HEAT.

CHAPTER I.

THERMOMETRY.

1. **Heat—Cold.**—The words *heat* and *cold* express sensations so well known as to need no explanation; but these sensations are modified by subjective causes, and do not furnish an invariable criterion of objective reality. In fact, we may often see one person suffer from heat while another complains of cold. Even for the same person the sensations of heat and cold are comparative. A temperature of 50° Fahr. suddenly occurring amid the heat of summer produces a very decided sensation of cold, whereas the same temperature in winter has exactly the opposite effect. We may mention an old experiment upon this subject, which is at once simple and instructive. If we plunge one hand into water at 32° Fahr., and the other into water at about 100°; and if after having left them some time in this position we immerse them simultaneously in water at 70°, they will experience very different sensations. The hand which was formerly in the cold water now experiences a sensation of heat; that which was in the hot water experiences a sensation of cold, though both are in the same medium. This plainly shows that the sensations of heat and cold are modified by the condition of the observer, and consequently cannot serve as a sure guide in the study of calorific phenomena. Recourse must therefore be had to some more constant standard of reference, and such a standard is furnished by the thermometer.

2. **Temperature.**—If several bodies heated to different degrees are placed in presence of each other, an interchange of heat takes place between them, by which they undergo modifications of opposite kinds; those that are hottest grow cooler, and those that are coldest grow warmer; and after a longer or shorter time these inverse phenomena cease to take place, and the bodies come to a state of mutual

equilibrium. They are then said to be at the same *temperature.* If a source of heat is now brought to act upon them, their temperature is said to *rise;* if they are left to themselves in a colder medium, they all grow cold, and their temperature is said to *fall.* *Two bodies are said to have the same temperature if when they are placed in contact no heat passes from the one to the other.* If when two bodies are placed in contact heat passes from one to the other, that which gives heat to the other is said to have the higher temperature. Heat always tends to pass from bodies of higher to those of lower temperature.

3. Expansion.—At the same time that bodies undergo these changes in temperature, which may be verified by the different impressions which they make upon our organs, they are subjected to other modifications which admit of direct measurement, and which serve as a means of estimating the changes of temperature themselves. These modifications are of different kinds, and we shall have occasion to speak of them all in the course of this work; but that which is especially used as the basis of thermometric measurement is change of volume. In general, when a body is heated, it increases in volume; and, on the other hand, when it is cooled its volume diminishes. The expansion of bodies under the action of heat may be illustrated by the following experiments.

1. *Solid Bodies.*—We take a ring through which a metal sphere

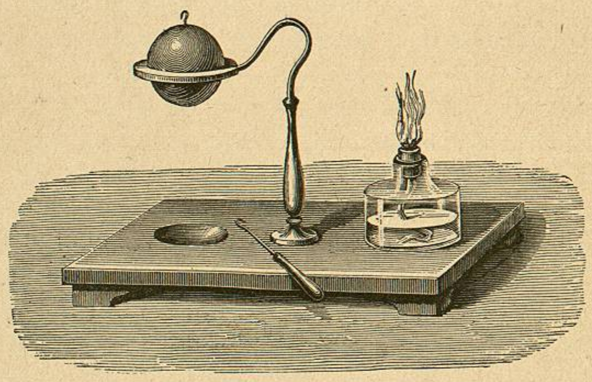

Fig. 1.—Gravesande's Ring.

just passes. This latter is heated by holding it over a spirit-lamp, and it is found that after this operation it will no longer pass through the ring. Its volume has increased. If it is now cooled by immersion in water, it resumes its former volume, and will again pass

through the ring. If, while the sphere was hot, we had heated the ring to about the same degree, the ball would still have been able to pass, their relative dimensions being unaltered. This little apparatus is called *Gravesande's Ring.*

