these earlier measurements had for their only aim the determination of the sun's temperature.

Later were developed the more elaborate and sensitive types of apparatus which were suitable also for laboratory investigations, and which were used, for example, in the experimental demonstration of the laws of radiation; and finally we have to-day several total-radiation pyrometers of simple construction which are of great usefulness both as industrial and as scientific instruments.

We shall consider in order the above-mentioned aspects of this development of total-radiation methods, noting that the early observers labored under a threefold handicap, — lack of knowledge of the temperature scale, of the radiation laws, and lack of sufficiently sensitive instruments.

*Pouillet's Pyrheliometer.* — Before Pouillet, Gasparin had already made some trials. His apparatus consisted of a hollow brass sphere mounted on a foot and blackened; a thermometer was used to measure the rise in temperature of the water contained in the sphere. The advantage of this arrangement was that the apparatus was always turned properly toward the sun.

The pyrheliometer of Pouillet consists of a calorimeter which measures directly the heat received by radiation (Fig. 91). A very thin silver box is carried by a hollow tube, cut along a generatrix to let the thermometer be seen. The box is of 100 mm. diameter by 15 mm. height; it contains 100 c.c. of water. At the lower part of the box is located a metallic disk of the same diameter as the box, and serving to turn the apparatus toward the sun; it suffices, in fact, for the shadows of the box and disk to coincide exactly in order that the system be properly pointed. A knob serves to turn the apparatus about its axis in order to stir the water. Finally a support gives the means of placing the system in any desired orientation.

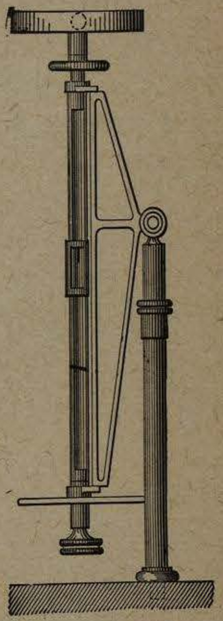

Fig. 91. Pouillet's Pyrheliometer.

To take an observation, the apparatus is set up and shielded from the sun's action by means of a screen; the readings of the thermometer are taken for five minutes; the screen is removed and the thermometer is read for five minutes; the screen is put back, and a new set of readings of the thermometer for five minutes is taken.

The first and the third sets furnish the corrections due to the surroundings. Pouillet observed in this way a rise of temperature of one degree in five minutes.

In the determination of the temperature of the sun, it was evidently necessary to take into account the heat absorbed by the atmosphere (it is about 20 per cent of the total radiation from the sun). Pouillet found by this method 1300° for the temperature of the sun.

*Violle's Actinometer.* — The principle of this apparatus is quite different from that of the preceding; one observes the stationary equilibrium of a thermometer receiving simultaneously radiation from an inclosure at fixed temperature, and that from the hot substance to be investigated (Fig. 92).

The apparatus consists of two spherical concentric coverings of brass, in which a water circulation may be set up at constant temperature, or ice may be substituted for water. The inner covering of 150 mm. diameter is blackened inside. The thermometer has a spherical bulb whose diameter varies from 5 to 15 mm.; the surface of the bulb is also blackened. The scale is divided into fifths of a degree. The entrance tube carries a diaphragm pierced with holes of different diameter; on the extension of this tube is located an opening closed by a ground-glass mirror slightly blackened, which permits of determining that the solar rays fall quite exactly upon the thermometer bulb.

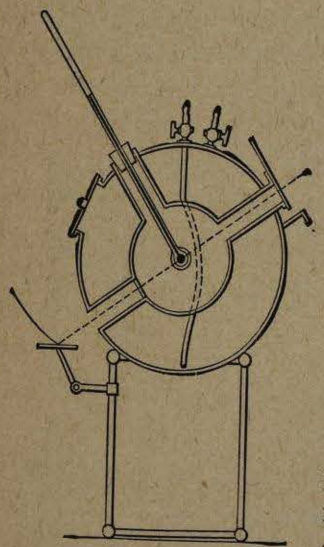

Fig. 92. Violle's Actinometer.

The establishment of the temperature equilibrium requires fifteen minutes, and the differences of temperature observed vary from 15° to 20°.

Violle found in this way, for the temperature of the sun, figures varying from 1500° to 2500°.

Pouillet and Violle made use of Dulong and Petit's law of radiation,

$$q = a^t,$$

that the discoverers had established by observations reaching only to 300°.

