independent of the properties of any particular substance, continuous from the absolute zero to the highest temperatures that may be produced, and one that is practically reproducible for all technical and scientific purposes, by methods that are available in the several standardizing laboratories.

CHAPTER II.

GAS PYROMETER.

Introduction. — We have seen that the standard scale of temperatures adopted by the International Committee of Weights and Measures is given by a certain constant-volume hydrogen thermometer, namely that of the International Bureau at Sèvres, which instrument, however, has not been used to measure temperatures above 100° C. The type of gas thermometer which is to be considered standard for higher temperatures has not as yet been agreed upon by any authoritative body, but for reasons which we shall develop, the constant-volume nitrogen thermometer appears to have the preference, at least for temperatures above 200° C. From what we have seen in the preceding chapter, it is practically immaterial in the definition of the high temperature scale what form of thermometer is actually used, as the indications of any of the gas thermometers may readily be compared with those of another by well established methods of computation and reduced with great accuracy to a common theoretical basis, that of the thermodynamic scale.

It may be well to recall, at this point, in what consists the actual operation of the location of a temperature on the chosen gas scale, and point out, at the same time, some of the difficulties involved. The gas thermometer bulb must be brought throughout its volume to a sufficiently uniform temperature. To obtain a volume of 500 c.c. of gas, for example, constant in temperature to 1° at 1000° C. has not yet been attempted by any experimenter. Whatever the system of gas thermometry used, on account of the transient nature of the phenomenon measured, pressure on a manometer, a mass of displaced mercury, etc., it is also necessary, except in certain special cases as some boiling points, to bring to this same temperature some other body whose registrations are more permanent, such as a mercury, platinum resistance, or thermoelectric thermometer, or rarely a metal at its melting point, and finally it is practically necessary to transfer the readings of the gas thermometer by means of this auxiliary thermometer to a series of fixed temperatures such as freezing and boiling points. The gas scale, therefore, is found in practice to be finally a discontinuous one, or at best represented by continuous interpolations in terms of some empirical law, not the gas law. We shall see that there are further and very serious limitations in the attainment of great accuracy with the gas thermometer; thus, the space containing gas between the hot and cold parts is at an unknown average temperature; the expansion of the bulb with heat must be corrected for; and the bulb must be of sufficient rigidity and impermeability at the highest temperatures.

The gas thermometer, as we have seen above, need not of necessity be used for the measurement of temperatures; it suffices to make use of it for the standardization of the different processes employed in the determination of temperatures, but *à priori* there are not on the other hand any absolute reasons for discarding it in cases other than these standardizations. Indeed, it has often been so employed, although, as we shall see, it is usually more convenient to make use of some other method in practice.

We shall describe first the standard gas thermometer, and then discuss in considerable detail the factors that enter into the construction and theory of gas thermometers suitable for high temperatures, and give an account of several of the various investigations in gas thermometry, and finally call attention to the requirements for future work in this domain.

Standard Gas Thermometer. — This thermometer, that of the International Bureau of Weights and Measures at Sèvres, France, is a constant-volume thermometer filled with pure, dry hydrogen, under the pressure of 1 m. of mercury at the temperature of melting ice. It consists of two essential parts: the *bulb*, enclosing the invariable gaseous mass, and the *manometer*, serving to measure the pressure of this gaseous mass.

The *bulb* is made of a platinum-iridium tube whose volume is 1.03899 liters at the temperature of melting ice. Its length is 1.10 m., and its outer diameter 0.036 m. It is attached to the manometer by a capillary tube of platinum of 0.7 mm. diameter. A diameter of 0.5 mm. is as small as can be allowed in the colder part of such capillaries on account of the lag in obtaining pressure equilibrium.