2. *Liquids.*—A liquid, as water for instance, is introduced into the

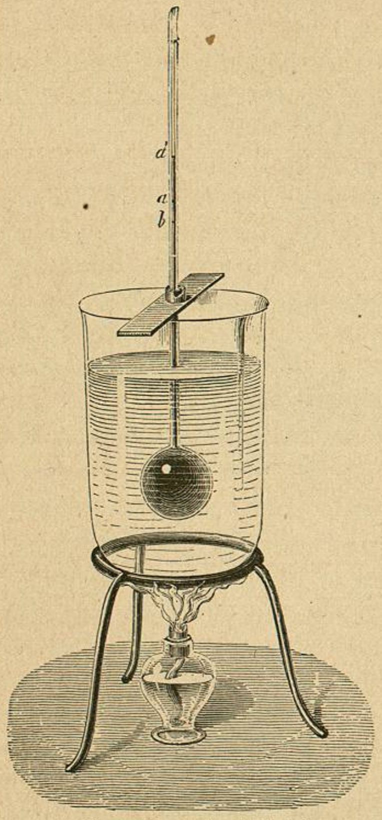

Fig. 2.—Expansion of Liquids.

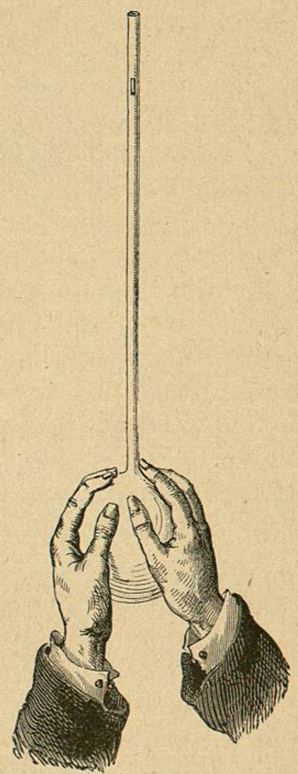

Fig. 3.—Expansion of Gases.

apparatus shown in Fig. 2, so as to fill at once the globe and a portion of the tube as far as *a*. The instrument is then immersed in a vessel containing hot water, and at first the extremity of the liquid column descends for an instant to *b*; but when the experiment has continued for some time, the liquid rises to a point *a′* at a considerable height above. This twofold phenomenon is easily explained. The globe, which receives the first impression of heat, increases in volume before any sensible change can take place in the temperature of the liquid. The liquid consequently is unable to fill the entire capacity of the globe and tube up to the original mark, and thus the extremity of the liquid column is seen to fall. But the liquid, receiving in its turn the impression of heat, expands also, and as it passes the original mark, we may conclude that it not only expands, but expands more than the vessel which contains it.

3. *Gases.*—The globe in Fig. 3 contains air, which is separated from the external air by a small liquid index. We have only to warm the globe with the hands and the index will be seen to be pushed quickly upwards, thus showing that gases are exceedingly expansible.

4. General Idea of the Thermometer.—Since the volume of a body is changed by heat, we may specify its temperature by stating its volume. And the body will not only indicate its own temperature by this means, it will also exhibit the temperature of the bodies by which it is surrounded, and which are in equilibrium of temperature with it. Any body which gives quantitative indications of temperature may be called a thermometer.

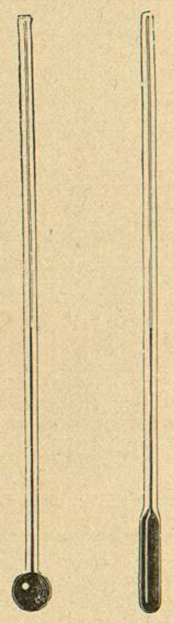

Fig. 4.—Mercurial Thermometers.

5. Choice of the Thermometric Substance.—As the expansions of different substances are not exactly proportional to one another, it is necessary to select some one substance or combination of substances to furnish a standard; and the standard usually adopted is the apparent expansion of mercury in a graduated glass vessel. The instrument which exhibits this expansion is called the mercurial thermometer. It consists essentially, as shown in Fig. 4, of a tube of very small diameter, called the *stem*, terminating in a reservoir which, whatever its shape, is usually called the *bulb*. The reservoir and a portion of the tube are filled with mercury. If the temperature varies, the level of the liquid will rise or fall in the tube, and the points at which it stands can be identified by means of a scale attached to or engraved on the tube.