The constant $a$ may be determined for each apparatus by a single experiment made at a known temperature. This law, as we shall show farther on, is not exact, so that, according to the temperature used to determine the constant, a different value of the latter is found, and consequently also different values at

temperatures calculated, assuming this law to hold. This is the reason for the differences between the three figures, 1300, 1500, and 2500, of Pouillet and Violle. They correspond to determinations of the constant obtained by means of preliminary experiments made at the temperatures of 100°, 300°, and 1500°.

The elder Secchi, making use of Newton's formula,

$$q = a(t_1 - t_0),$$

still more inexact, found for the sun's temperature several millions of degrees.

*Work of Rosetti.* — The Italian scientist, Rosetti, was the first to grasp the fundamental importance of the choice of the law assumed for radiating power; he showed that a graduation made by an experiment at 300° gave for the temperature of a body heated in the oxyhydrogen flame:

46,000 if one uses the law of Newton;
1,100 if one uses the law of Dulong and Petit.

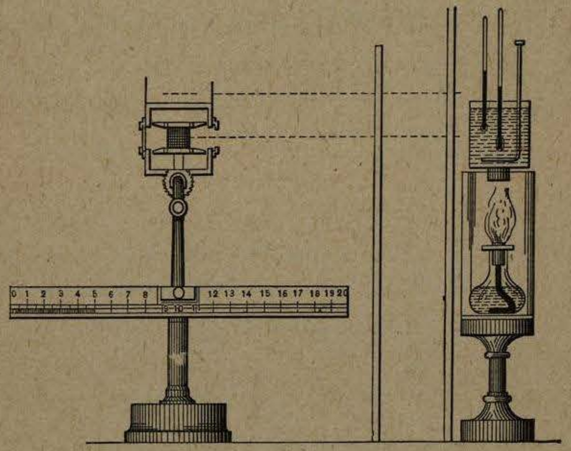

Fig. 93. Rosetti's Apparatus.

Now the temperature of the oxyhydrogen flame is about 2000°.

This physicist used a thermoelectric pile whose sensibility could be changed without touching the element; in the apparatus of Violle it is necessary, on the contrary, to change the thermometer, a proceeding which renders the observations comparable with difficulty.

The pile (Fig. 93) consists of twenty-five sheets of bismuth and antimony; these sheets are very thin, for the whole of the apparatus is but 5 mm. on a side. The whole is inclosed in a small metallic tube.

To make an experiment, there is placed before the pile a screen filled with water, which is removed at the instant of taking an observation.

A preliminary calibration made with a Leslie's cube of iron filled with mercury that is heated from 0° to 300° gave the following results:

| Excess of the temperature of the cube over the surrounding temperature. | Reading of galvanometer. |
|---|---|
| 32.8° | 10.0° |
| 112.8 | 55.0 |
| 192.8 | 141.9 |
| 272.8 | 283.5 |

Newton's law and that of Dulong and Petit giving no concordance between the numbers observed and those computed, Rosetti proposed the formula

$$Q = aT^2(T-\theta) - b(T-\theta),$$

where $T$ = absolute temperature of the radiating body, $\theta$ = the absolute temperature of the surroundings. This formula with two parameters permits necessarily a closer following of the phenomenon than a formula with but a single parameter.

| $T-\theta$. | Deflections observed. | Deflections computed. | |
|---|---|---|---|
| | | Dulong's law. | Rosetti's law. |
| 50 | $A =$ 17.2 | $A + 2.12$ | $A - 0.23$ |
| 100 | 46.4 | +0.95 | .... |
| 150 | 90.1 | −2.12 | +0.70 |
| 200 | 151.7 | +4.82 | +0.99 |
| 250 | 234.7 | +2.83 | −0.12 |

Rosetti showed later that the formula he proposed did not lead to absurd results for higher temperatures. A mass of copper was heated to redness in a flame, and the temperature was estimated by the calorimetric method (a quite uncertain method, as the variation of the specific heat of copper was not known). The two methods gave respectively 735° and 760°. This difference of 25° is less than the experimental uncertainties.

Disks of blackened metal placed in the upper part of a Bunsen flame gave, according to the formula, temperatures of the order of 1000°; oxychloride of magnesium in the oxyhydrogen blast lamp gave 2300°. All these numbers are possible.

Rosetti, using this formula, found 10,000° for the temperature of the sun, this figure resulting from an extrapolation above 300°.

**Modern Radiometric Apparatus.** — The principles most often made use of in modern receiving apparatus for thermal radiation are:

1. The generation of an electric current in a circuit composed of two dissimilar metals by the radiation which falls on one or more junctions, or the *thermopile* of Nobili, often called the Melloni thermopile, which we have just seen was used by Rosetti, and which has been in use for nearly a century, and in recent years rendered very sensitive.

