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The Cambridge Technical Series
General Editor: P. Abbott, B.A.

# ELEMENTARY PHYSICS FOR ENGINEERS

CAMBRIDGE UNIVERSITY PRESS
C. F. CLAY, MANAGER
London: FETTER LANE, E.C.
Edinburgh: 100 PRINCES STREET

New York: G. P. PUTNAM'S SONS
Bombay, Calcutta and Madras: MACMILLAN AND CO., LTD.
Toronto: J. M. DENT AND SONS LTD.
Tokyo: THE MARUZEN-KABUSHIKI-KAISHA

# ELEMENTARY PHYSICS FOR ENGINEERS

AN ELEMENTARY TEXT BOOK FOR FIRST YEAR STUDENTS TAKING AN ENGINEERING COURSE IN A TECHNICAL INSTITUTION

BY

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Cambridge :
at the University Press
1916

# PREFACE

THE importance of Physics to the engineer is inestimable but the student of engineering does not often recognise the fact.

This little volume is intended to appeal to him firstly because it is written specially for him and secondly because the author has attempted to present some essential facts of elementary physics as briefly and straightforwardly as possible without any pedantry or insistence upon details of no practical importance. He has also avoided all reference to historical determinations of physical constants and has described in all cases the simplest and most direct methods, merely indicating the directions in which refinements might be made. At the same time he has endeavoured to make no sacrifice of fundamental principle and no attempt has been made to advance with insufficient lines of communication.

The author frankly admits that he has tried to be interesting and readable, and in case this should be regarded as a deplorable lapse from the more generally accepted standards he pleads the privilege of one who has had considerable experience with students of engineering in Technical Institutions.

He hopes by this little volume to induce a greater number of engineering students to recognise that Physics is as essential to engineering as is Fuel to a Steam Engine.

J. P. Y.

LONDON, 1916.

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# CHAPTER I

## MATTER AND ITS GENERAL PROPERTIES

We all know that there are many different states or conditions of matter. Ice, water and steam are three different conditions of exactly the same kind of matter; they differ only in having distinctive physical properties, being constitutionally or chemically identical. Though they have certain distinctive characteristics—such for example as the definite shape of a piece of ice and the entire lack of shape of water or steam: the definite volume of a given weight of water and the indefiniteness of the volume of a given weight of steam which can be compressed or expanded with ease—they have nevertheless certain properties in common with all other forms of matter.

Indeed it is common to define matter as that which occupies space or that which has weight. Each of these definitions names a property common to all matter. It seems rather unnecessary to try to define matter: we feel that everyone must know what matter is: and the definitions are likely to introduce ideas more difficult to appreciate than the thing which is being defined. But we can see nevertheless that it may be useful and even necessary to have some definite dividing line between matter and the various sensations which can proceed from it. The colour of a rose is merely a sensation: its perfume is the same: but the rose itself is matter. Our distinction is that the rose has weight and occupies space. Colour has no weight, nor does it occupy space.

Again when a piece of coal is burning it is giving out Heat. Is that heat matter? Well, if we apply the test of weight to it we find that it is not. A hot object weighs neither more nor less than the same object cold. If we weigh the coal before it is ignited and then while it is burning if we collect all the products of the burning—that is to say all the gas and smoke and ash—we should find that there was no change in weight. This is a well-known experiment—though usually done with a piece of candle instead of coal—and it is being mentioned now to shew that though this burning matter is giving out heat, and also light, yet these things are weightless and are therefore outside our definition of matter. For if they had weight then the mere residue of the ash and the fumes would not have had the same weight as the original matter. We will return presently to the further question of how we shall classify Heat.

The experiment quoted above is one of many which have led us to the firm belief that matter cannot be destroyed. We can change its form both physically and chemically but we cannot annihilate it. This is one of the fundamental laws of physical chemistry and one of the greatest importance and usefulness.

**Weight.** All forms of matter possess *weight*. It is to be supposed that all readers know what is meant by the statement. In books of this kind much space and many words are used to convey to the readers' minds ideas with which they must already be sufficiently familiar. We explain that *Force* is that which produces or tends to produce motion: that it is also that which is necessary to destroy motion: that it is also necessary if the direction of motion of a body is to be changed. We then proceed to define *motion* as the change of position of a body with respect to some other body; and we may even devote some space to the explanation of what *position* is. It is extremely probable that everyone knows these things, though it is very likely that only a few could frame their knowledge in words.

In the same way weight is the attraction between every portion of matter and the earth. This attraction tends to draw everything vertically downwards towards the earth. It is called the force of gravitation; but nobody has the least idea *why* the earth attracts things or what this mysterious force is. We are so used to it, it is so continually present that we take it quite as a matter of course, and never pause to consider that it is mysterious and inexplicable. The attraction of a needle to a magnet fills us with wonder or awe but the attraction of a stone to the earth seems to be inevitable and ordinary.

Weight then is a *force*; it is a particular force which acts only in one direction upon matter, and that direction is vertically downwards. Of course the force is also tending to pull the earth vertically upwards, but the reader will have no difficulty in appreciating the fact that no movement of the earth as a whole would be detected by us. We can think of every portion of matter being attached to the centre of the earth by imaginary stretched elastic threads. These threads will be in tension and will tend to shorten by pulling the object *and* the earth towards each other. The pull will be equal in both directions—but when we think of the enormous *mass* of the earth compared with the *mass* of the object we may be considering we can readily see that the object will go downwards much more than the earth will come up. At the same time we can see the *tendency* and in seeing that we are also seeing something of a very important mechanical law about the reaction which accompanies every action.

We say then that matter is that which possesses weight. Air and all other gases can be weighed by taking a flask, exhausting the air from it by means of a vacuum pump, weighing it carefully, and then allowing either air or any other gas to enter it when it can be weighed again. The increase in weight will represent the weight of that flask of the gas at the particular pressure under which the flask was filled. If a higher pressure were used then, as more gas would be forced into the flask, the increase in the weight would be correspondingly greater.

**Mass.** This leads us naturally to the meaning of the word *mass*. By the mass of a body we mean the quantity of matter in it. This is often confused with bulk or volume and of course the greater the volume of any one particular kind of matter the greater must be the quantity of that matter. But on the other hand is there the same quantity of stuff in a cubic foot of cork as there is in a cubic foot of lead? Is there the same quantity of steam in a given boiler, with the water level at a certain point, whatever the steam pressure may be? The answers will suggest that we cannot compare the masses of different kinds of matter by comparing their volumes.

It is usual to compare masses of matter by weighing them. A quantity of cork weighing 1 pound contains the same quantity of matter as a piece of lead weighing 1 pound. At the same time we must be careful to remember that weight is simply the *force of attraction* between the matter and the earth and that *mass* is the quantity of stuff in it. When we ask for a pound of sugar we want a mass of it which is attracted to the earth with a force of 1 lb. weight.

It may help us to see this distinction if we remember —as most of us probably do—that a given object has slightly different weights or forces of attraction at different parts of the earth, owing to the shape of the earth and to the fact that at some places we are nearer to its centre than at others. Well, although an object may have different weights, yet we know that its mass must remain the same. This helps us to see the distinction between the two—though it may suggest certain difficulties in buying by weight from different parts of the earth. As a matter of fact the difference is very slight--about two parts in a thousand at the outside—and if the substances be weighed with balances and "weights" we can see that the "weights" will be equally affected and that we should get equal masses from different places. But if spring balances be used then a pound weight of sugar sent from a place far north would be a smaller mass than a pound sent from a place near the equator.

The reader will learn in the mechanics portion of his course of study how masses may be compared in other ways in which the weights are eliminated.

**Inertia.** There is another property, called *Inertia*, which is common to all forms of matter. When we say that matter has inertia we mean (*a*) that it cannot start to move without the application of some force, (*b*) that, if moving, it cannot stop without the application of force, (*c*) that if moving in any particular direction it will continue to move in that direction unless some force or forces be applied to it to make it change its direction. That is to say *force* is necessary to overcome *inertia*.

Inertia is not a cause and it is not a reason. It is the name given to the fact that every object tends to remain in whatever condition of motion or rest it may be at any given moment. That tendency means that it is very difficult to start anything *suddenly* or to stop it *suddenly* or to change its direction of motion *suddenly*. Experimental verification of these truths may be obtained by anyone during a short journey in a tramcar. If one is standing in a stationary car, scorning the friendly aid of "the strap," and the car starts abruptly one learns that matter (oneself in this case) tends to remain in its previous condition of rest, and that straps are really useful adjuncts of the car.

If the motorman suddenly applies his brakes and reduces the speed of the car the passengers shew a unanimous tendency to continue their previous speed by side-slipping along their seats in the direction of the car's motion. If one is walking towards the conductor's end during this slowing down process one finds considerable difficulty in getting there, just as though one was climbing a very steep hill against a stiff breeze. If one is walking towards the motorman's end and he slows down one finds it difficult not to run. In rounding a sharp curve—that is to say changing the direction of motion—there is always the tendency to be thrown towards the *outside* of the curve, shewing the tendency of moving matter to continue in its original direction.

There are countless examples of this property of matter. A hammer head reaches a nail, but it does not stop suddenly: the distance the nail is driven in depends on the kind of nail and the substance and the weight and the speed of the hammer. Chiselling, forging, pile-driving, wood-chopping, stone-breaking and cream-separating are amongst the many processes which depend upon the fact that matter possesses inertia. The "banking" of railway tracks at all curves so that the outer rail is higher than the inner is necessary to assist the train to change its direction of motion. When a motor car or a bicycle side-slips it is due to the tendency to continue in its original direction and if it is taken round the corner too sharply the result will be side-slipping or overturning to the *outside* of the curve. Most people fondly believe that if a cart is taken too suddenly round a bend it will fall *inwards*. Let the reader ask any half-dozen of his friends.

Then we know how difficult it is to start moving on a very slippery floor, or on ice, and how equally difficult it is to stop again. It is not suggested here that one's inertia is any greater than it would be on a rough floor: the point is that one cannot get a "grip" and thus cannot exert such a large force either to start or to stop. The skidding of a locomotive when starting with a train of great *mass* is another example of this point.

**Theory of Structure of Matter.** In order to explain and connect the many facts of nature it is necessary that we should have some idea of the structure of matter. The generally accepted theory is that known as the kinetic theory, a theory which assumes that all substances are composed of an enormous number of very small particles or grains called *molecules*. Further it assumes that these molecules are not generally in contact with their neighbours but are in a state of continued agitation and vibration; that collisions between them are of frequent occurrence; that even when any two or more are in contact with one another there are distinct interspaces between them called inter-molecular spaces.

According to this theory a portion of matter is not continuous substance but a conglomeration of small particles which attract one another with a force called *cohesion*.

The motion of the molecules in solid matter is very restricted: it is probably rather in the nature of vibration or oscillation than migration. In liquids the molecules are not supposed to be so close together and thus may thread their way through the mass like a person in a crowd. In the case of gases the spaces between the molecules are assumed to be still greater so that the molecules can move about with considerable freedom.

It is also believed that the hotter a body is the greater does the movement and vibration of each molecule become. That is to say, the energy of movement of each molecule is increased as the temperature is increased. Indeed from this theory it is argued that if the temperature could be lowered until there was no molecular agitation there could be no heat in the body and such a temperature would be the absolute zero of temperature.

**Classification of matter.** Apart from the properties which are common to all kinds of matter there are other properties which are peculiar to one form or another. Such properties enable us to classify matter into different groups. In physics such classification is based solely upon physical properties and our groups are only three in number namely, solids, liquids and gases. Sometimes indeed it is said that there are only two groups, solids and fluids, the word fluid including liquid and gas.

Solids are distinguished from fluids—that is from liquids and gases—in that each portion of a solid has a definite shape of its own. This property is termed *rigidity*. Liquids and gases have no rigidity: a portion of a liquid has no definite shape though it has a definite volume: a given weight of a gas has no definite shape, and its volume depends upon the pressure acting upon it. This latter fact helps us to distinguish between a liquid and a gas. A liquid is practically incompressible but a gas is readily compressed.

A fluid cannot resist a stress unless it is supported on all sides.

**Density.** Though all forms of matter have weight yet if we take the same bulk or volume of different forms such as cork, water, lead and marble we shall find that they have different weights.

The mass of a unit volume of a substance is called the *density* of that substance.

If we know the density of a substance we can calculate either the mass of any known volume or the volume of any known mass.

On the British system of units density would be expressed in pounds per cubic foot. On the metric system it is expressed in grammes per cubic centimetre.

Thus the density of pure water (at 4° C.) is 62·4 approximately on the British system and 1 on the metric system. Lead is 705·12 on the British and 11·3 on the metric. Of course in both systems the lead is 11·3 times as heavy as the same bulk of water. (See Chapter II.)

For the determination of the density of a substance it is only necessary to be able to weigh a portion of the substance and then to find its volume. If the substance has a regular form its volume can be calculated. If it be irregular it can be immersed in water and the volume of displaced water can then be measured. There are many simple methods of obtaining and measuring the displaced water. There is the obvious method of placing a label to mark the level of water in a vessel and then placing the substance in the vessel. The water above the label mark is now sucked out by means of a pipette until the level is restored. The volume of the water removed must of course be that of the substance and it can be measured in a graduated vessel.

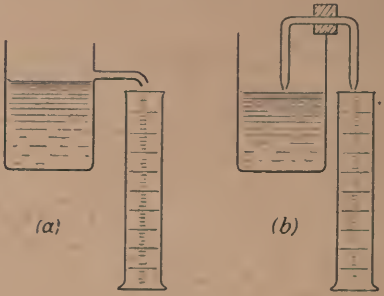


Fig. 1

Fig. 1 illustrates special forms of vessels designed to facilitate the collection and measurement of the displaced water. In (*a*) the vessel is filled up with water and allowed to adjust its level through the side spout.

