

strongly magnetic that, when placed in the spheroidal state in a cup of rock-salt beneath the poles of an electro-magnet, it leaped up as soon as the magnetizing current was turned on, and formed a bridge of hour-glass shape between the poles, as shown in Fig. 67A.¹ At

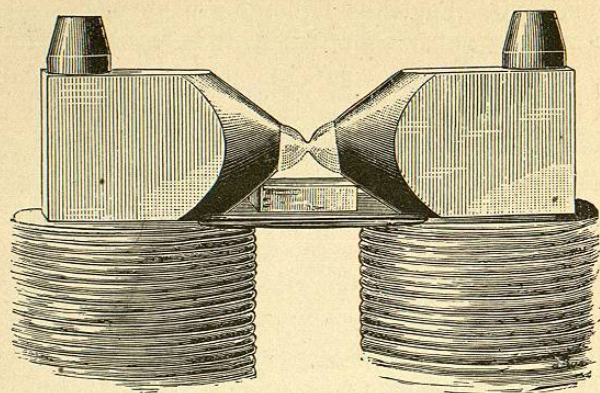


Fig. 67A.—Dewar's Experiment.

the temperature -200° C., it was chemically inert, exhibiting no action on phosphorus or potassium dropped into it.

Air was liquefied in a similar manner, its two constituents going down together into one liquid; and when tested by the electro-magnet all the liquid went to the poles. When it was allowed to evaporate, its nitrogen boiled off before its oxygen. When surrounded by a jacket of liquid oxygen, and subjected to rapid and sustained evaporation of its nitrogen by means of a powerful pump, it was reduced to a solid block of transparent ice. The boiling point of liquid nitrogen was found to be -190° C.

¹For this figure, which is copied from a photograph, we are indebted to Professor Dewar and the publishers of the *Engineer*.

CHAPTER IX.

EBULLITION.

107. **Ebullition.**—When an open vessel containing a liquid is placed upon a fire or held over the flame of a lamp, evaporation at first goes on quietly and the liquid steadily rises in temperature; but after a time the liquid becomes agitated, gives off vapour much faster, and remains nearly constant in temperature. The liquid is now said to *boil* or to be in a state of *ebullition*.

If we observe the gradual progress of the phenomena—as we can easily do in a glass vessel containing water, we shall perceive that, after a time, very minute bubbles are given off; these are bubbles of dissolved air. Soon after, at the bottom of the vessel, and at those parts of the sides which are most immediately exposed to the action of the fire, larger bubbles of vapour are formed, which decrease in volume as they ascend, and disappear before reaching the surface. This stage is accompanied by a peculiar sound, indicative of approaching ebullition, and the liquid is said to be *singing*. The sound is probably caused by the collapsing of the bubbles as they are condensed by the colder water through which they pass. Finally, the bubbles increase in number, growing larger as they ascend, until they burst at the surface, which is thus kept in a state of agitation; and the liquid boils.

108. **Laws of Ebullition.**—The following are the ordinary laws of ebullition.



Fig. 68.—Ebullition.

1. *At the ordinary pressure, ebullition commences at a temperature which is definite for each liquid.*

This law is analogous to that of fusion (§ 72). It follows from this that the boiling-point of any liquid is a *specific* element, serving to determine its nature.

The following table gives the boiling-points of several liquids at the pressure of 760 millimetres:—

Sulphurous acid,	-10° C.	Spirits of turpentine,	+130° C.
Hydrochloric ether,	+11°	Phosphorus,	290°
Common ether,	37°	Concentrated sulphuric acid,	325°
Alcohol,	79°	Mercury,	353°
Distilled water,	100°	Sulphur,	440°

2. *The temperature remains constant during ebullition.* If a thermometer be introduced into the glass vessel of Fig. 68, the temperature will be observed to rise gradually during the different stages preceding ebullition; but, when active ebullition has once commenced, no further advance of temperature will be observed.