2. The increase in resistance of a metallic strip, forming one or more branches of a Wheatstone bridge, due to the rise in temperature caused by the incident radiation, or the *bolometer* of Langley.

3. The deflection, by radiation, of vanes delicately mounted in vacuo, — the *radiometer* of Crookes.

There have been modifications and improvements in all of these types of apparatus, some of which we shall mention briefly, such as the combination of the thermopile and moving-coil galvanometer known as the *radiomicrometer*, due to d'Arsonval and Boys independently. They can all be used to measure temperatures when once calibrated in terms of black-body radiation, with the limitations already described in the preceding chapter or applications of the radiation laws.

It should perhaps also be emphasized at this point that for a strict application of the laws of radiation of the black body to such apparatus, not only the radiation source but also the receiver should be black. Plane surfaces covered with lamp- or platinum-black are an approximation to this condition, which may be still more closely realized, when possible instrumentally, by making the receiver conical, as done by Féry; or better, a hollow sphere with small opening, as attempted by Mendenhall; or by inclosing the sensitive portion of the receiving apparatus within a sphere brightened on the inside, as was done by Paschen; or finally, within a diaphragmed cylinder, such as used by Langley and Abbot. All of these forms of apparatus are rendered more sensitive by mounting in vacuo, and the radiometer can hardly be used otherwise; but there ensues the complication of the selective absorption of the window, which may become serious when extrapolating for high temperatures, especially if total radiation is used. The radiation of a narrow spectral band may also be used with all such apparatus, but this cuts down the sensibility enormously, and this method is hardly practicable for temperature measurements, except perhaps in very special cases in the laboratory.

Very little work has been done until recently with radiometric apparatus on the estimation of terrestrial temperatures, due perhaps to the existence of other methods of sufficient accuracy and sensibility; the radiometric methods being in practice largely reserved for investigation of the radiation characteristic of various substances at high temperatures and for the estimation of the temperature and spectral radiation of the sun, especially in the infra-red. The possibility of rendering the radiometric methods recording and the recent development of simple types of apparatus have given an impetus to their use in temperature measurements. As to the ultimate sensibility attainable with the various types of apparatus mentioned above, comparative examination by Coblentz has shown that there is very little choice in the matter, although each apparatus has its characteristics which render it more fit in certain classes of problems than the others.

*The Thermopile.* — This instrument was the earliest to be used in radiometric work, and its principle is, as we shall see, the only one, of those above mentioned, actually used in the construction of an instrument primarily designed for high-temperature measurements radiometrically. Types of multiple thermopiles are illustrated in Fig. 94. In *a* is shown the linear thermopile of Rubens of 20 junctions of 1 mm. constantan of wire about 0.1 mm. diameter with an exposed area of about 0.8 by 20 mm. The resistance can be cut down by shortening the connecting wires and the heat capacity and conduction lowered by using thinner wires of say 0.06 mm., and by making the unexposed junctions smaller than the others. These modifications, shown in *b*, are due to Coblentz. For sources of small area the form *c* may be used. A sensitive galvanometer is required whose best resistance for highest sensibility is that of the thermopile.

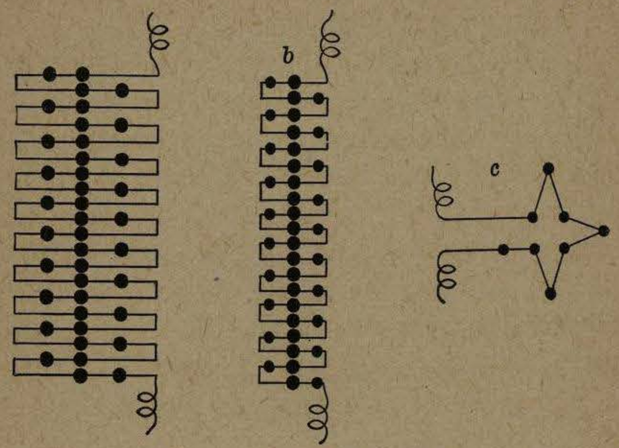

Fig. 94. Multiple Thermopiles.

Callendar has recently suggested several radio-balances for measuring radiation in absolute measure, which are suitable in certain forms for high-temperature measurement. Among these is his disk radio-balance (Fig. 95), in which heat supplied by radiations is directly compensated by the Peltier absorption of heat in a thermojunction, 1, through which a measured electric current is passed. In the simplest form of the instrument, radiation admitted through a measured aperture 2 mm. in diameter falls on a small copper disk 3 mm. in diameter by 0.5 mm. thick, to which two thermojunctions are attached, forming a Peltier cross. One couple is attached to a sensitive galvanometer *G* for