6. Construction of the Mercurial Thermometer.—The construction of an accurate mercurial thermometer is an operation of great delicacy, and comprises the following processes.

1. *Choice of the Tube.*—The first object is to procure a tube of as uniform bore as possible. In order to test the uniformity of the bore, a small column of mercury is introduced into the tube, and the length which it occupies in different parts of the tube is measured. If these lengths are not equal, the tube is not of uniform bore. When

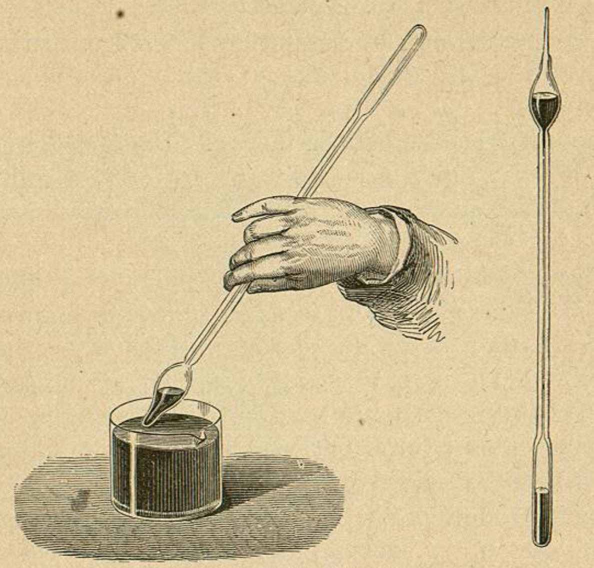

Fig. 5.—Introduction of the Mercury.

a thermometer of great precision is required, the tube is *calibrated;* that is, divided into parts of equal volume, by marking upon it the lengths occupied by the column in its different positions.

When a suitable tube has been obtained, a reservoir is either blown

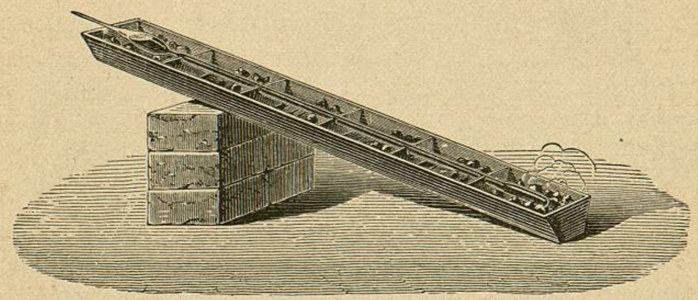

Fig. 6.—Furnace for heating Thermometers.

at one end or attached by melting, the former plan being usually preferable.

2. *Introduction of the Mercury.*—At the upper end of the tube a temporary bulb is blown, and drawn out to a point, at which there is

a small opening. This bulb, and also the permanent bulb, are gently heated, and the point is then immersed in a vessel containing mercury (Fig. 5). The air within the instrument, growing cold, diminishes in expansive force, so that a quantity of mercury is forced into the temporary bulb by the pressure of the atmosphere. The instrument is then set upright, and by alternate heating and cooling of the permanent bulb, a large portion of the mercury is caused to descend into it from the bulb at the top. The instrument is then laid in a sloping position on a special furnace (Fig. 6) till the mercury boils. The vapour of the boiling mercury drives out the air, and when the mercury cools it forms a continuous column, filling the permanent bulb and tube. If any bubbles of air are seen, the operation of boiling and cooling is repeated until they are expelled.

3. *Determination of the Fixed Points.*—The instrument, under these conditions, and with any scale of equal parts marked on the tube, would of course indicate variations of temperature, but these indications would be arbitrary, and two thermometers so constructed would in general give different indications.

In order to insure that the indications of different thermometers may be identical, it has been agreed to adopt two standard temperatures, which can easily be reproduced and maintained for a considerable time, and to denote them by fixed numbers. These two temperatures are the freezing-point and boiling-point of water; or to speak more strictly, the temperature of melting ice, and the temperature of the steam given off by water boiling under average atmospheric pressure. It has been observed that if the thermometer be surrounded with melting ice (or melting snow), the mercury, under whatever circumstances the experiment is performed, invariably stops at the same point, and remains stationary there as long as the melting continues. This then is a fixed temperature. On the Centigrade scale it is called zero, on Fahrenheit's scale 32°.