This phenomenon points to the same conclusion as the cold produced by evaporation. Since, notwithstanding the continuous action of the fire, the temperature remains constant, the conclusion is inevitable, that all the heat produced is employed in doing the work necessary to change the liquid into vapour. The constancy of temperature during ebullition explains the fact that vessels of pewter, tin, or any other easily fusible metal, may be safely exposed to the action of even a very hot fire, provided that they contain water, since the liquid remains at a temperature of about 100°, and its contact prevents the vessel from over-heating. We shall see hereafter that, under certain circumstances, the commencement of ebullition is delayed till the liquid has risen considerably above the permanent temperature which it retains when boiling. The second law also is not absolutely exact. Small fluctuations of temperature occur, and some parts of the liquid are slightly hotter than others. The temperature of the vapour is more constant than that of the water, and is accordingly employed in determining the "fixed points" of thermometers.

3. *The pressure of the vapour given off during ebullition is equal to that of the external air.*

Previous to ebullition, the upper part of the vessel in Fig. 68 contains a mixture of air and vapour, the joint pressure being sensibly equal to that of the external air; but when active ebullition

occurs, the air is expelled, and the upper part of the vessel, from the liquid to the mouth, is occupied by vapour alone, which, being in free communication with the external air, must be sensibly equal to it in pressure.

The following experiment furnishes an interesting confirmation of this third law.

We take a bent tube A, open at the longer extremity, and closed at the shorter. The short branch is filled with mercury, all but a small space containing water; in the long branch the mercury stands a little higher than the bend. Water is now boiled in a glass vessel, and, during ebullition, the bent tube is plunged into the steam. The water occupying the upper part of the short branch is partially converted into steam, the mercury falls, and it *assumes the same level in both branches*. Thus the pressure exerted by the atmosphere at the open extremity of the tube is exactly equal to that exerted by the vapour of water at the temperature of ebullition.

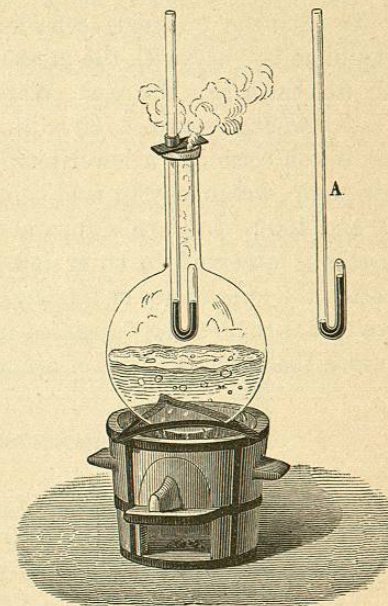


Fig. 69.—Tension of Vapour during Ebullition.

109. **Definition of Ebullition.**— This latter circumstance supplies the true physical definition of ebullition. *A liquid is in ebullition when it gives off vapour of the same pressure as the atmosphere above it.*

The necessity of this equality of tension is easily explained. If a bubble of vapour exists in the interior of a liquid (as at *m*, Fig. 70), it is subject to a pressure exceeding atmospheric by the weight of the liquid above it. As the bubble rises, the latter element of pressure becomes less, and the pressure of the vapour composing the bubble accordingly diminishes, until it is reduced to atmospheric pressure on reaching the surface.

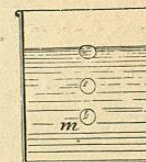


Fig. 70.

The boiling-point of a liquid at given pressure is therefore neces-

sarily fixed, since it is the temperature at which the pressure of the vapour at saturation is equal to this pressure. It must be remarked, however, that the boiling-point varies in the different layers of the liquid, increasing with the depth below the surface. Accordingly, in determining the second fixed point of the thermometer, we have stated that the instrument should be plunged into the steam, and not into the water.

110. **Effect of Pressure upon the Boiling-point.**—It evidently follows from the foregoing considerations that the boiling-point of a liquid must vary with the pressure on the surface; and experiment shows that this is the case. Water, for instance, boils at 100° under the external pressure of 760 millimetres; but if the pressure decreases, ebullition occurs at a lower temperature. Under the receiver of an air-pump, water may be made to boil at any temperature between 0° and 100° . In Carré's apparatus (Fig. 61) the water in the glass bottle is observed to enter into active ebullition a few moments before the appearance of the ice. The reason, therefore, why boiling water has come to be associated in our minds with a fixed temperature is that the variations of atmospheric pressure are comparatively small.