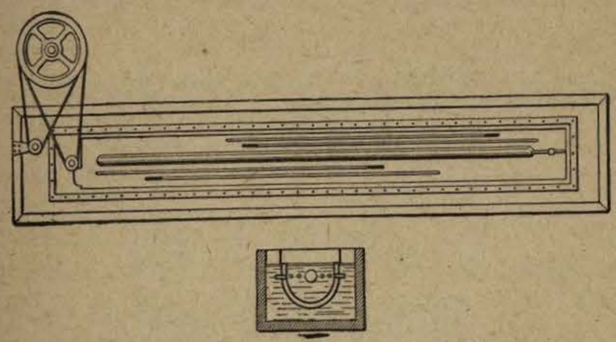

Fig. 2. Mounting of Thermometer Bulb.

This bulb is supported horizontally in a double box with interior water circulation. For the determination of the 100° mark, indispensable for standardization, the bulb can be placed in the same way in a horizontal heater supplied with steam and composed of several concentric coverings.

Manometer. — The manometric apparatus is mounted upon an iron support of 2.10 m. height, which is made of a railway rail firmly bolted to a tripod of wrought iron. The lateral parts attached to this rail, planed their entire length, carry sliding pieces to which are fastened the manometer tubes and a barometer. Fig. 3 represents, in a slightly modified form, the manometric apparatus. It is composed essentially of a manometer open to the air whose open arm *A* serves as cistern for a barometer *R*. The other arm *B*, closed half-way up by a piece of steel *H*, is attached to the thermometric bulb by the capillary tube of platinum *C*. The two manometer tubes, each of 25 mm. interior diameter, have their lower ends fixed into a block of steel *S*. They communicate with each other by holes of 5 mm.

diameter bored in the block. A stopcock *E* permits closing this connection. A second three-way cock *F* is screwed on the same block. One of its branches can serve to let mercury run out; the other, to which is attached a long flexible steel tube, puts the manometer in communication with a large reservoir of mercury *D* which can be raised or lowered the length of the support, either rapidly by hand, or slow-motioned by means of a screw.

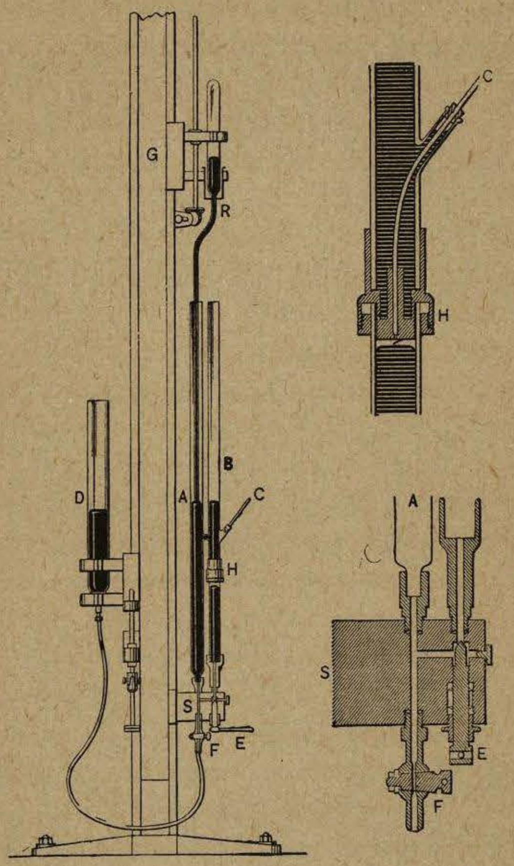

Fig. 3. Manometer of Standard Thermometer.

The barometer which sets in the open branch is fixed at its upper part on a carriage *G* whose vertical displacement is regulated throughout a length of 0.70 m. by a strong screw. The latter is held at its two ends by two nuts which permit it to turn without longitudinal motion; it works in a screw attached to the carriage, and carries at its lower end a toothed pinion which works into a cogwheel. It suffices to turn this wheel by acting upon the rod which serves as axis in order to raise or lower the carriage with the barometer tube. This last has a diameter of 25 mm. in its upper part. The chamber is furnished with two indexes of black glass soldered to the interior of the tube at 0.08 m. and 0.16 m. from the end. The points of these indexes, convex downwards, coincide sensibly with the axis of the barometric chamber. The part of the barometer which fits into the open manometer arm has a diameter greater than 0.01 m., and ends below in a narrower tube curved upwards.