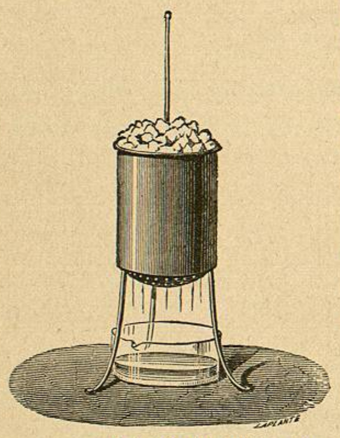

Fig. 7.—Determination of Freezing-point.

In order to mark this point on a thermometer, it is surrounded by melting ice, which is contained in a perforated vessel, so as to allow

the water produced by melting to escape. When the level of the mercury ceases to vary, a mark is made on the tube with a fine diamond at the extremity of the mercurial column. This is frequently called for brevity the *freezing-point.*

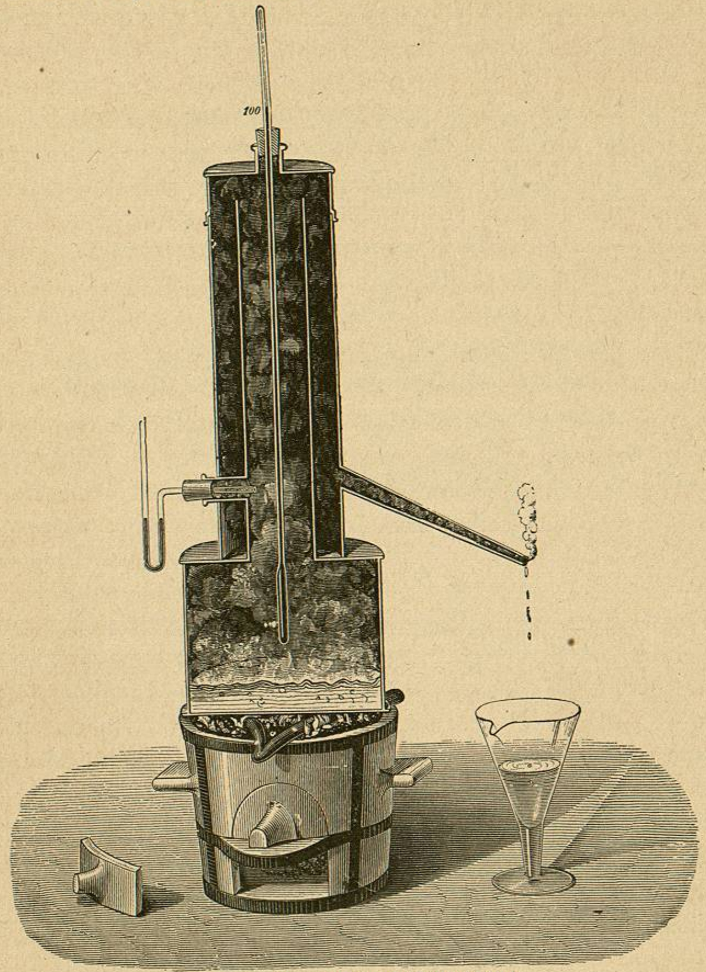

Fig. 8.—Determination of Boiling-point.