A dry measuring vessel is then placed under the spout and the substance whose volume is required is carefully lowered into the water. The other form (*b*) is called a volumenometer and it utilises a small siphon with the ends drawn out to fine points. This prevents the siphon from emptying itself. Its use is obvious.

More refined methods depend upon weighing instead of measuring the displaced water (as with the specific gravity bottle) and upon the principle of Archimedes. The reader will be able to appreciate these after reading Chapter II.

*Densities of some common substances.*

| Substance | Density in lbs. per cubic foot (approx.) | Density in grammes per cubic centimetre * |
|---|---|---|
| Platinum | 1344 | 21·522 |
| Gold | 1200 | 19·245 |
| Lead | 712 | 11·4 |
| Silver | 655 | 10·5 |
| Copper | 549–556 | 8·8 –8·9 |
| Iron (wrought) | 466–487 | 7·47–7·8 |
| Iron (cast) | 378–468 | 6·9 –7·5 |
| Steel | 435–493 | 7·73–7·9 |
| Brass | 505–527 | 8·1 –8·45 |
| Oak | 43·2–61·9 | 0·69 to 0·99 |
| Water | 62·4 | 1 |

* Since the mass of 1 cubic centimetre of water is 1 gramme it follows that the density of a substance in grammes per cubic centimetre is *numerically* equal to its *relative density* or specific gravity with respect to *water* (see page 25).

**Properties of Solids.** Different solids differ from one another not only in chemical composition but also in physical characteristics. Such properties of solids as porosity, hardness, malleability, ductility, plasticity and elasticity are shewn in various degrees in different substances. The nature of the properties denoted by the words above is generally understood—with the exception, perhaps, of that property called elasticity.

**Elasticity.** If the reader were asked to state what was the most highly elastic substance we know of he would probably give india-rubber without much hesitation. Now elasticity is measured by the magnitude of the force which is necessary to produce a given change in the shape of a substance: and for such comparison it is necessary that all the substances used be of the same original dimensions. If we were going to compare elasticity so far as stretching is concerned then we would use wires of equal length and equal diameter and we would find out what weights we should have to load on the bottom end in order to stretch them by the same amount. That substance which required the largest weight would have the greatest *elasticity*.

Of course it would be necessary to see that when the weights were removed again the wires returned to their original lengths. If they did not—that is if they were permanently stretched—then we must have loaded them beyond their *limits of elasticity*. Some substances can be temporarily stretched to a great extent and such are said to have wide limits of elasticity. Thus india-rubber has not a very high degree of elasticity—that is to say it is easily stretched—but it has very wide limits of elasticity. Steel has a high degree of elasticity but very narrow limits.

The same statements apply to compression, to bending and to twisting.

**Stress and Strain.** When the form or shape of a body has been altered by the application of a force the alteration is called a *strain*. If a piece of india-rubber is stretched (from 6 inches to 7 inches) the change is called a *strain*. The same term would be used if it was compressed to 5 inches, or twisted round through any number of degrees, or bent to form an arc. The force producing the strain is called a *stress*. In strict usage the word *strain* is used to denote the change produced per unit of length. In a case of stretching for example the extension per unit length of the substance is the strain. If a wire be 60 inches long and it is extended by 1·5 inches then the strain is

$$\frac{1{\cdot}5}{60} = {\cdot}025.$$

Similarly *stress* is used to denote the force per unit area of cross section. Thus if the wire quoted above has a diameter of 0·05 inch and the stretching force was 10 lbs. weight the stress would be 10 ÷ area of cross section of the wire

$$\frac{10}{3{\cdot}14 \times ({\cdot}025)^2} = 5095 \text{ lbs. per sq. inch.}$$

**Hooke's Law.** From a series of experiments Hooke deduced the law that within the limits of elasticity *the extension of a substance is directly proportional to the stretching force.*

It may also be expressed that strain is directly proportional to stress. The ratio of $\frac{\text{stress}}{\text{strain}}$ for any substance is called Young's *modulus* for that substance. This is an important quantity in that section of engineering work dealing with the strength of materials.

Hooke's law also applies to twisting. If a wire be rigidly fixed at one end and a twisting force applied to the other the angle of twist or *torsion* will be directly proportional to the twisting force. It also applies to bending. If a beam be laid horizontally with each end resting on a support and it be loaded with weights at the centre it will bend. The extent to which the centre of the beam is depressed vertically below its original position is called the *deflexion* of the beam. The deflexion is directly proportional to the bending force.

It will be obvious that in all these cases—stretching, compressing, twisting or bending—the amount of change produced will depend not only upon the force applied but also upon the original length of the substance, upon its cross sectional area and upon the particular material used.

## EXAMPLES

(*See table above for densities*)

1. What is the weight of a cylinder of copper (*a*) in lbs., (*b*) in grammes, if it is 6″ high and 2″ diameter and an inch is approximately 2·54 cms.?

2. What would be the volume of a piece of gold which would have the same weight as 1 cubic foot of silver?

3. If sheet lead costs £27 per ton, what will be the cost of a roll 32 feet long, 3 feet wide and ⅛″ thick?

4. What is the density of the sphere which weighs 4 lbs. and has a diameter of 3 inches?

5. In what proportions should two liquids *A* and *B* be mixed so that the mixture shall have a density of 1·2, the density of *A* being 0·8, that of *B* 1·6.

6. A wire of diameter 0·035 inch and 6 feet long is found to become longer by 0·25 inch when an extra weight of 14 lbs. is hung on to it. What is the stress and the strain and Young's modulus of elasticity?

# CHAPTER II

## PROPERTIES OF LIQUIDS

As we have seen liquids have no *rigidity* and therefore have no definite shape. A given mass of liquid will always assume the shape of the portion of a vessel which it occupies. Moreover a liquid is practically incompressible and in this respect it differs from those fluids which we call gases.

If we place some water in a vessel we know that the weight of the water must be acting on the base of that vessel. But we also know that the water does not merely exert a downward pressure. If holes are pierced in the vessel at positions *A* and *B*—as shewn in Fig. 2—we find that the water streams out through

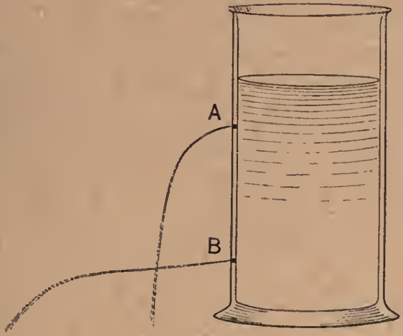


Fig. 2

them and that it comes out from *B* with a greater velocity than from *A*. This indicates firstly that the water must be exerting horizontal pressure on the sides of the vessel: and secondly that the pressure at *B* is greater than that at *A*.

**Pressure at different depths.** It does not require any deep reasoning to realise that as we pour more water into a given vessel the downward pressure upon its base must increase and that the greater the depth of liquid the greater will be this downward pressure.

If we did not conduct any investigations we might be led to conclude that if we place a piece of cork sufficiently far below the surface of water it would sink—forced downwards by the enormous pressure which would be exerted at a great depth. But our experiences—that is to say our investigations, whether they were deliberate or casual—tell us that this is not true. Our experiences tell us that when we put our hands under water we are *not* conscious of an extra weight upon them: that when we put them at greater depths we are not conscious of any greater weight than when they were near the surface: that, in fact, we are conscious that our hands seem to be altogether *lighter* when held under the water and that different depths do not appear to make any difference at all upon the sensation of lightness. Our experiences teach us that when we dive into water, instead of being weighed down by the weight of water above us we are in fact buoyed up and we ultimately come—at any rate those of us who are reading must always have come—to the surface.

Well then, our experiences tell us that somehow or other there appears to be an upward pressure in a liquid. One simple experiment to illustrate this is to take a piece of glass tube open at both ends; close one end by placing a finger over it; place the tube vertically in a tall jar of water with the open end downwards. A *little* water will be forced up the tube—compressing the air inside. As it is lowered further more water will be forced up the tube and the air inside will be more compressed. There must be some *upward* pressure to do this. Then remove the finger from the top: water will rush up the tube and may even be forced out through the top in the first rush. Ultimately it will settle down so that the water level inside the tube is the same as that outside—suggesting therefore that this upward pressure at the bottom of the tube is exactly equal to the downward pressure there.

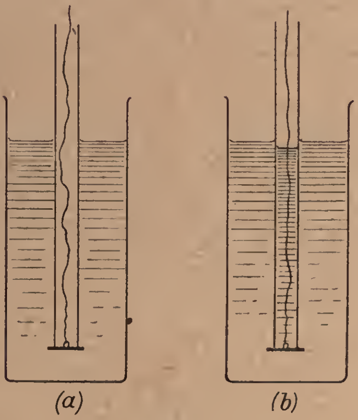

(a) (b)

Fig. 3

A more convincing experiment is illustrated by Fig. 3. A fairly wide glass tube open at both ends has one end carefully ground flat and a circular disc of aluminium is placed against this end. It is held tightly on by means of a piece of string passing up through the middle of the tube. It is then immersed in a tall jar of water—the disc-covered end downwards—and it is found that the string is no longer necessary to hold on the disc. The upward pressure on the bottom of the disc is sufficient to hold it on.

If now some water be poured carefully into the tube it will be found that the disc will not fall off until the level of the water inside the tube is very *nearly* equal to that in the jar. If the disc were made of a substance of the same density as water it would hold on until the level was quite up to that in the jar. This experiment shews very clearly that the upward pressure on the bottom of the disc was equal to the downward pressure which would have been exerted on it if it had been immersed at the same depth—for when the tube was filled with water to the same depth as in the jar we found that the downward pressure of this depth just counter-balanced the upward pressure—making due allowances for the weight of the disc.

In addition to this it can be shewn by a similar experiment that the liquid exerts a horizontal pressure and that the horizontal pressure is also equal to the downward and the upward pressures: that in fact at a given point in a liquid there is a pressure in every direction and that it is equal in every direction.

**Pressure at a point.** It is necessary that we should have some clear idea of what is meant by the pressure at a given point in a liquid. If we consider the base of a vessel, for example, it is clear that the weight of water on the base depends not only upon the height of water above it but also on the area of the base. And since different vessels may have different base areas it will be necessary for us in speaking of pressure at any point to speak of the *pressure per unit area* at that point. We may speak of the pressure per square foot or per square inch or per square centimetre, and the *total pressure* on any base will be the pressure per square unit multiplied by the number of square units contained in the base.

Let us suppose that we have a rectangular vessel having a base area of 1 square foot and that it is filled with water to a height of 1 foot. There is therefore 1 cubic foot of water weighing 1000 ozs. resting on a square foot of base. Since there are 144 square inches in the square foot the pressure per square inch must be $\frac{1000}{144} = 6{\cdot}94$ ozs. (approx.). We can say therefore that the pressure at any point on that base area is 6·94 *ozs. per square inch*. And further whatever the shape or size of the base may be if the water above it is 1 foot high the pressure *per square inch* on the base will be 6·94 ozs.

**Pressure at a point depends only on vertical depth and density.** This last statement needs substantiation. An experiment may be performed with a special U-tube —shewn in Fig. 4 (*a*)—which is provided with a screw collar at *sc* on which different shaped and sized limbs may be screwed. Different limbs are shewn in (*b*), (*c*) and (*d*). It is found that if water be poured into the U-tube it will always rise to the same level on each side whatever the shape or size of the limbs may be. Since it follows that when the liquid comes to rest the pressure exerted by the water in the two limbs must be equal, therefore the pressure produced at a given point is not dependent on the size or shape or quantity of water in the vessel but only upon the *vertical* depth (see (*d*)) of the point below the surface and upon the density of the liquid. And it follows that if we have a number of vessels having equal *bases* but having different shapes and volumes the pressure on the bases will be equal if they contain only the same vertical depth of the same liquid. The explanation of this fact may not be very obvious to the reader, but if he has any knowledge of elementary mechanics he will know that there will be "reaction" at every point of the walls of the vessel. If these walls be quite vertical as in (*a*), then the reactions will be horizontal and will balance one another, but in the case of inclined walls the reactions, which will be at right angles to the wall, will therefore add to the mere water weight on the base in (*c*) whilst they will counterbalance the extra water weight in the case (*b*).

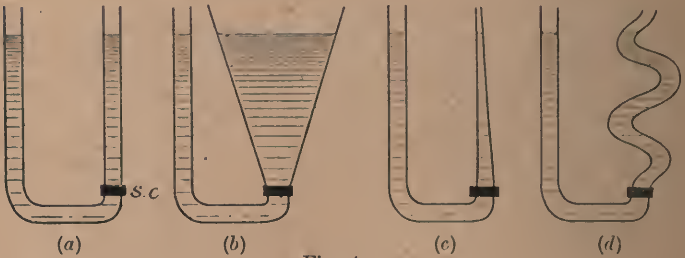


Fig. 4

Therefore in speaking of the pressure at a point in a liquid we have only to think of the vertical depth of that point and the density of the liquid. At a point 1 foot below the surface of water the pressure is 6·94 ozs. per sq. inch *in every direction*: at a point *L* feet below it will be *L* × 6·94 ozs. per sq. inch. If the liquid be *D* times as heavy as water bulk for bulk then the pressure at any point $L$ feet below the surface will be $D \times L \times 6{\cdot}94$ ozs. per square inch.

