

unit sectional area, C will denote the capacity of unit volume, and p the longitudinal stress in units of force per unit of area.

226. **Adiabatic Coefficients of Elasticity.**—Neglecting the exceptional cases of bodies which do not expand with heat, the resistance of a liquid to compression, and the resistance of a solid to both compression and extension, are greater under adiabatic conditions than under the condition of constancy of temperature. Thus, in the circumstances discussed in § 224 the pressure p produces an elevation of temperature τ , and the expansion due to this, namely $e\tau$, must be subtracted from the compression which would be produced at constant temperature. This latter is $\frac{p}{E}$, where E denotes the coefficient of elasticity at constant temperature; so that the compression will be only $\frac{p}{E} - e\tau$. The coefficient of elasticity is in the inverse ratio of the compression; hence, to find the adiabatic coefficient, we must multiply E by

$$\frac{\frac{p}{E}}{\frac{p}{E} - e\tau}, \text{ or by } \frac{1}{1 - \frac{Ee\tau}{p}}$$

Substituting for τ its value $\frac{Te\gamma}{JC}$, we find

$$\frac{Ee\tau}{p} = \frac{Ee^2T}{JC}.$$

In assigning the numerical values of E and J , it is to be remembered that if E is expressed in C.G.S. measure, as in the table of elasticities in Part I., the value of J will be 41.6 millions.

The factor for Young's modulus will be of the same form, E now denoting its value at constant temperature, and e the linear expansion for 1° , while C will still denote the thermal capacity of unit volume, which can be computed by multiplying the specific heat by the density.

227. **Freezing of Water which has been Cooled below 0° .**—We have seen in § 80 that when freezing begins in water which has been cooled below its normal freezing-point, a large quantity of ice is suddenly formed, and the temperature of the whole rises to 0° . In § 81 we have calculated the quantity of ice that will be formed, and we will now revise the calculation in the light of thermo-dynamics.

The same final condition would have been attained if the whole

mass (unity) of water at $-t^\circ$ had first been raised in the liquid state to 0° , and the mass x had then been frozen. The external work would also have been the same, being, in both cases, the product of atmospheric pressure by the excess of the final above the initial volume. Hence the algebraic sum of heat required is the same in both cases. But in the one case it is $t - 79.25x$, and in the other case (that is, in the actual case) it is zero. Hence we have

$$t - 79.25x = 0 \\ x = \frac{t}{79.25}.$$

The calculation in § 81 therefore requires no correction.

228. **Lowering of Freezing-point by Pressure.**—When a litre (or cubic decimetre) of water is frozen under atmospheric pressure, it forms 1.087 of a litre of ice, thus performing external work amounting to $.087 \times 103.3 = 9$ kilogramme-decimetres = .9 of a kilogramme, since the pressure of one atmosphere or 760 mm. of mercury is 103.3 kilogrammes per square decimetre. Under a pressure of n atmospheres, the work done would be $.9n$ kilogrammetres, neglecting the very slight compression due to the increase of pressure. If the ice is allowed to melt in vacuo, no external work is done upon it in the melting, and therefore, in the whole process, at the end of which the water is in the same state as at the beginning, heat to the amount of $\frac{.9n}{424} = .00212n$ of a kilogramme-degree is made to disappear. This process is *reversible*, for the water might be frozen in vacuo and melted under pressure; and hence, by appendix (2) to the second law of thermo-dynamics, we have

$$.00212n : Q :: T - T' : T;$$

where Q denotes the heat taken in in melting, which is 79.25 kilogramme-degrees, T the absolute temperature at which the melting occurs, about 273° , and T' the absolute temperature of freezing under the pressure of n atmospheres. Hence we have

$$.00212n : 79.25 :: T - T' : 273;$$

whence

$$T - T' = .0073n;$$

that is, the freezing-point is lowered by .0073 of a degree Cent. for each atmosphere of pressure.

229. **Heat of Chemical Combination.**—There is potential energy between the particles of two substances which would combine chemi-

cally if the opportunity were afforded. When *combination* actually takes place, this potential energy runs down and yields an equivalent of heat. We may suppose that the particles rush together in virtue of their mutual attraction, and thus acquire motions which constitute heat.

In every case of *decomposition*, an amount either of heat or some other form of energy must be consumed equivalent to the heat of combination.