It has also been observed that if water be made to boil in an open metallic vessel, under average atmospheric pressure (76 centimetres, or 29·922 inches), and if the thermometer be plunged into the steam, the mercury stands at the same point during the entire time of ebullition, provided that the external pressure does not change. This second fixed temperature is called 100° in the Centigrade scale (whence the name), and 212° on Fahrenheit's scale. In order to mark this second point on the thermometer, an apparatus is employed which was devised by Gay-Lussac, and perfected by Regnault. It consists of a copper boiler (Fig. 8) containing water which is raised to ebullition by means of a furnace. The steam circulates through a double casing, and escapes by a tube near the bottom. The thermometer is fixed in the interior casing, and when the mercury has become stationary, a mark is made at the point at which it stops, which denotes what is commonly called for brevity the *boiling-point.*

A small manometric tube, open at both ends, serves to show, by the equality of level of the mercury in its two branches, that the ebullition is taking place at a pressure equal to that which prevails externally, and consequently that the steam is escaping with sufficient freedom. It frequently happens that the external pressure is not exactly 760 millimetres, in which case the boiling-point should be placed a little above or a little below the point at which the mercury remains stationary, according as the pressure is less or greater than this standard pressure. When the difference on either side is inconsiderable, the position of the boiling-point may be roughly calculated by the rule, that a difference of 27 millimetres in the pressure causes a difference of 1° in the temperature of the steam produced. We shall return to this point in Chap. ix.

It now only remains to divide the portion of the instrument between the freezing and boiling points into equal parts corresponding to single degrees, and to continue the division beyond the fixed points. Below the zero point are marked the numbers 1, 2, 3, &c. These temperatures are expressed with the sign —. Thus the temperature of 17° below zero is written —17°.

7. Adjustment of the Quantity of Mercury.—In order to avoid complicating the above explanation, we have omitted to consider an operation of great importance, which should precede those which we have just described. This is the determination of the volume which

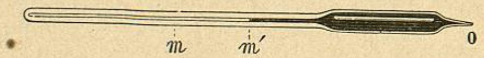

Fig. 9.

must be given to the reservoir, in order that the instrument may have the required range. When the reservoir is cylindrical, this is easily effected in the following manner. Suppose we wish the thermometer to indicate temperatures comprised between —20° and 130° Cent., so that the range is to be 150°; the reservoir is left open at O (Fig. 9),

and is filled through this opening, which is then hermetically sealed. The instrument is then immersed in two baths whose temperatures differ, say, by 50°, and the mercury rises through a distance *m m′*. This length, if the quantity of mercury in the reservoir be exactly sufficient, should be the third part of the length of the stem. The quantity of mercury in the reservoir is always taken too large at first, so that it has only to be reduced, and thus the space traversed by the liquid is at first too great. Suppose it to be equal to $\frac{3}{4}$ths of the length of the stem. The degrees will then be too long, in the ratio $\frac{3}{4}:\frac{1}{3}=\frac{9}{4}$; that is, the reservoir is $\frac{9}{4}$ of what it should be. We therefore measure off $\frac{4}{9}$ths of the length of the reservoir, beginning at the end next the stem; this distance is marked by a line, and the end O is then broken and the mercury suffered to escape. The glass is then melted down to the marked line, and the reservoir is thus brought to the proper dimensions. It only remains to regulate the quantity of mercury admitted, by making it fill the tube at the highest temperature which the instrument is intended to indicate.

If the reservoir were spherical, which is a shape generally ill adapted for delicate thermometers, the foregoing process would be inapplicable, and it would be necessary to determine the proper size by trial.

8. Thermometric Scales.—In the *Centigrade* scale the freezing-point is marked 0°, and the boiling-point 100°. In *Réaumur's* scale, which is still popularly used on the Continent, the freezing-point is also marked 0°, but the boiling-point is marked 80°. Hence, 5 degrees on the former scale are equal to 4 on the latter, and the reduction of temperatures from one of these scales to the other can be effected by multiplying by $\frac{4}{5}$ or $\frac{5}{4}$.

Fig. 10.
Thermometric Scales.

For example, the temperature 75° Centigrade is the same as 60° Réaumur, since $75\times\frac{4}{5}=60$; and the temperature 36° Réaumur is the same as 45° Centigrade, since $36\times\frac{5}{4}=45$.

The relation between either of these scales and that of *Fahrenheit* is rather more complicated, inasmuch as Fahrenheit's zero is not at freezing-point, but at 32 of his degrees below it.

As regards intervals of temperature, 180 degrees Fahrenheit are equal to 100 Centigrade, or to 80 Réaumur, and hence, in lower terms, 9 degrees Fahrenheit are equal to 5 Centigrade, or to 4 Réaumur.