On the metric system it is even simpler because 1 cubic centimetre of water weighs 1 gramme. Therefore the pressure per square centimetre at any point below the surface will be $D \times L$ *grammes*, where $L =$ depth of the point in centimetres and $D =$ the number of times that the liquid is heavier than water. On the metric system this $D$ will be the *density* in grammes per cubic centimetre.

**Pressure on the sides of a vessel.** Since at any given point the pressure is equal in all directions it follows that the pressure on the sides or walls of a vessel at any point is determined in exactly the same way as it would be for a point on a horizontal surface at the same depth. But of course it will be seen that the pressure on the walls increases gradually with the depth and that the total pressure on the side can only be found by determining the pressure on each unit area and adding them all together.

If the vessel has rectangular sides then we can get the total pressure very simply by finding the pressure at a point half-way down from the surface of the liquid to the bottom and multiplying this by the total number of square inches (or cms., according to units used) which are under the water.

For example, in the case of the tank shewn in Fig. 5, which is a cubical tank of 6 foot side filled to a depth of 5 feet with water, the average pressure on one side will be the pressure at a depth of 2·5 feet below the surface. This is $2{\cdot}5 \times 6{\cdot}94$ ozs. per square inch which is 17·35 ozs. per square inch. There are $5 \times 6 = 30$ square feet below the water and since there are 144 square inches to the square foot it follows that the total pressure on the side will be

144 × 30 × 17·35 ozs. = 74952 ozs. = 4684·5 lbs.

The total pressure on the base will be

(5 × 6·94) × 6 × 6 × 144 = 179,885 ozs.

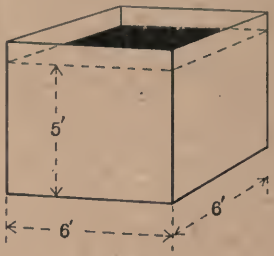


Fig. 5

In the same way the total pressure on a lock gate would be calculated though in that case there would be some water on both sides of the gate at the lower portion. Further, though we get the total pressure in this way it is not of much use in designing a lock gate since it is necessary to design it to stand a much greater pressure at the bottom than at the top of the gate. The same applies to water tanks of any appreciable depth—such as a ship's ballast tanks which are strengthened towards the bottom.

**Buoyancy.** If we imagine that a substance is placed under water, as shewn in Fig. 6, we can see that the water will exert upon it pressure in every direction. But since the substance occupies space it is not a *point* and therefore the pressure in every direction will not be equal. On the upper surface *A* the downward pressure will be due to the vertical depth *SA*; whilst on the lower surface the upward pressure will be due to the vertical depth *SB*, and the side pressures will balance one another. Thus we find that the upward pressure is greater than the downward pressure.

Whether it will sink or float depends now upon the weight of the substance. If this weight is greater than the difference of the upward and downward water pressures then the substance will sink: but if its weight is less than the difference between the upward and downward pressures it will rise to the surface and float.

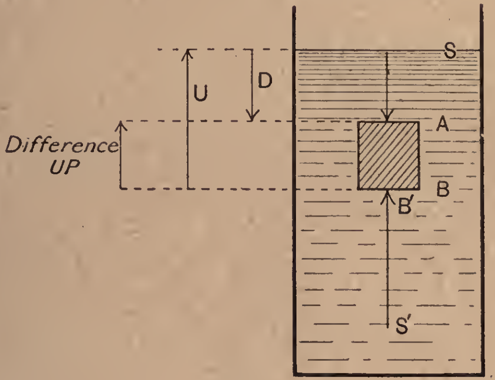


Fig. 6

This will be true whatever the liquid may be, but of course the difference between the upward and downward pressures will be different if we use liquids of different density, and thus substances which would sink in one liquid might float in another.

**Floating Bodies.** When a body floats so that the top of it is above the surface then there is no downward liquid pressure upon it at all. Therefore it will float to such a depth that the upward liquid pressure upon it is just equal to its own weight. If, therefore, we take some similarly shaped pieces of different substances which will float, and put them on water the denser substances will sink deeper than the lighter, and the volumes of the submerged portions will be in proportion to the densities of the several substances.

**Archimedes' experiment.** Figure 7 (*a*) represents a spring balance on the hook of which is suspended a hollow cylinder or bucket. Under this is also suspended a solid cylinder having the same external dimensions

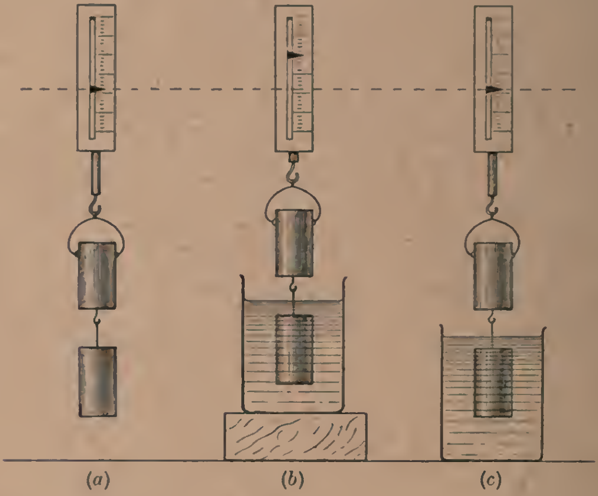


Fig. 7

as the internal dimensions of the bucket and having therefore the same volume. It does not matter what this solid cylinder is made of provided that it will sink in water. The reading of the spring balance is shewn. The solid cylinder is then immersed in water—(*b*)—and of course the arrangement weighs less than before as shewn by the balance. The bucket is then gradually filled with water. When it is quite full (*c*) the balance is found to shew the same weight as it did originally.

This is known as Archimedes' experiment and it shews that the cylinder weighed less in water than in air *by the weight of its own volume of water.*

If the experiment be repeated using some other liquid it will be found that when the bucket is filled with that liquid the original weight will be registered on the balance.

Thus it is said that when a body is immersed in any liquid its net weight is less than its weight in air by the weight of the liquid which it *displaces.*

This is equivalent to saying that the difference between the downward and the upward pressures on an immersed body is equal to the weight of the liquid which the body displaces. When the body is wholly immersed the volume of displaced liquid is equal to the volume of the body.

In speaking of a ship's weight it is customary to state that its "displacement" is so many tons—a statement which means that the volume of the water which is displaced by the vessel when floating to its "no cargo" line would weigh that number of tons. This, of course, means that the ship and its fittings also have that weight.

**Determination of Specific Gravity or Relative Density.** The specific gravity of a substance—*which is the ratio of the weight of any given volume of the substance to the weight of the same volume of water*—may be determined in many ways. The direct methods consist simply in weighing the substance and then weighing an equal bulk of water. It is not always simple to find the volume of the substance—though this can always be done "by displacement," that is by immersing the substance in a graduated vessel of water and noting the level of the water before and after the substance is immersed. The difference in the two volumes will be the volume of the substance and such a volume of water can then be weighed. If the substance is one which dissolves in water—like copper sulphate crystals for example—then it can be placed in the graduated vessel containing some liquid in which it does not dissolve—such as alcohol in the case chosen. The difference in volume will give the volume of the crystals and an equal volume of water can then be weighed out.

The specific gravity or relative density as it is often called is the ratio

$$\frac{\textit{Weight of a given volume of the substance}}{\textit{Weight of an equal volume of water}}.$$

The reader will doubtless have many opportunities of making this kind of measurement and it should be unnecessary to give any details in these pages.

It should be pointed out however that these direct methods may not give very accurate results owing to the errors likely to arise in the volume measurements—especially when such volumes are small. Thus it is more usual to determine relative densities by utilising the principle of Archimedes. If a substance be weighed firstly in air and secondly suspended in a vessel of water—as shewn in Fig. 8—the difference between these weights represents the weight of the same volume of water as the substance. Thus the specific gravity or relative density can be determined at once: and it will be recognised that the weighing can be done with great accuracy and that the whole measurement will take less time than a "direct" method.

If the substance is one which floats in water, then, after weighing it in air, a "sinker," of lead say, can be attached to it and a second weighing done with the sinker under water and the substance in air: then a third weighing with both sinker and substance under water. The difference between the second and third weighings will be the weight of a volume of water of the same bulk as the substance.

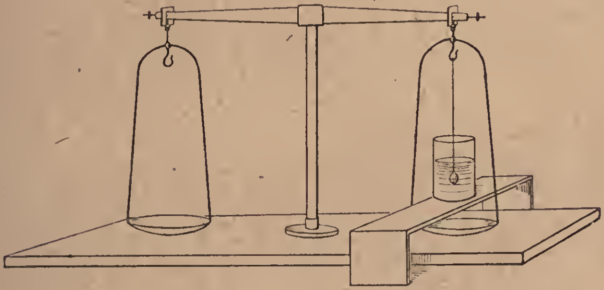


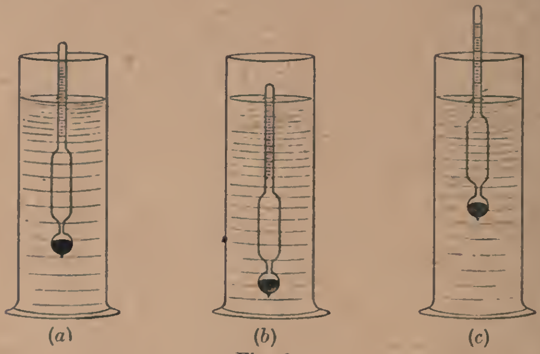
Fig. 8

The relative density of a liquid is determined by weighing a solid in air, then in water and thirdly in the liquid. The difference between the first and second weighings is the weight of a volume of water equal to the volume of the substance; and the difference between the first and third weighings is the weight of the same volume of the liquid.

The relative density of a solid soluble in water is found by weighing in air and then in a liquid in which it is not soluble. The specific gravity or relative density of this liquid must be known or found. The difference between the weighings is the weight of a volume of liquid equal to the volume of the solid. The weight of the same volume of water may then be calculated since the relative density of the liquid is known. From this the relative density of the soluble substance is found.

In the case of powdered substances like chalk or sand the "specific gravity bottle" is used. This is a bottle having a ground glass stopper through which a fine hole is bored. The bottle is filled with water. When the stopper is put in the excess is forced out through the hole and thus the bottle may be completely filled. It is then weighed. The powdered substance is weighed and then put into the bottle. It displaces its own bulk of water. The bottle is weighed again. The specific gravity of the powder can readily be obtained from these weighings.

**The Hydrometer.** The hydrometer is a simple device for measuring directly the specific gravity of a liquid. It is made of glass and usually in the form shewn in Fig. 9. It floats in an upright position and the thin neck has a scale on it which indicates the specific gravity of the liquid in which it is floating. It will always float to such a depth that the weight of the



(*a*) (*b*) (*c*)

Fig. 9

liquid which it displaces will be equal to its own weight. Thus in a lighter liquid it will sink further than in a heavier liquid. In the figure (*a*) represents the position in water, (*b*) in alcohol, and (*c*) in battery strength sulphuric acid. It is usual to have a set of hydrometers to cover a wide range of specific gravities.

Hydrometers are used in many different branches of commerce and the "scales" are usually designed to meet the particular cases. They are not usually direct reading in terms of specific gravity but in terms which meet the needs of the persons who use them. The sailor's hydrometer for example simply indicates the number of ounces above 1000 which will be the weight of 1 cubic foot of sea water. If the hydrometer sinks to 25 it means that 1 cubic foot of that water will weigh 1025 ounces. The brewer's hydrometer has a scale which is used in conjunction with a specially compiled set of tables. And even some of the ordinary hydrometers have scales which require the use of some constant or some empirical formula in order to obtain the specific gravity of the liquid in which they are immersed. Of such kinds perhaps Beaumé's and Twaddell's are best known.

**Pumps.** The action of the simple pumps should not require any detailed explanation after the foregoing discussions. The diagrams shewn should be nearly sufficient.

Fig. 10 illustrates a simple lift pump. In the pump a piston *B* can be moved up and down in a cylinder. In the base of the cylinder is a valve—shewn in the diagram as a flap—which will open if the pressure below is greater than that above and shut if it is less. In the piston *B* is a similar valve which opens and shuts under similar conditions. The cylinder base is connected to the water through a fall pipe.

When the piston is raised the effect is to expand the air between *A* and *B* and so lower the pressure there. This shuts the valve in *B* and the water from the well is forced up the pipe *P* by the excess of the atmospheric pressure over the cylinder pressure. Thus the cylinder becomes filled. The piston is then pushed down. This shuts the valve *A* and opens *B* so that the water is forced to the top of the piston. The piston is raised again and with it, of course, the water above it which comes out of the outlet *O*. At the same time the previous action is going on below the piston.

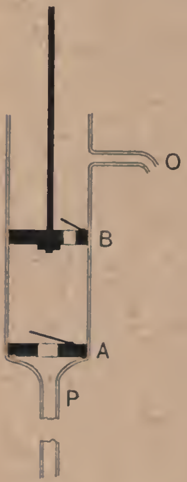


Fig. 10

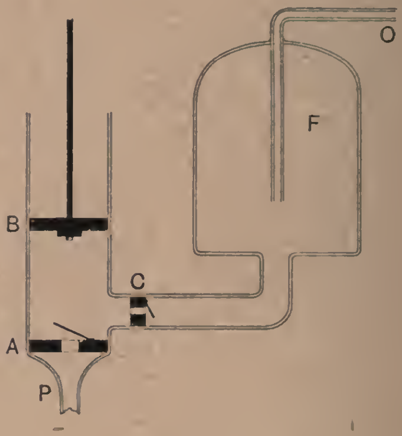


Fig. 11

Fig. 11 illustrates a force pump in which the water is forced out of the outlet under pressure. This is the type of pump used for fire-engine work, garden pumps, etc.