The piece of steel which ends the closed arm at *H* is adjusted to this tube, leaving between itself and the tube but a very slight space, which is filled with sealing wax. It rests upon the upper rim of this tube, to which it is besides pressed by leather washers tightly screwed up. At its lower end it terminates in a perfectly smooth polished plane, which is adjusted to be horizontal. In the middle of this surface, near to the opening of the canal which prolongs the joining tube, there is fixed a very fine platinum point, whose extremity, meant to be used as a reference mark, is at a distance of about 0.6 mm. from the plane surface.

Above this piece is a tube *B* of 25 mm. interior diameter, open above and connected below to the open arm of the manometer.

Since the measurement of a column of mercury is more easily made and with greater precision when the menisci whose difference of level it is desired to find are situated along the same vertical, the barometer tube *R* is bent so as to bring into the same vertical line the axis of the closed arm of the manometer and that of the barometer. Under these conditions, the communication between the two manometer arms *A* being established through *E*, the total pressure of the gas inclosed in the reservoir of the thermometer is given by the difference of level of the mercury in these superposed tubes *B* and *R*.

The measurement of the pressures is made by means of a cathetometer furnished with three telescopes, each of which is provided with a micrometer and level. The micrometer circle is divided into 100 parts; at the distance from which the manometer is read, each division of the circle corresponds to about 0.002 mm.

The method adopted for the measurement of pressures consists in determining the position of each mercury meniscus in terms of a fixed scale, hung near the manometer tubes, at the same distance as these latter from the telescopes of the cathetometer.

One of the principal difficulties arising in the measurement of pressures is that of the lighting of the menisci. The method employed by Chappuis consists in bringing up to the surface of the mercury an opaque point until its image reflected by the mercury appears in the observing telescope at a very small distance from that of the point itself. These two images being almost in contact, it is easy to set the micrometer cross-wire midway between them, at the precise point where would be the image of the reflecting surface. In order to have a very sharp image of the point, it is well to illuminate from behind by means of a beam of light passing through a vertical slit. The point and its image then stand out black on a bright background. The use of a stylus of black glass is preferable to that of a steel point on account of unchangeableness and of the greater sharpness of the edges.

The method with stylus cannot be advantageously employed except in wide tubes, where the reflecting surface of the mercury which aids in the formation of the image does not have a sensible curvature.

Dead Space. — This consists of the space occupied by the gas: (1) in that part of the capillary tube which does not undergo the same variations of temperature as the thermometric bulb; (2) within the piece of steel forming the plug which caps the closed arm of the manometer; (3) in the manometer tube between the mercury and the horizontal plane in which ends the piece of steel. The mercury is supposed to just touch the stylus serving as reference mark.

The capacity of the capillary tube has been determined by mercury calibration; it was found equal to 0.567 c.c. The length of the capillary tube being 1 m., if we deduct from this capacity

that of 3 cm. of the tube which are exposed to the same temperatures as the reservoir, that is 0.015 c.c., this leaves 0.552 c.c.

The capillary tube fits for a length of 27 mm. into the piece of steel serving as plug. The total thickness of this plug is 28.3 mm.; thus the portion of the canal included between the end of the capillary tube and the lower face of the plug is 1.3 mm. in length. As its diameter is 1.35 mm., the capacity of this canal is 0.0019 c.c.

The space included between a cross section of the manometer tube passing through the stylus and the plane surface of the plug is 0.3126 c.c.

To have the total volume occupied by the gas it is necessary to add as well to this space the volume of the depressed mercury in the manometric tube caused by the curvature of the meniscus. The radius of this tube being equal to 12.235 mm., we find for this volume 0.205 c.c.