The conversion of temperatures themselves (as distinguished from intervals of temperature) will be best explained by a few examples.

Example 1. To find what temperatures on the other two scales are equivalent to the temperature 50° Fahrenheit.

Subtracting 32, we see that this temperature is 18 Fahrenheit degrees above freezing-point, and as this interval is equivalent to $18 \times \frac{5}{9}$, that is 10 Centigrade degrees, or to $18 \times \frac{4}{9}$, that is 8 Réaumur degrees, the equivalent temperatures are respectively 10° Centigrade and 8° Réaumur.

Example 2. To find the degree on Fahrenheit's scale, which is equivalent to the temperature 25° Centigrade.

An interval of 25 Centigrade degrees is equal to $25 \times \frac{9}{5}$, that is 45 Fahrenheit degrees, and the temperature in question is above freezing-point by this amount. The number denoting it on Fahrenheit's scale is therefore $32+45$, that is 77°.

The rules for the conversion of the three thermometric scales may be summed up in the following formulæ, in which F, C, and R denote equivalent temperatures expressed in degrees of the three scales:—

$$F = \tfrac{9}{5}\,C + 32 = \tfrac{9}{4}\,R + 32.$$
$$C = \tfrac{5}{4}\,R = \tfrac{5}{9}\,(F - 32).$$
$$R = \tfrac{4}{5}\,C = \tfrac{4}{9}\,(F - 32).$$

It is usual, in stating temperatures, to indicate the scale referred to by the abbreviations *Fahr.*, *Cent.*, *Réau.*, or more briefly by the initial letters F., C., R.

9. Displacement of the Zero Point.—A thermometer left to itself after being made, gradually undergoes a contraction of the bulb, leading to a uniform error of excess in its indications. This phenomenon is attributable to molecular change in the glass, which has, so to speak, been tempered in the construction of the instrument, and to atmospheric pressure on the exterior of the bulb, which is unresisted by the internal vacuum. The change is most rapid at first, and usually becomes insensible after a year or so, unless the thermometer is subjected to extreme temperatures. Its total amount is usually about half a degree. On account of this change it is advisable not to graduate a thermometer till some time after it has been sealed.

10. Sensibility of the Thermometer.—The power of the instrument to detect very small differences of temperature may be regarded as measured by the length of the degrees, which is proportional to the capacity of the bulb directly and to the section of the tube inversely (§ 24).

Quickness of action, on the other hand, requires that the bulb be small in at least one of its dimensions, so that no part of the mercury shall be far removed from the exterior, and also that the glass of the bulb be thin.

Quickness of action is important in measuring temperatures which vary rapidly. It should also be observed that, as the thermometer, in coming to the temperature of any body, necessarily causes an inverse change in the temperature of that body, it follows that when the mass of the body to be investigated is very small, the thermometer itself should be of extremely small dimensions, in order that it may not cause a sensible variation in the temperature which is to be observed.

11. Alcohol Thermometer.—In the construction of thermometers, other liquids may be introduced instead of mercury; and alcohol is very frequently employed for this purpose.

Alcohol has the disadvantage of being slower in its action than mercury, on account of its inferior conductivity; but it can be employed for lower temperatures than mercury, as the latter congeals at —39° Cent. (—38° Fahr.), whereas the former has never congealed at any temperature yet attained.

If an alcohol thermometer is so graduated as to make it agree with a mercurial thermometer (which is the usual practice), its degrees will not be of equal length, but will become longer as we ascend on the scale. If mercury is regarded as expanding equally at all temperatures, alcohol must be described as expanding more at high than at low temperatures.

12. Self-registering Thermometers.—It is often important for meteorological purposes to have the means of knowing the highest or the lowest temperature that occurs during a given interval. Instruments intended for this purpose are called maximum and minimum thermometers.

The oldest instrument of this class is *Six's* (Fig. 11), which is at once a maximum and a minimum thermometer. It has a large cylindrical bulb C filled with alcohol, which also occupies a portion of the tube. The remainder of the tube is partly filled with mercury,