The piston *B* has no valve. When it is lifted valve *A* is opened and *C* is closed. Water enters the pump cylinder. On the downward stroke *A* is closed and the water is forced through *C* into the chamber *F*. As the water rises in this chamber above the lower level of the outlet pipe it will compress the air until ultimately the pressure will be sufficient to force the water through *O* in a more or less continuous stream.

It should be remembered that since pressure is distributed equally in every direction in a liquid a force pump having a small cylinder can nevertheless be used to produce a total enormous pressure. For example if a steam boiler is to be tested for pressure, the test employed is a "water test" in which the boiler is filled completely with water. A *hand* pump capable of generating 300 lbs. per sq. inch pressure is then coupled to the boiler and the pump is operated. This pressure is communicated to the boiler and the water will exert an outward pressure of 300 lbs. per sq. inch on every square inch of the boiler. Any leak will shew itself: and in the event of the boiler breaking down no hurt is likely to be caused to those conducting the test.

It is in the same way that the hydraulic press, the hydraulic ram and hydraulic jack are operated.

The reader possibly knows that the feed water pump of a steam boiler pumps water into the boiler against the steam pressure. If the steam pressure is 150 lbs. per sq. inch then the feed water must be pumped in at a greater pressure. This can be done with quite small pumps, for the pressure which can be generated and distributed does not depend upon the capacity of the cylinder.

**Capillarity.** If we examine the surface of water in a glass vessel we notice that all round the edge next to the glass the water is curved upwards. If we dip a piece of clean glass tube into the water we notice the same curving against the wall of the tube both inside and outside. If the tube has a fine bore we also notice—perhaps to our surprise—that the water rises inside this tube to a greater height than the water outside. If we use tubes of different internal diameters we shall find that the water rises to a greater height in the fine bored tubes than in the large bores. Because of this fact—that the phenomenon is shewn best with tubes as fine as hairs—it is called *capillarity*.

If we use mercury instead of water we observe a reversed formation of the surface, and the mercury in the tube will be depressed below the surface of that outside. Again as we use finer and finer tubes the depression will become correspondingly greater. Fig. 12 illustrates the surface formations in the two cases. Fig. 13 shews what happens when these liquids are poured into U-tubes having a thick and a thin limb—the thin limb being a capillary tube[1].

Mercury does not "wet" glass and if any liquid be placed in a vessel of material which it does not wet its surface would be formed similarly to the mercury in glass. If a pencil of paraffin wax be dipped into water it will be found that the edge of the water against the wax is turned down. If a piece of clean zinc be dipped into mercury the edge of the mercury near to the zinc will be curved upwards—just like water against glass.

There are many illustrations of capillary action.

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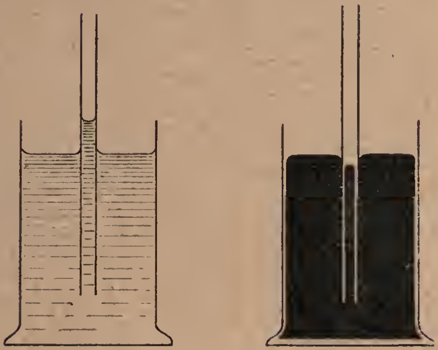
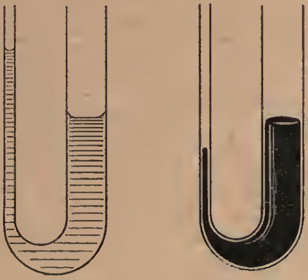
[1] The size of the capillary tube is exaggerated for the purpose of the diagram.

There is the feeding of a lamp-flame with oil: the wetting of a whole towel when one end is left in water: the absorption of ink by blotting paper: the absorption of water by wood and the consequent swelling of the wood.



*Water* *Mercury*

Fig. 12



*Water* *Mercury*

Fig. 13

**Surface Tension.** The surface of any liquid acts more or less like a stretched membrane. A needle can be floated on water if it first be rested on a cigarette paper which will ultimately sink, leaving the needle resting in a little depression on the surface—but actually not making any contact with the water. Many insects walk on the surface of water. A camel-hair brush under water has its hairs projecting in all directions, but when it is withdrawn all the hairs are drawn together as though they were in a fine india-rubber sheath. The formation of a drop of water shews the same thing—how the water seems to be held in a flexible skin. This skin is under tension and endeavouring to contract. Hence we find rain drops are spherical: drops of water run off a duck's back like hailstones off an umbrella: lead shot is made by "raining" molten lead from the top of a tall tower into a water vat at the bottom.

Different liquids have different surface tensions which can be determined or compared either by observing the heights to which they rise in capillary tubes of equal diameter, allowances being made for the different densities of the liquids, or by a direct weighing method. This consists in suspending a thin plate of glass vertically from one arm of a balance and adjusting the balance. A vessel of water is then placed beneath the glass and gradually raised until the water just touches the lower edge—when the surface tension pulls down the balance. Weights are placed on the other pan until the glass is brought up again so that its lower edge just touches the water or whatever liquid is being tested.

**Diffusion.** If we place some coloured salt solution at the bottom of a vessel of water—and we can do it very easily by means of a pipette—we shall find quite a sharp dividing line between the heavier salt solution and the lighter water. But if we leave them undisturbed we shall find that very gradually some of the heavy liquid will have come to the top and some of the lighter water will have gone to the bottom and that eventually the liquids will become mixed. This gradual intermingling—done apparently against the laws of gravity—is called *diffusion*.

Diffusion takes place more readily between gases than between liquids, and every gas can diffuse into every other gas: this cannot be said of liquids.

In the case of gases it is impossible to keep them separated one upon another—like oil upon water. This is fortunate for us, because if gases arranged themselves layer upon layer with the heaviest at the bottom and the lightest at the top our atmosphere would consist of successive layers of carbonic acid gas, oxygen, nitrogen, water vapour and ammonia. Animal life would be impossible. As it is however gases diffuse so readily that they are all intimately mixed—and even in the immediate neighbourhood of an oxygen manufactory which takes its oxygen from the atmosphere there is no sign of a scarcity of oxygen; this is due to the rapid diffusion which takes place.

**Viscosity.** Some liquids are more *viscous* than others. It is easier to swallow water than castor oil, not so much because of any special or objectionable flavour but because of the slow deliberate manner in which the oil trickles down the gullet. The oil is said to be viscous; and treacle, honey and thick oils have this property of viscosity to a great degree. It may be said to be due to frictional forces between adjacent layers.

Liquids which flow readily—like water or alcohol or petrol—are called *mobile* liquids.

The viscosity of a liquid is usually lowered by an increase in temperature: so much so that when superheated steam is used in a steam engine the question of lubrication becomes more difficult.

Viscosity of different liquids may be compared by finding the rate at which they may be discharged through equal tubes under equal pressures.

### EXAMPLES

1. What is the total pressure on the base of a rectangular tank full of water, the internal dimensions being 6′ deep, 8′ long and 4′ wide? Also find the total pressure and the average pressure in lbs. per square inch on each side of the tank.

2. A diver is at a mean depth of 30 feet below the surface of the sea. What must be the least pressure of the air supplied to him in lbs. per square inch so that he does not feel the pressure of the water upon his diving suit? The relative density of sea water is 1·025.

3. A substance weighs 256 grammes in air and its relative density or specific gravity is 8·4. What would it weigh if immersed in water? What would it weigh in a liquid of specific gravity 1·25?

4. A substance weighs 7·6 ozs. in air and 6·95 ozs. in water. What is its specific gravity? What is its volume in cubic inches?

5. A substance weighs 32·6 grammes in air and 26 grammes in a liquid whose specific gravity is 0·84. What is the specific gravity of the substance and what is its volume?

6. Four lbs. of cork of specific gravity 0·18 are securely fastened to 15 lbs. of lead of specific gravity 11·4. Will they sink or float when immersed in water?

# CHAPTER III

## PROPERTIES OF GASES

As we have already seen a gas is a portion of matter which has no rigidity and which is readily compressed. It has neither definite shape nor definite volume, for a given mass of it may be made to occupy various volumes at will by varying the pressure to which it is subjected.

We have already seen that gases have weight and it is the weight of the air surrounding the earth which causes the pressure commonly called the atmospheric pressure. It is that same weight which causes the air to hang round the earth instead of distributing itself through the vast vacuous spaces which nature is said to abhor. As the reader probably knows, the belt of air about the earth does not extend to the moon—as was supposed to be the case in the early part of the seventeenth century—but is only a few miles deep. The total weight of this belt of air on the earth's surface is enormous, and if the reader would like to know exactly how much it is he can calculate it from the fact that the pressure of the air is, on the average, 14·7 lbs. to the square inch. He has therefore only to calculate the number of square inches on the surface of the earth and multiply this by 14·7 and he will have the total weight of the air in pounds.

When a gas is enclosed in any space it exerts pressure

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in *every* direction. Moreover it exerts pressure *equally* in every direction. One of the simplest illustrations which can be offered of the truth of this statement is that of the soap bubble. It matters not how we blow into the bubble, or what manner of pipe we use, the bubble is beautifully spherical. If the pressure of the gas both inside and outside the soap film were not equal in every direction then clearly the bubble would not be spherical in form.

If we construct a cylinder—as shown diagrammatically in Fig. 14—and provide it with a number of pressure gauges, then when a piston is forced into the cylinder it will be seen that all the gauges indicate the same pressure at a given moment. On the other hand we know that if the cylinder were filled with a solid—like steel for example—and pressure was applied to the piston there would be no pressure exerted on the sides of the cylinder: it would only be exerted on the end. If we filled the cylinder with water we should find that it exerted pressure in all directions equally.

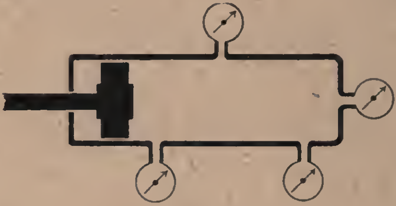


Fig. 14

The fact that a gas exerts pressure equally in all directions accounts for our unconsciousness of the existence of atmospheric pressure. It would be impossible for us to hold our arms out at length if the atmospheric pressure of 14·7 lbs. per square inch were only acting *downwards*. The air would indeed be a burden to us.

A simple experiment illustrating the magnitude of this pressure may be made by exhausting the air from the inside of a tin can. The surest and simplest way of doing this is to put a little water inside the can and boil it. When steam is coming freely from the opening remove the flame, cork up the can, and plunge it into a vessel of cold water. The can will immediately collapse. The explanation is that the air was driven out of the can by the steam, and that the cold water condensed the steam thus reducing the pressure inside the can to practically nothing. The pressure of the air outside acting in every direction upon the can is sufficient to crush it. It is probably known to many readers how in certain engineering operations—tunnelling under a river for example—the workmen work in a high pressure space in a special "shield." The pressure of the air in this shield is considerably higher than that of the atmosphere outside and the men have to pass through a sort of air lock in which the pressure is *gradually* raised to that inside the shield or gradually lowered to that of the atmosphere according to the direction in which the men are going. The change of pressure is decidedly unpleasant unless it is done very gradually so that the pressure inside the body may never differ sensibly from that outside.

It is well known that if a piece of paper be placed over the top of a tumbler filled with water the whole may be held in an inverted position and the water will not force the paper away. In this case the downward pressure on the paper is represented by the weight of the water in the tumbler and the upward pressure is the atmospheric pressure of 14·7 lbs. to the square inch. There is no downward atmospheric pressure on the paper because there is no air in the tumbler. Unless the tumbler be 34 feet or more in length the upward atmospheric pressure will be greater than the downward pressure of the water in the tumbler: hence it will not run out.

If a glass tube of about 36 inches length be arranged as shewn in Fig. 15 so that one end dips under some mercury and the other end is connected to a vacuum

Fig. 15

pump the mercury will rise in the tube as the vacuum improves until finally it reaches about 30 inches above the mercury in the lower vessel. Beyond this it will not rise however good the vacuum may be. If the experiment be repeated with other liquids—and in such a case the tube should be 40 feet long—it will be found that water will rise to about 34 feet, glycerine to about 30 feet, and so on. But in every case the height to which the liquid rises will be such that it will produce a pressure of about 14·7 lbs. per square inch at the bottom of the column—which is to say that the liquid will rise up to such a height that it produces a downward pressure equal to that of the atmosphere.

**The Barometer.** It is on this principle that we usually measure atmospheric pressure, the instrument used being called a *barometer*. To construct a barometer a glass tube of 36 inches length having a fairly thick wall and a bore of about $\frac{1}{4}$ inch is sealed at one end and filled with clean mercury. Care must be taken that no air bubbles or water vapour are left in; and to this end the tube should be thoroughly cleaned and dried before filling. A finger is then placed over the end and the tube is inverted and its lower end placed in a dish or cistern of mercury. The finger is then removed and the mercury will fall a little in the tube—as shewn in Fig. 16 (*a*). Since there is no air in the tube the column of mercury will adjust itself to such a height that its downward pressure is the same as that of the atmosphere. The "height" of the barometer

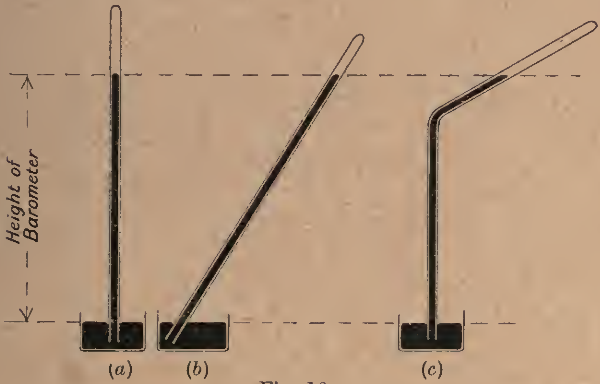


Fig. 16

is the vertical difference of level between the mercury in the tube and the mercury in the cistern. If the tube be tilted as shewn in Fig. 16 (*b*) or made in the form shewn in Fig. 16 (*c*) the mercury will adjust itself so that the vertical difference of level is the same as in the straight vertical tube.