When the heat evolved in combination is so great as to produce incandescence, the process is usually called *combustion* or *explosion*, according as it is gradual or sudden. In combustion the action takes place at the surface of contact of the two combining bodies. In explosion they have been previously mingled mechanically, and combination takes place throughout the whole mass.

Chemical combination is often accompanied by diminution of volume, or by change of state from gas or solid to liquid or *vice versa*. These changes sometimes tend to the evolution of heat, as

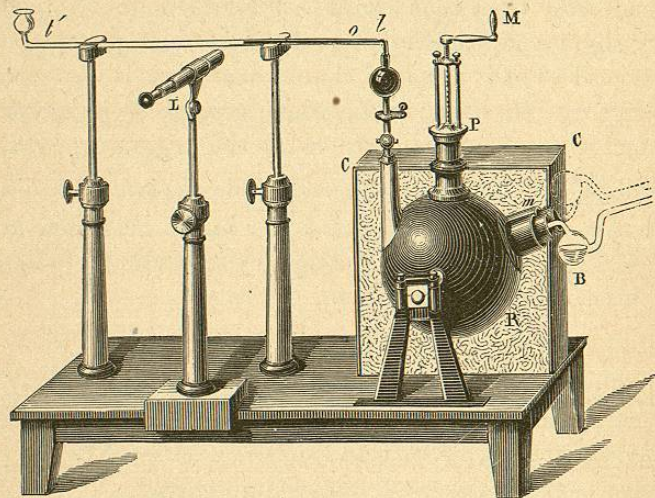


Fig. 129.—Calorimeter of Favre and Silbermann.

when oxygen and hydrogen unite to form liquid water; and sometimes to its absorption, as in freezing-mixtures. The observed thermal effect is therefore the sum or difference of two separate effects; and in general no attempt has been made to assign their respective proportions.

230. Observations on Heat of Combination.—Elaborate observa-

tions on the heats of combination of various substances have been made by Andrews, by Favre and Silbermann, and by Thomsen (of Copenhagen). The apparatus chiefly employed by Favre and Silbermann is represented in Fig. 129.

It is a kind of large mercurial thermometer, the reservoir R of which is made of iron, and contains one or more cylindrical openings similar to that shown at *m*. Into these are fitted tubes of glass or platinum, in which the chemical action takes place. One of the substances is introduced first, and the other, which is liquid, is then added by means of a pipette bent at B, and containing the liquid in a globe, as shown in the figure. This is effected by raising the pipette into the position indicated by the dotted lines in the figure.

In the upper part of the reservoir is an opening fitted with a tube containing a steel plunger P, which descends into the mass of mercury, and can be screwed down or up by turning the handle M. To prepare the apparatus for use, the plunger is so adjusted that the mercury stands at the zero-point of the graduated tube *tt'*, the action is then allowed to take place, and the movement of the mercurial column is observed with the telescope L. In order to measure the quantity of heat corresponding to this displacement, a known weight of hot water is introduced into the reservoir, and allowed to give up its heat to the mercury; the displacement of the mercurial column is then observed, and since the quantity of heat corresponding to this displacement is known, that corresponding to any other displacement can easily be calculated. The iron reservoir is inclosed in a box filled with wadding or some other non-conducting material.¹

When the chemical action takes the form of combustion, a different arrangement is necessary. The apparatus employed by Favre and Silbermann for this purpose is of too complex a construction to be described here. Fig. 130 represents the much simpler apparatus employed for the same purpose by Dulong.

It consists of a combustion-chamber C surrounded by the water contained in a calorimeter D, in which moves an agitator whose stem

¹ In the mode of experimentation adopted by Dr. Andrews, the combination takes place in a thin copper vessel inclosed in a calorimeter of water to which it gives up its heat; and the rise of temperature in the water is observed with a very delicate thermometer, the water being agitated either by stirring with a glass rod or by making the whole apparatus revolve about a horizontal axis.