We thus have as the total of the dead space the sum of the following volumes:

	C.c.
Capacity of capillary tube	0.5520
Volume of canal in the plug	19
Capacity of the manometer tube between the stylus and the plane	3126
Volume of depressed mercury	2050
Total dead space	1.0715

When the mercury does not just touch the stylus, we shall have to add to this value 0.4772 c.c. per millimeter separation of the stylus from the top of the meniscus.

The *expansion of the metal of the bulb* was measured by Fizeau's method; this volume was found to have at different temperatures the following values:

	Liters.
−20°	1.03846
0	1.03899
20	1.03926
40	1.04007
60	1.04061
80	1.04117
100	1.04173

The *variation of the capacity of the bulb* due to changes of pressure has also been studied; per millimeter of mercury it is 0.02337 $\overline{\text{mm.}}^3$; or

For	0 mm.	0 $\overline{\text{mm.}}^3$
"	100	2.3
"	200	4.7
"	300	7.0
"	400	9.3

The zero is verified from time to time by bringing the bulb to the temperature of melting ice; there is absolute constancy even after heating to 100°. The deviation is at the most 0.03 mm. for a pressure of 995 mm.

Chappuis made a most careful calibration of four mercury in verre dur thermometers in terms of this standard gas thermometer in an apparatus such as shown in Fig. 2, and these mercury thermometers, with copies that have been made and distributed, represent to-day the practical standards of temperature in the interval − 35° to + 100° C., with an accuracy of about 0.002° C.

After a discussion of the formulæ involved, we shall consider the question of the experimental establishment of the high temperature scale, a problem which has occupied a great many able investigators for many years, and which is by no means as yet conclusively solved, there being, as we shall see, embarassing outstanding uncertainties in determinations of temperatures, for example, of 0.5° at 500° C. and some 20° at 1600° C., due wholly to experimental difficulties.

Formulæ and Corrections. — To illustrate the principles involved we shall cite as examples some of the earlier work with porcelain bulbs. As we shall see later, all of the errors here discussed have been greatly reduced in magnitude in the latest work with quartz and metal bulbs.

1. *Thermometer at Constant Volume.* — We must now render more precise the formula of the gas thermometer given in the preceding chapter by taking account of the variations of volume of the bulb, of the surrounding air temperature which changes the density of the mercury, and finally of the volume of the dead space.

We have three series of observations to make in order to determine a given temperature:

$$P_0V_0 = n_0RT_0, \quad \ldots \quad (1)$$

$$P_{100}V_{100} = n_{100}RT_{100}, \quad \ldots \quad (2)$$

$$PV = nRT. \quad \ldots \quad (3)$$

Putting

$$T = \frac{1}{\alpha} + t,$$

the first two series serve to determine $\frac{1}{\alpha}$.

It is preferable, except in researches of very great precision, to take $\frac{1}{\alpha}$ from previously obtained results, and not to make the observations at 100°, unless one does so to check his experimental skill.

Dividing the third equation by the first, we have the relation

$$\frac{PV}{P_0V_0} = \frac{H\Delta_0V}{H_0\Delta V_0} = \frac{nRT}{n_0RT_0} = \frac{nT}{n_0T_0}, \quad \ldots \quad (4)$$

where H and H_0 are the heights of mercury, Δ and Δ_0 the densities of this metal.

For a first approximation let us neglect the differences between V and V_0, n and n_0, Δ and Δ_0. We shall have then an approximate value T' for the temperature sought:

$$T' = \frac{1}{\alpha} \cdot \frac{H}{H_0}, \quad \ldots \quad (5)$$

for

$$T_0 = \frac{1}{\alpha}.$$

Let us find now the *correction* dT to T' to obtain the exact temperature. In order to find this, take the logarithmic differential of (4):

$$\frac{dT}{T'} = \frac{d\Delta}{\Delta_0} + \frac{dV}{V_0} - \frac{dn}{n_0}. \quad \ldots \quad (6)$$