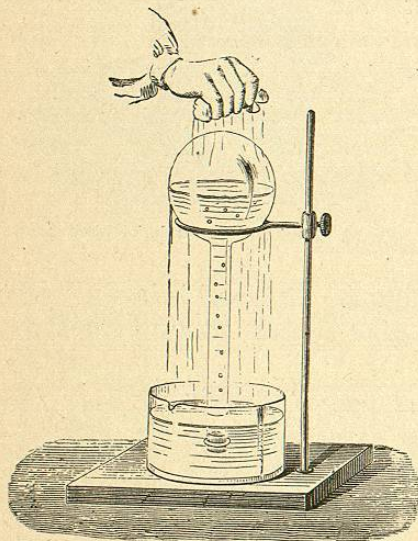


Fig. 71.—Franklin's Experiment.

A little water is boiled in a flask for a sufficient time to expel most of the air contained in it. The flask is then removed from the source of heat, and is at the same time securely corked. To render the exclusion of air still more certain, it may be inverted with the corked end immersed in

At Paris, for instance, the external pressure varies between 720 and 790 millimetres (28.3 and 31.1 inches), and the boiling-point, in consequence, varies from 98.5° to 101.1° , the difference being at the rate of about 27^{mm} per degree.

111. **Franklin's Experiment.**—The boiling of water at a temperature lower than 100° may be shown by the following experiment:—

A little water is boiled in a flask for a sufficient time to expel most of the air contained in it. The flask is then removed from the source of heat, and is at the same time securely corked. To render the exclusion of air still more certain, it may be inverted with the corked end immersed in

water which has been boiled. Ebullition ceases almost immediately; but if cold water be now poured over the vessel, or, better still, if ice be applied to it, the liquid again begins to boil, and continues to do so for a considerable time. This fact may easily be explained: the contact of the cold water or the ice lowers the temperature and pressure of the steam in the flask, and the decrease of pressure causes the renewal of ebullition.

112. **Determination of Heights by Boiling-point.**—Just as we can determine the boiling-point of water when the external pressure is given, so, if the boiling-point be known, we can determine the external pressure. In either case we have simply to refer to a table of maximum pressures of aqueous vapour at different temperatures.

As the mercurial barometer is essentially unsuitable for portability, Wollaston proposed to substitute the observation of boiling-points as a means of determining pressures. For this purpose he employed a thermometer with a large bulb and with a scale of very long degrees finely subdivided extending only a few degrees above and below 100° . He called this instrument the barometric thermometer.

Regnault has constructed a small instrument for the same purpose, which he calls the *hypsometer*. It consists of a little boiler heated by a spirit-lamp, and terminating in a telescope tube with an opening at the side through which the steam escapes. A thermometer dips into the steam, and projects through the top of the tube so as to allow the temperature of ebullition to be read.

This temperature at once gives the atmospheric pressure by reference to a table of vapour-pressures, and the subsequent computations for determining the height are the same as when the barometer is employed (see Part I.).

When only an approximate result is desired, it may be assumed that the height above sea-level is sensibly proportional to the differ-

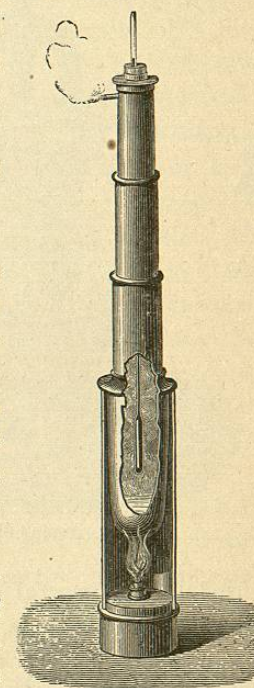


Fig. 72.—Hypsometer.

ence between the observed boiling-point and 100° C., and Soret's formula¹ may be employed, viz.:

$$h = 295 (100 - t),$$

where h is expressed in metres and t in degrees Centigrade.

Thus, at Quito, where the boiling-point of water is about 90.1° , the height above sea-level would be $9.9 \times 295 = 2920$ metres, which agrees nearly with the true height 2808 metres.

At Madrid, at the mean pressure, the boiling-point is 97.8° , which gives $2.2 \times 295 = 649$ metres; the actual height being 610 metres.