**Standard Barometer.** In the usual standard pattern of mercury barometer the cistern is provided with a plunger, worked by means of a screw, which can be adjusted so that the level of the mercury in the cistern coincides with the zero mark of the scale of inches and centimetres. This adjustment must always be made before the height of the barometer is read. It will be clear that unless some arrangement of this kind is provided a rise in the barometer will draw some mercury out of the cistern and the level will be below the zero of the scale; whilst a fall in the mercury will raise the cistern level above the zero of the scale. In the usual domestic pattern this is compensated for in the marking of the scale: and it will be found that the distances marked off are slightly less than true inches. It is of course cheaper to do this than to provide a special cistern.

**Boyle's Law.** The relationship between the volume which a given mass of a gas occupies and the pressure to which it is subjected is expressed in a law known as Boyle's law. This states that *the volume of a given mass of a gas, kept at constant temperature, varies inversely as the pressure to which it is subjected.*

Most of us learned something about this law when we played with popguns. We learned that as we decreased the volume of the air in the barrel of the gun by pushing in the plunger we increased the pressure on the cork and on the plunger until finally the cork was blown out. We found that the plunger was harder to push as it got further into the barrel and in learning this we had got the main idea of Boyle's law, that if we increase pressure we decrease volume. What we had not learnt was the exact relationship between the two, namely that the one varies inversely as the other. Thus if the pressure be doubled the volume will be halved: if the pressure be increased seven times the volume will be reduced to one-seventh and so on.

This law may be experimentally verified by means of the apparatus shewn in Fig. 17, in which we have

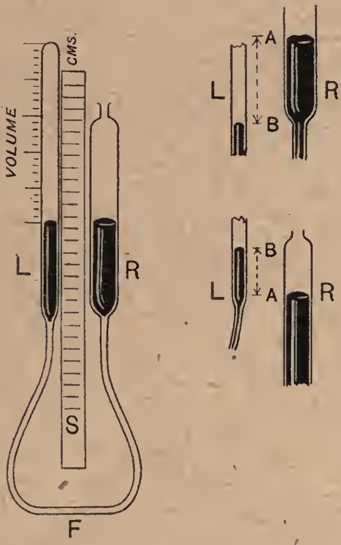


Fig. 17

two tubes *L* and *R* connected by some rubber tubing. *L* is sealed at the top and is graduated in cubic centimetres or inches or any other scale of volume. *R* is open to the atmosphere and is arranged so that it can be raised or lowered. A certain volume of dry air (or any other dry gas) is enclosed in *L* by means of mercury and the volume can be read off on the scale. By raising or lowering *R* the pressure and volume of the gas in *L* can be changed.

If the side *R* be adjusted so that the level of the mercury is the same in both tubes then it follows that the pressure is the same also. But the pressure on the surface of the mercury in *R* is the atmospheric pressure and therefore if we read the height of the barometer we know the pressure of the gas in *L* and we can read the volume on the volume scale. If *R* be now raised, as shewn in the top diagram on the right, so that the level of its mercury is above the level of the mercury in the tube *L*, then it follows that the pressure of the gas in *L* is greater than the atmospheric pressure by the pressure represented by a column of mercury of length *AB*—since it can support this column of mercury in addition to the atmospheric pressure. Therefore the new pressure is the atmospheric pressure in inches or cms. *plus* the difference in the level of the mercury in the two limbs also in inches or cms. as the case may be. If, on the other hand, the limb *R* be lowered so that its mercury is below that in *L* it follows now that the atmospheric pressure is greater than that in *L* by an amount represented by the difference in level *AB*, so that the pressure of the gas in *L* is the atmospheric pressure *minus* the difference in level *AB*.

The following are some results obtained with this apparatus:

| VOLUME of gas in $L$ | Height of barometer in cms. | Difference of level $AB$ in cms. | PRESSURE of gas in $L$ in cms. of mercury | PRESSURE × VOLUME |
|---|---|---|---|---|
| 8 | 75·8 | + 53 | 128·8 | 1030 |
| 11 | 75·8 | + 17·7 | 93·5 | 1028 |
| 12 | 75·8 | + 9·6 | 85·4 | 1024 |
| 15 | 75·8 | – 7·1 | 68·7 | 1030 |
| 16 | 75·8 | – 11·4 | 64·4 | 1030 |
| 17 | 75·8 | – 15·2 | 60·6 | 1030 |
| 18 | 75·8 | – 18·4 | 57·4 | 1033 |
| 24 | 75·8 | – 32·8 | 43 | 1032 |

In the last column of the tabulated results the product of the pressure and the volume is given and it is seen that this product is practically the same right down the column. When one quantity varies inversely as another and a number of results are taken *under equal conditions* then it will always be found that the product of the two quantities is constant.

If $P_1$ represents the pressure when the volume is $V_1$ and $P_2$ represents it when the volume is $V_2$ then Boyle's law may be expressed

$$\frac{V_1}{V_2} = \frac{P_2}{P_1}.$$

That is to say the ratio of the volumes is equal to the inverse of the ratio of the pressures under equal circumstances.

Therefore $$V_1P_1 = V_2P_2.$$

Hence the fact that our last column is practically constant is an experimental verification of the law.

The relationship between the volume and pressure may also be plotted as a graph. Fig. 18 shews the graph given by the results above. The form of this curve is known mathematically as a rectangular hyperbola.

It will be seen later that Boyle's law is not universally true, though for dry gases it can be regarded as sufficiently true for all practical purposes.

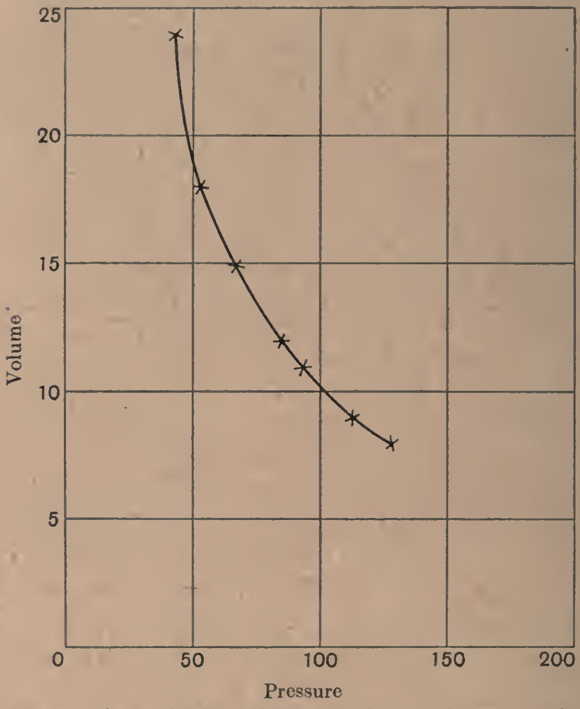


Fig. 18. Curve shewing relation of volume and pressure of air at constant temperature.

**Airships.** The principle of Archimedes is as true for gases as it is for liquids. Any object weighs less in air than it would do in a vacuum by the weight of its own volume of air. It also weighs less near to the ground where the air is dense than it would do at a higher level.

A balloon or any other lighter-than-air ship is filled with a gas lighter than air and is made of such a volume that the weight of air which it displaces is greater than its own weight. It is thus buoyed up and will rise to a height such that the weight of air displaced at that height is equal to weight of airship and contents. To ascend the volume of air displaced must either be increased (as in the Zeppelin type) or the weight must be decreased by dropping ballast. To descend the volume of air displaced must be decreased.

## EXAMPLES

1. A certain mass of air has a volume of 12 cubic feet when there is a pressure of 14·7 lbs. per square inch (1 *atmosphere*) acting upon it: what will its volume be when the pressure is (*a*) 10 lbs., (*b*) 17·5 lbs. per square inch?

2. A steel oxygen cylinder has an internal volume of 3 cubic feet. It is filled with oxygen at a pressure of 120 lbs. per square inch. What would be the volume of the gas at atmospheric pressure?

3. If a mercury barometer reading was 29·4 inches, what would be the reading of a glycerine barometer at the same time—the specific gravity of glycerine being 1·21 and that of mercury 13·6?

4. Plot the graph shewn in Fig. 18 and extend it on each side to shew the volume changes between the pressures of 20 and 200.

5. A balloon on the ground where the atmospheric pressure is 14·7 lbs. per square inch displaces 30,000 cubic feet of air. What volume will it displace when at such a height that the atmospheric pressure is 12 lbs.?

6. When a certain steam boiler is working at a pressure of 120 lbs. per square inch it is capable of discharging 20 lbs. of steam per minute. If the pressure be worked up to 150 lbs. per square inch and maintained there what would be the possible discharge rate?

7. A cylindrical steel cylinder is 5 feet long and 8 inches internal diameter and is filled with "Poison gas" at a pressure of 100 lbs. per square inch. What space would this gas occupy when let out into the air when the barometer reads 30 inches of mercury?

# CHAPTER IV

## FORCE, WORK AND ENERGY

**Work.** We buy coal, not for its own sake, but for the *heat* which we can get out of it. We buy gas from the gas company for the *light* which we can get from it in burning. Neither heat nor light can be regarded as matter: they have no weight and no other property which we associate with matter.

We classify them as forms of *energy* and we define energy as the capability of doing *work*.

For scientific purposes we have a definite meaning for the word work, and it is restricted to the production of motion of matter. We say that when a force acting upon a body produces motion then work has been done. Unless motion is produced however no work is done.

**Force.** In order to produce motion we must apply force. We have seen already that weight is a force; we possess a system for measuring weights and we can therefore measure our forces in terms of pounds weight, or grammes weight or any other units of weight that we care to use. We can also indicate these forces by means of spring balances so that we can be quite independent of the force of gravity.

If we raise a bucket of water vertically upwards we shall have to apply a force which, it can be seen, will be equal to the total weight of the bucket and its contents. If we just haul it along the ground without lifting it the force which we shall have to apply will depend entirely upon the surface of that ground. If this is very smooth—like ice—very little force will be needed to haul the bucket along; but if the surface be rough and gritty then the force required might be considerable.

We can take a better illustration from railway traction. If we have to raise a truck bodily off the rails then we must apply a force equal to the total weight: but if we have to move it along the rails then it is only necessary to apply a force sufficient to overcome the friction of the bearings and the rails, and that force is about 10 to 15 lbs. for every ton which the truck and its contents weigh. Thus if the truck and its contents weighed 10 tons then the force to lift it vertically upwards would be 10 tons or 22,400 lbs.: but the force necessary to move it along the rails would only be 100—150 lbs. according to the quality of the truck and the track.

Now work is measured by the force required to produce the motion and by the amount of movement produced; that is to say by the product of the force producing the motion and the distance through which the object moves *in the direction in which the force is being applied.*

**Units of Force and Work.** Clearly a unit of work will be done when a unit of force produces motion through a unit of length in its own direction. It follows therefore that we may have many different units. On the British system the unit most commonly used is the *Foot-Pound*—namely the work done when a force of one pound produces motion to the extent of one foot in its own direction.

In scientific work the units of force chiefly used differ from the "weights" which have been given. A unit of force is defined as that force which acting for a unit of time upon a unit of mass produces a unit change of velocity. For example it is found that if a force of $\frac{1}{32 \cdot 2}$ lbs. weight be applied to a mass of 1 lb. mass which is free to move without friction, it will move and its velocity will increase by 1 foot per second every second. Therefore the unit of force according to this definition is $\frac{1}{32 \cdot 2}$ lbs. weight. This is called a *Poundal.*

Similarly it is found that a force of $\frac{1}{981}$ gramme weight will cause the velocity of a mass of 1 gramme to increase by 1 centimetre per second every second. Thus the metric unit of force is $\frac{1}{981}$ gramme weight. This is called a *Dyne.*

Returning to our units of work again we see that *the true unit of work* on the British system would be a *foot-poundal*, which is $\frac{1}{32 \cdot 2}$ of the foot-pound; and on the metric system we have the *centimetre-dyne* which is called an *erg.* This is a very small quantity of work, and the practical unit of work on the C.G.S. system is a multiple of the erg, namely 10,000,000 *ergs*, and this unit is called a *Joule.*

1 joule is equivalent to 0·737 foot-pound. This is the electrical engineer's unit of work.

Mechanical engineers generally prefer to use *one pound weight* as a unit of force and one foot-pound as the unit of work. This means that the engineer's unit of mass must be correspondingly increased in order to meet the conception of a unit of force being that force which would produce a change of velocity of 1 foot per sec. in one second when acting on a *unit mass.* A force of 1 *lb. weight* would produce a change of 32·2 feet per sec. in one second on a mass of 1 *lb. mass*: but if the mass were increased to 32·2 *lbs. mass* the change of velocity per second produced by a force of 1 *lb. weight* would only be 1 foot per sec. Therefore the engineer's unit of force is the *pound* weight and the unit of mass is 32·2 *lbs.* No name has been given to this although the remarkable word *slug* was once suggested.