In experimenting on the heat of combustion, the oxygen and the substance to be burned are introduced into the thin copper vessel, which is inclosed in the calorimeter as above, and ignition or explosion is produced by means of electricity.

is shown at A. The combustible substance, if it be a gas, is conducted into the chamber through the tube *h*, and the oxygen necessary for its combustion enters by one of the tubes *f* or *p'*. The products of combustion pass through the worm *s*, and finally escape, but not until they have fallen to the temperature of the water in the calorimeter. This condition is necessary to the exactness of the result, and its precise fulfilment is verified by observing the temperatures indicated by the thermometers *t* and *t'*, the former of which gives the temperature of the water, and the latter that of the products of combustion at their exit. These two temperatures should always agree. The progress of the combustion is observed through the opening *p*, which is closed by a piece of glass.

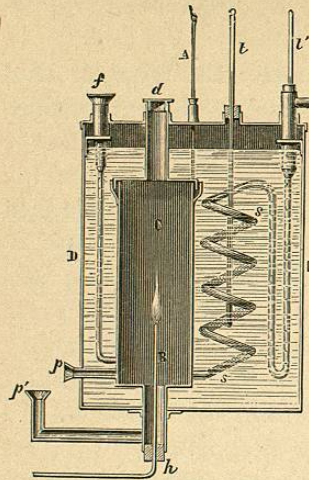


Fig. 130.—Dulong's Calorimeter for Combustion.

The following table exhibits some of the principal results. The numbers denote the mass of water which would be raised 1° C. in temperature by the heat evolved in the combustion of unit mass of the substance, the combustion being supposed to take place in air or oxygen, with the exception of the second example on the list.

HEATS OF COMBUSTION.			
Hydrogen,	34,462	Soft sulphur,	2,258
Hydrogen with chlorine,	23,783	Sulphide of carbon,	3,400
Carbonic oxide,	3,403	Olefiant gas,	11,857
Marsh-gas,	13,063	Ether,	9,028
Charcoal,	8,080	Alcohol,	7,184
Graphite,	7,797	Stearic acid,	9,616
Diamond,	7,770	Oil of turpentine,	10,852
Native sulphur,	2,261	Olive-oil,	9,862

Of all substances hydrogen possesses by far the greatest heat of combustion. This fact accounts for the intense heating effects which can be obtained with the oxy-hydrogen blow-pipe, in which an annular jet of hydrogen is completely burned by means of a central jet of oxygen.

231. *Animal Heat and Work.*—We have every reason to believe that animal heat and motions are derived from the energy of chemical combinations, which take place chiefly in the act of respiration, the

most important being the combination of the oxygen of the air with carbon which is furnished to the blood by the animal's food. The first enunciation of this view has been ascribed to Lavoisier. Rumford certainly entertained very clear and correct ideas on the subject, for he says, in describing his experiments on the boring of cannon:—

“Heat may thus be produced merely by the strength of a horse, and, in a case of a necessity, this heat might be used in cooking victuals. But no circumstances could be imagined in which this method of procuring heat would be advantageous; for more heat might be obtained by using the fodder necessary for the support of a horse as fuel.”

When the animal is at rest, the heat generated by chemical combination is equal to that given off from its body; but when it works, an amount of heat disappears equivalent to the mechanical effect produced. This may at first sight appear strange, in view of the fact that a man becomes warmer when he works. The reconciliation of the apparent contradiction is to be found in the circumstance that, in doing work, respiration is quickened, and a greater quantity of carbon consumed.

Elaborate experiments on this subject were conducted by Hirn. He inclosed a man in a box containing a tread-mill, the shaft of which passed through the side of the box; and the arrangements were such that the man could either drive the mill against external resistance, by continually stepping from one tread to the next above in the usual way, or could resist the motion of the mill when driven from without, by continually descending the treads, thus doing negative work. Two flexible tubes were connected, one with his nostrils, and the other with his mouth. He inhaled through the former, and exhaled through the latter, and the air exhaled was collected and analysed. The heat given off from his body to the box was also measured with some degree of approximation. The carbon exhaled, and heat generated, were both tolerably constant in amount when the man was at rest. When he was driving the mill by ascending the treads, the heat given out was increased, but the carbon exhaled was increased in a much greater ratio. When he was doing negative work by descending the treads, the heat given out, though less in absolute amount, was greater in proportion to the carbon exhaled, than in either of the other cases.

232. *Vegetable Growth.*—In the growth of plants, the forces of chemical affinity do negative work. Particles which were previously

held together by these forces are separated, and potential energy is thus obtained. When wood is burned, this potential energy is converted into heat.