113. **Papin's Digester.**—While a decrease of pressure lowers the boiling-point, an increase of pressure raises it. Accordingly, by putting the boiler in communication with a reservoir containing air at the pressure of several atmospheres, we can raise the boiling-point to

110° , 115° , or 120° ; a result often of great utility in the arts. But in order that the liquid may actually enter into ebullition, the space above the liquid must be sufficiently large and cool to allow of the condensation of the steam. In a confined vessel, water may be raised to a higher temperature than would be possible in the open air, but it will not boil. This is the case in the apparatus invented by the celebrated Papin, and called after him *Papin's digester*. It is a

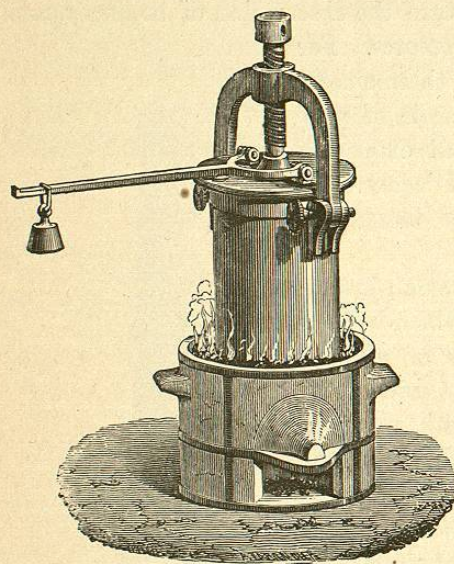


Fig. 73.—Papin's Digester.

bronze vessel of great strength, covered with a lid

secured by a powerful screw. It is employed for raising water to very high temperatures, and thus obtaining effects which would not be possible with water at 100° , such, for example, as dissolving the gelatine contained in bones.

It is to be observed that the pressure of the steam increases rapidly

¹ If h be expressed in feet, and t in degrees Fahrenheit, the formula becomes

$$h = 538 (212 - t).$$

with the temperature, and may finally acquire an enormous power. Thus, at 200° , the pressure is that of 16 atmospheres, or about 240 pounds on the square inch. In order to obviate the risk of explosion, Papin introduced a device for preventing the pressure from exceeding a definite limit. This invention has since been applied to the boilers of steam-engines, and is well known as the *safety-valve*. It consists of an opening, closed by a conical valve or stopper, which is pressed down by a lever loaded with a weight. Suppose the area of the lower end of the stopper to be 1 square inch, and that the pressure is not to exceed 10 atmospheres, corresponding to a temperature of 180° . The magnitude and position of the weight are so arranged that the pressure on the hole is 10 times 15 pounds. If the tension of the steam exceed 10 atmospheres, the lever will be raised, the steam will escape, and the pressure will thus be relieved.

It is a remarkable fact that, while the steam from an ordinary kettle scalds the hand, no injury is sustained by holding the hand in the jet of steam which issues from the safety-valve of a high-pressure boiler, although the temperature within the boiler is much higher than that within the kettle. The explanation appears to be that the steam which issues from the safety-valve is dry, and, like any other gas, is slow in raising the temperature of bodies exposed to it; while the steam from the kettle, being at saturation, deposits scalding-hot water on surfaces colder than itself. The subject has been much discussed in connection with "the specific heat of saturated steam" (see § 258). The expansion of the steam in escaping through the safety-valve has a powerful cooling effect, which would of itself be sufficient to produce partial condensation; but this effect is counteracted by the heat generated by the violent friction of the steam against the sides of the orifice, and the resultant effect is to leave the steam in a superheated condition.

114. **Boiling-point of Saline Solutions.**—When water holds saline matters in solution, the boiling-point rises as the proportion of saline matter in the water increases. Thus with sea-salt the boiling-point can be raised from 100° to 108° .

When the solution is not saturated, the boiling-point is not fixed, but rises gradually as the mixture becomes concentrated; but at a certain stage the salt begins to be precipitated, and the temperature then remains invariable. This is to be considered the normal boiling-point of the saturated solution. Supersaturation, however, sometimes occurs, the temperature gradually rising above the normal boiling-