This list of units is very dull and uninteresting but of very great importance. A student who slurs these over is storing up trouble for himself, for there can be no doubt that the man who understands all his units will have little or no trouble with the various numerical problems of his subjects.

**Examples of work.** We may briefly illustrate the use of these units. If a railway truck requires a force of 100 lbs. to pull it along so that it is just moving against the friction then the work required will be 100 foot-lbs. for every foot along which it is moved. Let us find out how many ergs and joules this is equivalent to. Since there are 453·6 grammes to the pound, the force = 453·6 × 100 grammes weight; and since there are 981 dynes of force to the gramme weight the force in dynes = 453·6 × 100 × 981.

Further since there are 30·48 centimetres to the foot the work done in centimetre-dynes, i.e. in *ergs*, will be 453·6 × 100 × 981 × 30·48 or 1,356,303,916 ergs. And since there are $10^7$ ergs to 1 joule the work done in joules will be 135·63 joules.

If work is done by a force which varies in magnitude, then the product of the *average force* and the distance through which it is applied will give the measure of that work. The measurement of the work done on the piston of a steam engine during its motion along the cylinder is an example of this kind, and the indicator diagram represents how the force is changing for each position of the piston. From the diagram the average force can be determined (see Chapter XIII).

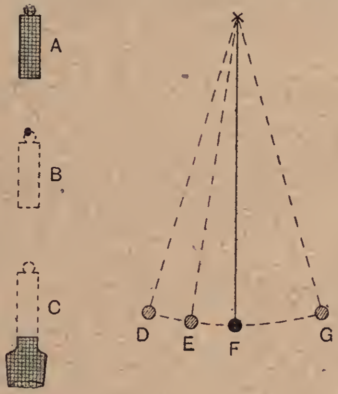
**Energy.** We say that a body has energy when it is capable of doing work and therefore we measure its energy by the number of units of work it can do.

For example, the weight of an eight-day clock when wound up to the top is capable of doing a certain amount of work in falling gradually to its lowest position. If the weight weighs 7 lbs. and the distance between its highest and lowest position is 4 feet then when wound it possesses 28 foot-lbs. of energy which it can give out to keep the clock going. When it has fallen half-way it only possesses 14 foot-lbs. of clock energy—the other 14 having been given up.

There are two general divisions of energy. Some bodies, like the clock weight, possess energy on account of their position or state. A compressed spring, a coiled-up watch spring, a sprung bow, an elevated pile-driver, a stone on the edge of a cliff and some water in a high reservoir are examples of things possessing energy because of their condition, position or state. We say that these things have *potential* energy.

Other bodies are capable of doing work because of their motion. A flying bullet, a falling stone, the water of a waterfall, the steam forced from a high pressure boiler, the wind, a hammer head just at the moment of impact, are examples of things possessing energy due to their motion. We say that these have *kinetic* energy.

The energy of a body is capable of being changed from potential to kinetic and *vice versa*. Fig. 19 (*a*) represents a pile driver: position *A* shews the driver at rest at its highest position where its energy is all potential: position *B* represents it moving downwards towards the pile, and though its potential energy must be less than it was at *A* yet it now has kinetic energy due to its motion: position *C* represents it at the moment of impact, and here its potential energy in relation to the pile is zero but its kinetic energy is greater than it was at *B* since it has gained speed.



(*a*) (*b*)

Fig. 19

Fig. 19 (*b*) represents a pendulum swinging between extreme positions of *D* and *G*. At the positions *D* and *G* it is at rest at its highest position and its energy is all potential. At *F* it is at its lowest position and its pendulum energy is all kinetic. At *E* its energy is partly potential and partly kinetic.

The reader will learn that in all these cases the sum of the potential and kinetic energies at any moment is a constant quantity; and that what a body loses in potential energy it gains in kinetic energy.

**Principle of the Conservation of Energy.** Many experiments have been performed in comparatively recent times which go to shew that though we can alter the *form* of the energy of a body yet we cannot destroy energy nor yet can we create it. We shall deal with some of these experiments at a later stage, but it should be made clear to the reader now that this is regarded as an established fact and that it is practically the fundamental basis of modern science. It is known as the principle of the conservation of energy and it is exactly parallel to the principle that matter can neither be created nor destroyed though it can be changed in form and condition.

The reader will ask what happens to the energy of the pile driver when the driver has come to rest on the pile head? It is found that it has been changed into another form—a form which we call *Heat*. With the aid of heat mechanical work can be done and it has been shewn that the amount of mechanical work which a given "quantity of heat" can do is such that if this same amount of mechanical work be converted into heat it will produce in turn the same "quantity of heat" as that with which we started. And further, in whatever way we do work which produces heat—whether by friction or by hammering or by boring or by percussion—we always get the same "quantity of heat" if we do the same amount of work. This is discussed in detail in Chapter XIII.

In the same way heat energy can be converted to light energy. Heat energy can also be converted to electrical energy, mechanical energy can be converted to electrical energy which in turn can be converted to heat or to light or to mechanical energy again. In fact it is just that "flexibility" of electrical energy which makes it of such use to mankind, for it is so easy to transmit from one place to another and it is so easily changed to whatever form or forms we desire. Then in coal we have a store of chemical energy which changes to heat in burning; the heat is given to water and produces steam at a high pressure charged as it were with potential energy; the steam is liberated and its kinetic energy is given up to the piston of an engine; the kinetic energy of the engine is transmitted to the dynamo and converted to electrical energy; the electrical energy is transmitted to where it is needed and there transformed to any form we wish—to heat, to light, to chemical energy in secondary cells and in chemical manufacturing process and to mechanical energy in motors. But all this energy has come from the boiler furnace; we have not made any; we have not destroyed any; but we may possibly have *wasted* a considerable quantity. We have not used all the heat given by the coal—much has gone up the chimney so to speak; we have produced heat at all our bearings because we cannot make them mechanically perfect and frictionless, and so the energy necessary to overcome that friction has been changed to heat.

We may sum up then by saying that energy like matter can neither be created nor destroyed but that it can be changed from any one form to any other form of which it is susceptible.

**Power.** In scientific work this word has a very restricted meaning and one which differs considerably from its meaning in common usage. By power we mean the *rate at which work is done.* 20 foot-lbs. of work may be done in a second or in an hour and though the actual work done will be the same in each case yet the rate of working will be very different. The unit of power would naturally be the rate of working when a unit of work is done in a unit of time. In practice, engineers take as a unit of power 550 foot-lbs. of work per second which is called 1 *horse-power*. This is equivalent to 33,000 foot-lbs. per minute. The electrical engineer's unit of power is 1 *joule per second* which is called a *watt*. 1000 watts or 1000 joules per second is called a *kilowatt* and this is more generally used in heavy electrical engineering. 1 horse-power is equivalent to 746 watts.

It might be well to point out here that a 1 horse-power motor might be constructed to work at high speed so that it could, for example, haul up a load of 1 lb. through 550 feet in a second, whilst another 1 horse-power motor could haul up 550 lbs. through 1 foot in a second. Thus a mere knowledge of the horse-power does *not* give us any idea of the hauling capacity of the motor or engine and it is *entirely* wrong to imagine that a 1 horse-power motor can necessarily pull with the same pull as that which can be exerted by an average horse.

The reader can ask himself what is the object of the gear box of a motor car.

### EXAMPLES

1. How much work would be done in pumping 120,000 gallons of water from a depth of 22 feet? If this work were done in 2 hours what would be the rate of working (*a*) in foot-lbs. per minute, (*b*) in horse-power?

2. How many ergs of work are equivalent to 1 foot-lb.? (There are 453·6 grammes per lb. and 2·54 cms. to the inch.)

How many joules of work is this equivalent to and if the work was done in 1/5th sec. what would be the rate of working in watts?

# CHAPTER V

## HEAT AND TEMPERATURE

It may be well to begin by saying that we do not know what *heat* really is. All we can say with any degree of definiteness is that heat is an agent which produces certain effects. We can study the nature of these effects and the conditions under which they may be produced and their application generally for the benefit of mankind. A moment's reflection will shew that we need not necessarily know the precise nature of this thing which we call heat, although, on the other hand, we can see that such knowledge might help us considerably both in the production and use of this most valuable agent.

We know that heat can produce certain effects. Our first knowledge is of its comforting effects upon our person and of its chemical effects upon our food. And as our vision grows more extended we become conscious of its effects upon life in both the animal and vegetable worlds. Then we find how it can change the physical state of matter from solid to liquid and from liquid to gas. Then again we begin to realise that it is an agent which can do work for us. We think of the steam engine and reflect that after all it is the burning of the fuel which yields us all the energy; and further knowledge shews us that in the gas engine, the oil engine and the petrol engine, combustion and the production of heat give us the source of all their energy of motion. How important then it is that we should know as much as possible about the various effects which heat can produce and the various methods of producing and using it.

**Production of Heat.** We have already seen that energy can shew itself in many different forms, and that one of these forms is heat. We have realised that energy like matter can be changed from one form to another, and that it can neither be created not yet destroyed. It follows therefore that whenever we produce heat it is at the expense of an equivalent amount of energy which was previously existing in some other form.

The chief method of production is by the expenditure of chemical energy. All forms of burning or combustion are examples of this, from the combustion of that great mass which we call the sun down to the burning of the humble match. If we burn a given mass of anything—coal or candle—and keep *all* the residue we shall find the mass of matter the same as before, but that mass has no longer the energy which it had before combustion. The heat was obtained not at the expense of any of the matter or stuff but at the expense of its chemical energy—that mysterious weightless attribute of the coals or candles for which we really pay when we buy them. We do not really want the coal as such when we buy it: we want the chemical energy which it contains and which we can change to heat energy whenever we desire to do so. The same statement applies to any other kind of fuel and to all those fearsome mixtures termed explosives.

Further it is probably known to most readers that heat can be produced by chemical changes without combustion. If some water be added to strong sulphuric acid heat will be produced at once, and consequently great care must be taken in the dilution of acids. Further everyone knows how heat is developed in a haystack if the hay be stacked before it is dry.

The mechanical energy of motion may be changed into heat. Whenever there is any kind of resistance to motion—that is to say any kind of friction—heat is developed in direct proportion to the amount of energy necessary to overcome that friction. Such heat is, as a general rule, waste energy; but as friction is always present the loss is unavoidable. An engine driver tests the bearings of his engine by feeling them. Bad bearings become unduly heated, and the increase in warmth serves as a danger signal. The striking of a match is an example of the useful conversion of mechanical to heat energy. The old flint and tinder, and the yet older rubbing of dry sticks together are similar examples. "Shooting stars" are examples of the heat produced by the resistance of the air to bodies falling through it at an enormous speed. The melting of a rifle bullet on striking a steel target affords another example of the changing of mechanical energy to heat.

Electrical energy can also be converted to the form of heat and every reader knows something about electric lighting and heating.

In short whenever work is done without producing its equivalent in some other form of energy the balance is shewn in the form of heat..

**Temperature.** We know that a reservoir of water is capable of doing work and that such work can only be done by the motion of some of the water. It can do work, for example, by a downflow to a water-turbine and we know that the amount of work which the reservoir can do depends upon the quantity of water it contains and the height of the reservoir *above the water-turbine*. That is to say the energy of the reservoir is measured by the product of the mass of water and the height above the turbine, and we could get the same energy out of a reservoir at half the height if it held twice as much water.

Let us imagine that any furnace or source of heat is a sort of reservoir of heat energy—the energy depending upon some quantity we will call *heat* and upon some kind of height which we will call *temperature* or heat-level.

The analogy between this reservoir and the water reservoir will hold good for most things but it ought to be borne in mind that it is only an analogy and that we are taking a considerable licence in comparing heat to water. But just as we say that water will always flow from a reservoir at a higher level to one at a lower level quite irrespective of the size or shape or quantity of water or amount of energy in those reservoirs, so also may we say that heat is only transmitted from a body at a higher temperature to one at a lower temperature whatever may be the other differences between those bodies.

We may thus take it that temperature is a sort of level of heat as different from the agent heat itself as height or level is different from water. Nobody would confuse a reservoir of water with its height, yet most people confuse heat and temperature.

**Measurement of Temperature.** It will be necessary to measure temperatures or differences in temperature if we are going to make any really valuable investigations into the effects of heat upon bodies. Our senses enable us to form a rough estimate of temperature such as saying that this body is hotter (i.e. at a higher temperature and not necessarily containing more heat energy) than that. But our senses are not reliable, for they can lead us into the declaration that one thing is hotter than another when they are actually at the same temperature. An example of this may be furnished at any moment, for if we go into any room which has been without a fire for some time, having therefore a uniform temperature or heat level all over, and touch various articles such as the fender or curb, the hearthrug and a table leg, we shall find that they all appear to have different temperatures. The explanation of this lies simply in the fact that the articles conduct heat to or from the body at different rates and so produce different sensations.

Temperature is measured by means of a *thermometer* which depends for its action upon the fact that when heat is given to matter it generally produces an increase in volume.