We are not, however, to suppose that plants, any more than animals, have the power of *creating* energy. The forces which are peculiar to living plants are merely *directive*. They direct the energy of the solar rays to spend itself in separating the carbon and oxygen which exist united in the carbonic acid of the air; the carbon being taken up by the plant, and the oxygen left.

Coal is the remnant of vegetation which once existed on the earth. Thus all the substances which we are in the habit of employing as fuel, are indebted to the sun for the energy which they give out as heat in their combustion.

233. *Solar Heat*.—The amount of heat radiated from the sun is great almost beyond belief. The best measures of it have been obtained by two instruments which are alike in principle—Sir John Herschel's *actinometer* and Pouillet's *pyrheliometer*. We shall

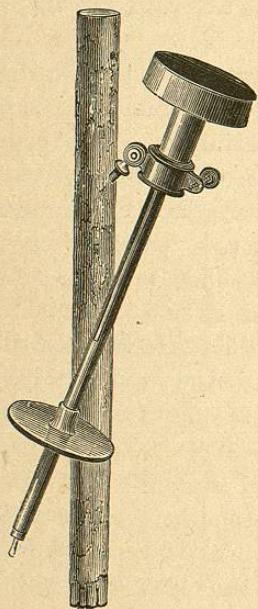


Fig. 131.—Pyrheliometer.

describe the latter, which is represented in Fig. 131. At the upper end, next the sun, is a shallow cylinder composed of very thin copper or silver, filled with water in which the bulb of a thermometer is inserted, the stem being partially inclosed in the hollow tube which supports the cylinder. At the lower end of the tube is a disc equal and parallel to the base of the cylinder. This is intended to receive the shadow of the cylinder, and thus assist the operator in pointing the instrument directly towards the sun. The cylinder is blackened, in order that its absorbing power may be as great as possible.

The instrument, initially at the temperature of the atmosphere, is first placed for five minutes in a position where it is exposed to the sky, but shaded from the sun, and the increase or diminution of its temperature is observed; suppose it to be a fall of θ° . The screen which shaded it from the sun is then withdrawn, and its rise of temperature is observed for five minutes with the sun shining upon it;

call this rise T° . Finally, it is again screened from the sun, and its fall in five minutes is noted;—call this θ° . From these observations it is inferred, that the instrument, while exposed to the sun, lost $\frac{\theta + \theta'}{2}$ to the air and surrounding objects, and that the whole heat which it received from the sun was $T + \frac{\theta + \theta'}{2}$, or rather was the product of this difference of temperature by the thermal capacity of the cylinder and its contents. This is the heat which actually reaches the instrument from the sun, but a large additional amount has been intercepted by absorption in the atmosphere. The amount of this absorption can be roughly determined by comparing observations taken when the sun has different altitudes, and when the distance traversed in the air is accordingly different. Including the amount thus absorbed, Pouillet computes that *the heat sent yearly by the sun to the earth would be sufficient to melt a layer of ice 30 metres thick, spread over the surface of the earth*; and Sir John Herschel's estimate is not very different.

The earth occupies only a very small extent in space as viewed from the sun; and if we take into account the radiation in all directions, the whole amount of heat emitted by the sun will be found to be about 2100 million times that received by the earth, or sufficient to melt a thickness of two-fifths of a mile of ice per hour over the whole surface of the sun.

234. *Sources of Solar Heat*.—The only causes that appear at all adequate to produce such an enormous effect, are the energy of the celestial motions, and the potential energy of solar gravitation. The motion of the earth in its orbit is at the rate of about 96,500 feet per second. The kinetic energy of a pound of matter moving with this velocity is equivalent to about 104,000 pound-degrees Centigrade, whereas a pound of carbon produces by its combustion only 8080. The inferior planets travel with greater velocity, the square of the velocity being inversely as the distance from the sun's centre; and the energy of motion is proportional to the square of velocity. It follows that a pound of matter revolving in an orbit just outside the sun would have kinetic energy about 220 times greater than if it travelled with the earth. If this motion were arrested by the body plunging into the sun, the heat generated would be about 2800 times greater than that given out by the combustion of a pound of charcoal. We know that small bodies are travelling about in the celestial spaces; for they often become visible to us as meteors, their incan-