Let a glass flask be taken and filled with water (or any other liquid) and provided with a cork and tube so that the water rises to some height $A$ in the tube, as shewn in Fig. 20. If now some hot water be poured over the flask it will be noticed that at first the water drops to a position such as $B$ but soon rises again to such levels as $C$ and $D$. We might perhaps imagine that water therefore contracts for a moment when heated: but if we heat the water from within—by means of a small coil of wire through which a current of electricity can be passed—

we shall find that there is no initial drop. If we bend a piece of glass tube or rod into the form of a triangle and bring the two sides together at the apex so that they can just grip a coin—as shewn in Fig. 21—and then heat the base we shall find that glass expands when heated; this will be shewn by the coin dropping from the apex of the triangle. We therefore conclude that the dropping of the water in the first instance—when the hot water was poured over the flask—was due to the glass receiving the heat first and expanding, thus having a larger volume. But when the heat got through to the water inside then that expanded too, and since it ultimately went above its original mark *A* we conclude

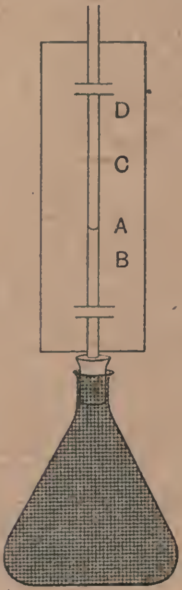


Fig. 20

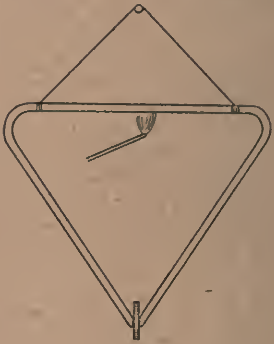


Fig. 21

that water expands more than glass does. As a matter of fact liquids in general expand more than solids.

Now if we put this flask into vessels of water at different temperatures we shall find that the water in the tube will set at a different level for each temperature.

This furnishes us with the basis of temperature measurement. We could mark a scale off in any way we desired and it would be sufficient perhaps for our purpose—but if everybody had his own scale of temperature we could hardly make any progress. What the scale is really does not matter; but it is of first importance that we should all use the same. The well-known case of the bricklayer's labourer who was sent to make a certain measurement and came back with the result as three bricks and half a brick and a hand and two fingers, furnishes an example. His measurement could be reproduced by himself—but it was useless to others. The length of a foot is quite a detail: it is only important that we should agree to call a particular length one foot. And the same applies to temperature measurement; it is unimportant what a *degree of temperature* is, but we must all understand it and agree to it and be able to reproduce it.

**The Fixed Points of Temperature.** In making a scale of temperature it will be necessary to have two fixed points of temperature to which reference can be made at any time. One of these—the lower fixed point—is the temperature at which pure ice melts or pure water freezes. This is found to be a constant temperature. The other fixed point—the upper fixed point—is the temperature of steam over water which is boiling at standard atmospheric pressure. This is a rather complicated fixed point, and the reasons for its complexity lie in the following facts. Firstly the temperature at which water boils is largely affected by the presence of any impurities—such as dirt or salt—whilst the temperature of the *steam* above the water is not affected in any way by these. If we throw a few pinches of salt into a saucepan of boiling water we shall find that the temperature of the water will rise, but the temperature of the steam will remain as it was.

Secondly the temperature at which water boils is slightly affected by the kind of vessel it is boiled in. Water boils at a slightly higher temperature in glass than in copper, but the steam temperature is the same in both. These two points account for the choice of steam.

Thirdly, the temperature of steam depends upon the pressure to which it is subjected—rising with an increase of pressure and falling with a decrease. Daily changes of atmospheric pressure will affect the temperature of steam; therefore in defining a fixed point of temperature we must clearly specify that the steam shall be under some definite pressure. Standard atmospheric pressure is defined as the pressure equivalent to 30 inches of mercury at sea level in latitude 45° at the temperature of the lower fixed point.

These fixed points are called the *freezing point* and the *boiling point* respectively.

**Construction of Thermometer.** The usual thermometer consists of a glass bulb and stem containing mercury or quicksilver. The flask shewn in Fig. 20 is not quite suitable for temperature measurements. It is too big: it will absorb a large quantity of heat itself: and it will need quite a long time to take up the temperature required. But the idea is sound enough and so we make a small bulb at the end of a tube of thick wall and very fine bore. That is to say we reduce the whole thing in proportion so that we get a reasonably small instrument which will absorb very little heat. Then we use mercury instead of water because it conducts heat better; it requires less heat to raise the temperature of the same volume a given amount; it remains liquid over a wider range of temperature; and it does not wet the glass, and therefore runs up and down the tube with greater ease.

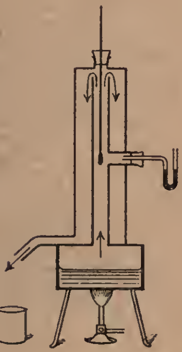


Fig. 22

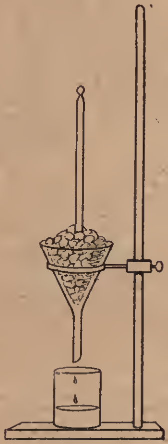


Fig. 23

We need not discuss the details of filling, sealing and resting of the thermometer. We need hardly say anything about the marking of the fixed points except to state that the thermometer bulb and stem as far as possible should be immersed in steam or in melting ice under the conditions specified in our statements of the fixed points of temperature. There is no doubt that every reader will be testing the fixed points of a thermometer in the laboratory and he can there study the arrangements which will resemble those shewn in Figs. 22 and 23.

**Scales of Temperature.** It is rather unfortunate that there are three scales of temperature in existence and use. These three are known as the *Centigrade*, the *Fahrenheit* and the *Reaumur* respectively. Fig. 24 illustrates the essential features of these scales and their differences. Celsius, who gave us the Centigrade scale, called the freezing point 0—written 0° C.—and the boiling point 100, and he divided up the interval into 100 equal parts each of which he called 1° C.

Fahrenheit originally took different fixed points: he took a mixture of ice and salt and he imagined that that was the lowest temperature which could be obtained and so called it 0° F. Then he took the temperature of the human body as his upper fixed point and called it 100° F. The interval he divided up into 100 equal parts so that his scale was a Centigrade scale, though different from Celsius' scale. On Fahrenheit's scale the temperature of pure melting ice was found to be 32° F., and the boiling point 212° F. Thus the interval between the freezing and boiling points is 180 Fahrenheit degrees.

Reaumur's scale differs from Celsius' in that the boiling point is called 80°—because 80 is an easier number to subdivide than 100!

**Conversion from one scale to another.** In this country both the Fahrenheit and Centigrade scales are used. The scale in common use is the Fahrenheit, the Centigrade being used for scientific work and by electrical engineers. Mechanical engineers have generally used the Fahrenheit but there are signs of the more general adoption of the Centigrade scale. Conversion from one scale to another is a simple matter and should not be beyond the powers of our readers without any further assistance in these pages.

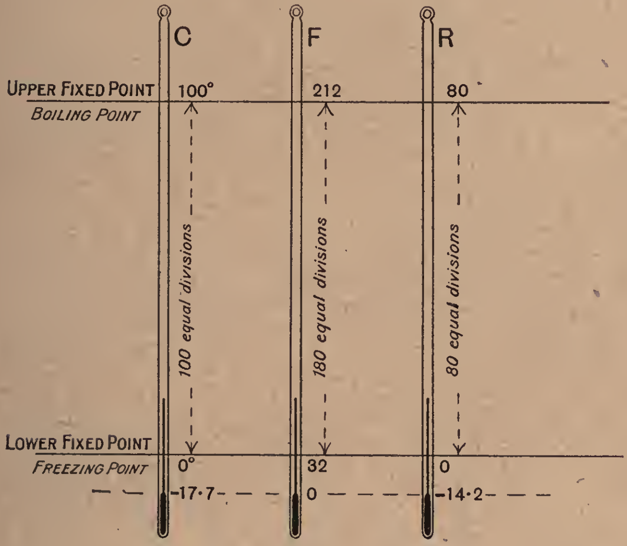


Fig. 24

It need only be pointed out that since 100 Centigrade degrees cover the same temperature interval as 180 Fahrenheit degrees and 80 Reaumur degrees therefore 1 Centigrade degree = $\frac{9}{5}$ Fahrenheit degree = $\frac{4}{5}$ Reaumur degree.

It must also be noted that since the scales start from different points the Fahrenheit temperature has a sort of handicap allowance of 32 above the other two. This allowance must be added or subtracted according to the direction of conversion.

Thus 15° C. = 15 C. degrees above the freezing point,

and since 1 C. degree = $\frac{9}{5}$ F. degree,

∴ 15 C. degrees = 15 × $\frac{9}{5}$ = 27 F. degrees,

i.e. 27 F. degrees above the freezing point,

∴ 15° C. = 27 + 32 = 59° F.

Similarly 15° C. = 15 × $\frac{4}{5}$ = 12° Reaumur.

Again let us convert 113° F. to Centigrade and Reaumur.

113° F. = 113 − 32 F. degrees above the freezing-point = 81 F. degrees,

since 1 F. degree = $\frac{5}{9}$ C. degree.

∴ 81 F. degrees above the F.P. = $\frac{81 \times 5}{9}$ C. degrees above F.P. = 45° C.

and 81 F. degrees above the F.P. = $\frac{81 \times 4}{9}$ R. degrees above the F.P. = 36° R.

All readings below 0° on any scale are called *minus* quantities.

**Other thermometers.** The mercury-in-glass thermometer has a wide range of general usefulness but when temperatures below − 40° C. (which, by the way, is also − 40° F. as the reader should verify) are to be measured, some other form must be employed since mercury freezes at − 40° C. or F. Generally alcohol is used instead of mercury and it can be used down to − 110° C. For lower temperatures than this gaseous and electrical thermometers are generally used. These will be discussed later.

For temperatures above 250° C. or 482° F. mercury thermometers must also be superseded. The boiling point of mercury is 350° C., but unless the upper part of the stem is filled with some inert gas it cannot be used beyond 250° C.

For higher temperatures recourse is usually made to a class of instruments called *pyrometers*. Some of these depend upon the expansion of solids, but the majority in use in engineering practice at the present time are electrical and depend upon the fact that when a junction of two dissimilar metals is heated a current of electricity is generated which increases as the temperature of the junction increases. This current operates a delicate detector—really a voltmeter—the scale of which is marked off directly in degrees of temperature. These are very valuable instruments and are of great service in measuring any high temperatures such as superheated steam, flue temperatures, boiler-plate temperatures and so on. Fig. 25 is a diagram illustrating the principle of a pyrometer as supplied by Messrs R. W. Paul. We cannot well discuss it in detail since it is possible that many readers have not progressed sufficiently into the study of the sister science of electricity to be able to appreciate

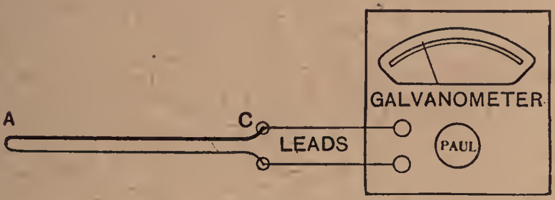


Fig. 25

it. Those who have will be able to understand it well enough from what has been said.

**Self-registering Thermometers.** If it is desired to know the highest or lowest temperature reached during any particular interval of time a self-registering thermometer is used. A simple form (Rutherford's) of *maximum* thermometer is shewn in Fig. 26 (*a*), and (*b*) illustrates the thermometer for recording the minimum temperature. The maximum thermometer is just an ordinary mercury thermometer provided with a little index *I* which can slide freely along the tube. As the mercury expands it pushes the index along and when it contracts the index will be left *I′*. The position of the left-hand end of the index will be the maximum temperature recorded since the index was last set in position against the thread of mercury.

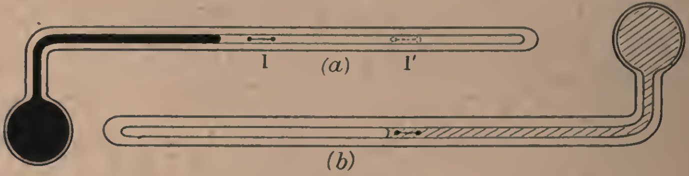


Fig. 26

The minimum thermometer contains alcohol instead of mercury and the index is placed inside the alcohol in the tube. As the alcohol contracts this index will be drawn back, but when the temperature rises again it will remain at its lowest point. Of course the index must be small enough not to impede the flow of alcohol up the stem. The indexes are set in position by tilting the thermometer and tapping them gently. In some forms they are made of iron and are set in position by means of a small magnet.

Fig. 27 illustrates the doctor's or *clinical* thermometer. The bore of the tube is constricted at the point *a*. When the mercury is expanding the force of expansion is great enough to push the mercury through this narrow part of the tube; but on contracting the thread of mercury breaks at the constriction thus leaving the thread in the stem at the same position it occupied when in the patient's mouth. Before the thermometer can be used again the thread must be shaken down—an operation frequently resulting in disaster to the thermometer.

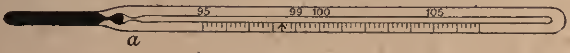


Fig. 27

## EXAMPLES

1. Convert the following Centigrade temperatures to Fahrenheit: 36°, 2000°, - 273°, - 40°.

2. Convert the following Fahrenheit temperatures to Centigrade: 10°, 0°, - 40°, - 400°, 98·4°, 2000°.

3. Convert the following Reaumur temperatures to Fahrenheit and to Centigrade: 12°, - 32°, - 218·4°, 160°.

# CHAPTER VI

## EXPANSION OF SOLIDS

One of the chief effects of heat upon matter is the change of volume which it produces. In the vast majority of cases an increase in the temperature of a body is accompanied by an increase in the volume, but there are cases in which the converse is true.

In the case of solids we may have expansion of length, breadth and thickness—and this is generally the case. India-rubber in a state of tension contracts in *length* when heated—but its *volume* increases. All metals however expand proportionately in all directions. If a sphere of metal be heated it will expand but will still be a sphere. All metals expand with increase in temperature and contract with decrease in temperature, and metals expand more than any other *solids* under the same conditions. Further, different metals expand differently under equal conditions.

**Laws of expansion.** We will consider firstly the expansion of length or linear expansion of a substance. It has been shewn—and can be shewn again by the apparatus illustrated in Fig. 28—that the length of a solid increases uniformly with the increase in temperature. An increase of 20° of temperature will produce twenty times the *increase in length* which would be produced by a 1° increase in temperature.

Secondly it can be shewn in the same way that the actual amount of expansion produced for a given increase in temperature depends upon the original length of the substance. That is to say a 10 foot length of metal would have a total expansion 10 times greater than a 1 foot length of the same metal for the same increase in temperature.

Thirdly, the expansion produced depends upon the substance which is expanding. Obviously if we wish to compare the expansion of different substances we must take equal lengths and heat them through equal ranges of temperature. It is also obvious that it would be most convenient to take unit lengths and to heat them through 1° of temperature.

**Coefficient of linear expansion.** *The increase in the length of a unit length produced by increasing the temperature* 1° is called the *coefficient of linear expansion of a substance.*

Strictly, the definition given above is not true. It should be the increase in the length of a unit length *at the freezing point* when increased 1°. But the value of the coefficient is so small that for all practical purposes the definition with which we started is sufficiently accurate and is certainly simpler.

A foot of brass when heated 1° C. becomes 1·0000188 foot. Similarly 1 centimetre of brass when heated 1° C. becomes 1·0000188 centimetre. From our definition it follows that the coefficient of linear expansion of brass is 0·0000188 per degree Centigrade, and we can readily see that if an increase of 1° C. produces an increase in length of 0·0000188 unit, then an increase of 1° F., which is only $\frac{5}{9}$th of a degree Centigrade, will only produce an increase in length of $\frac{5}{9} \times 0{\cdot}0000188$ or

0·00001044 unit. That is to say the coefficient of expansion per degree Fahrenheit will only be $\frac{5}{9}$ths of that per degree Centigrade.

Again though we have only spoken of *expansion*, the same laws exactly apply to contraction produced by a decrease in temperature, and we might even define the coefficient of expansion (or contraction) as the increase (or decrease) in the length of a unit length of a substance for an increase (or decrease) of 1° of temperature.

**Calculations.** Calculations are obviously quite simple for we have only to remember that the increase (or decrease) in length is directly proportional to

(*a*) the increase (or decrease) in temperature,
(*b*) the original length,
(*c*) the coefficient of linear expansion of the substance,

and we can apply the simple rules of proportion. There is clearly no need to deduce any formula for such straightforward work.

*Example.* A rod of copper is 33″ long at 15° C.: what will be its length at 100° C., the coefficient of linear expansion of copper being 0·0000172 per degree C.

It follows therefore that

1 inch of copper heated through 1° C. expands by 0·0000172 of an inch,

∴ 33 inches of copper heated through 1° C. will expand by $33 \times {\cdot}0000172''$,

∴ 33 inches of copper heated through 85° (i.e. $100 - 15$) will expand by $33 \times 85 \times {\cdot}0000172''$

$$= 0{\cdot}048246''.$$

Therefore the length of the rod at 100° C. will be 33·048246″ or, as we should express it in practice, 33·048″.

**Determination of coefficient of linear expansion.** Fig. 28 illustrates a simple form of apparatus which can be used to determine the coefficient of expansion of a solid. The rod *R* to be tested is placed inside a jacket *J* which can be filled with steam or water at any desired temperature. The rod is fixed between two screws as shewn, *AS* being an adjusting screw and *MS* a micrometer screw. The micrometer is adjusted to zero and the rod is tightened up by means of the adjusting screw. This should be done at the higher temperature first. Then the temperature of *J* is lowered and the *micrometer* screw is turned until the rod is tight again. The decrease in the length of the rod is thus given by the micrometer screw: the original and final temperatures are given by the thermometer: and the original length of the bar is obtained by removing the rod and measuring it with a straight-edge. From these particulars the coefficient of linear expansion may be calculated.

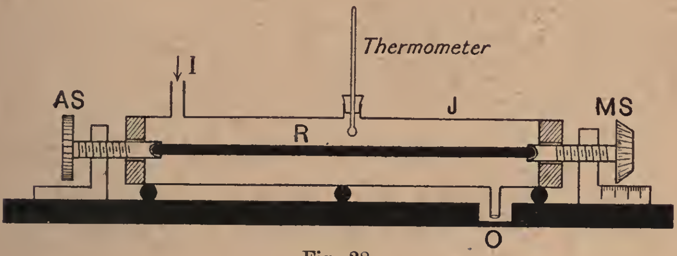


Fig. 28

The above method is not very accurate, the chief source of error lying in the expansion and contraction of the screws. But it will serve to illustrate the general principle and the reader will be quite able to understand the many more refined arrangements for this measurement if he understands this one.

*Table shewing some coefficients of linear expansion per degree Centigrade.*

| | |
|---|---|
| Zinc | 0·0000294 |
| Copper | 0·0000172 |
| Iron, soft | 0·0000122 |
| Steel, soft | 0·0000108 |
| Nickel steel (36% nickel) | 0·00000087 |
| Nickel steel (45 % nickel) | 0·0000082 |
| Cast iron | 0·000011 |
| Tin | 0·000025 |
| Lead | 0·000028 |
| Silver | 0·000021 |
| Gold | 0·000015 |
| Platinum | 0·000009 |
| Porcelain | 0·0000088 |
| Glass (soft) | 0·000009 |

These numbers represent average values only.

**Some advantages of expansion and contraction.** Much practical advantage can be taken of the expansion and contraction of substances due to temperature changes. The forces exerted by the expansion or contraction may be very great and they are used to advantage in such operations as fixing iron tyres on wheels and other "shrinking" operations. The tyre is made of such a size that it will just fit on to the wheel when it is hot and the wheel is cold. When the tyre cools it grips the wheel tightly. Similarly one sleeve or cylinder may be shrunk on to a smaller cylinder.

Then we have a very universal application in the case of hot rivetting. The plates are drawn tightly together by the rivetters with their hammers—but the contraction of the rivet as it cools will always exert an additional force.

The forces exerted by expansion and contraction of an iron bar may be shewn very strikingly by means of the apparatus sketched in plan in Fig. 29. *B* is an iron bar having a screw thread and a large nut *S* at one end and a hole through which a cast iron pin *P* is inserted at the other end. The screw can be adjusted so that the bar is held rigidly between the end fixtures on the metal base. If the bar is heated the pin *P* will be broken or the bar *B* will buckle. The force of contraction can also be shewn by placing the pin and the nut on the other sides of the end fixtures and tightening up whilst the bar is hot. On cooling the pin will be broken.

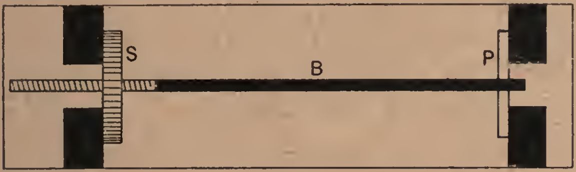


Fig. 29

Small automatic switches for switching an electric lamp on and off at frequent intervals are amongst other applications of the expansion of metals.

If two equal lengths of different metals be rivetted together closely then when this compound bar is heated it will bend so that the metal which expands the greater amount will be on the outside of the curve. On cooling it will bend in the opposite direction. Fire alarms which operate an electric bell are often made on this principle, and the balance wheel of a watch is compensated in the same way.

**Some disadvantages of expansion and contraction.** Nobody suffers more from the drawbacks of expansion than the engineer. Fortunately the effects can always be compensated—but such compensation has to be nicely adjusted and necessarily adds to the cost. Everyone knows why railway lines are laid in sections, why no two rails butt on to one another, why the rails are "fixed" in chairs with wooden wedges, and why they are "fixed" together with fish plates. And a little calculation will shew why the lengths of the rail sections in use are not greater than they are. It would be bad for rolling stock, rails and passengers if we had to leave large gaps between sections: and even as it is there is a distinct difference between summer and winter travelling.

Tramway rails are buried—and thus we have not the same trouble because the rail temperature will never differ appreciably from the earth temperature. But of course it is too costly a method for long distance railways.

Every branch of structural engineering has to take this expansion and contraction into consideration. The Forth Bridge is built in such a way that a total change of length of 18 inches must be allowed for between winter and summer. Clearly, it must not be taken up all at one place.

Furnace bars must fit loosely: pipe joints of exposed gas or water mains must be telescopic: patterns for castings must be of such a size that they take account of the contraction of the metal, and sometimes must be designed specially to prevent fractures which may be produced by one part of the casting cooling quicker than another part and setting up undesirable stresses.

The standard yard measure is only correct at one temperature, 60° F.

A clock regulated by a pendulum will gain or lose as its pendulum contracts or expands. There are many devices for compensating pendulums all of which depend upon the fact that different substances expand differently. The gridiron pendulum affords us a useful example since this principle is also applied to other compensations. Fig. 30 illustrates this. Two different metals are used, iron and zinc. The iron rods can expand downwards and the zinc rods can expand upwards. The lengths of $I$ and $Z$ are chosen so that the total expansion of the iron is the same as that of the zinc. In this way the position of the centre of gravity of the pendulum bob will remain constant.

Fig. 30

**Surface or superficial expansion.** If we take a square of a metal of side 1 foot and heat it, it will expand in all directions. If we heat it 1° and if its coefficient of expansion is $K$ then each side will be $(1 + K)$ feet. Therefore its area will become $(1 + K)^2$ square feet, that is $1 + 2K + K^2$ square feet. That is to say the coefficient of superficial expansion is $(2K + K^2)$. Now since $K$ is always a very small quantity it follows that $K^2$ will be much smaller and indeed is so small that it can be neglected in comparison with $2K$. It is therefore usual to say that the *coefficient of superficial* *expansion is twice that of linear expansion* and of course is *expressed in square measure.*

**Cubical or voluminal expansion.** In the same way if we take a cube of 1 foot side and heat it 1° of temperature each side will become $1 + K$ feet and its volume will become $(1 + K)^3$ cubic feet or $1 + 3K + 3K^2 + K^3$ cubic feet. The coefficient of cubical expansion is thus $(3K + 3K^2 + K^3)$ but again we may neglect $(3K^2 + K^3)$ in comparison with $3K$, and it is usual to say that the *coefficient of cubical expansion is three times that of linear expansion expressed in cubic measure.*

## EXAMPLES

1. What is the expansion of an iron rail 37 feet long at 60° F. when it is heated to 140° F.? The coefficient of expansion of the rail = 0·000012 per degree *Centigrade.*

2. The distance from London to Newcastle is 271 miles. What is the total expansion of the rails between the lowest winter temperature (say 10° F.) and the highest summer temperature (say 120° F.)?

3. What must be the length of a rod of zinc which will expand the same amount as 39·2 inches of iron? See table on p. 76 for coefficients of expansion.

4. A plate of copper is 10″ × 8″ at 15° C. What will be its area at 250° C.?

5. A sphere of brass has a diameter of 2·2″ at 32° F. What will be its volume and what its diameter at 212° F.?

6. The height of a barometer at 15° C. is found to be 76 cms. when measured with a brass scale which is correct at 0° C. What is the true height of the barometer?

7. A certain rod is 36 inches long at 0° C. and 36·04 inches at 50° C. What is the coefficient of expansion of the rod?

# CHAPTER VII

## EXPANSION OF LIQUIDS

Obviously we are only concerned with change of volume in the case of liquids, since they have no rigidity. Further they must be in some kind of a containing vessel and since in all probability this will expand we shall have to be careful to distinguish between the real and the apparent expansion of the liquid. The experiment illustrated by Fig. 20 indicates this. If we know the increase in the volume of the containing vessel and the apparent increase in the volume of the liquid the real expansion of the liquid will be the sum of the two.

The coefficient of real expansion will therefore be greater than the coefficient of apparent expansion by an amount equal to the coefficient of expansion of the material of the containing vessel.

Most liquids—molten metals excepted—do not expand uniformly. Fig. 31 is a graph illustrating the relationship between the volume and the temperature of a given mass of water. It is seen that the change in volume per degree of temperature is an increasing quantity after a temperature of 4° C. has been passed. It is therefore clear that we cannot give a number which represents the coefficient of expansion of water. We can give it for a definite range of temperature, but that is all. Thus between the temperatures of 4° C. and 14° C. the mean coefficient of expansion (real) of water is 0·00007, but between the temperatures of 50° C. and 60° C. it is 0·00049.

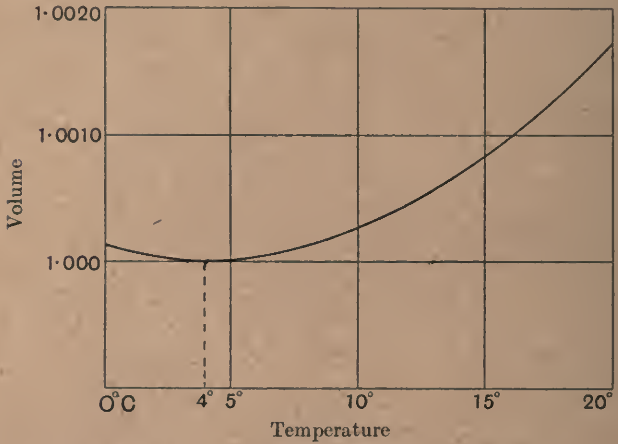


Fig. 31. Volume and Temperature of Water

**Methods of determination of coefficient of expansion.** The apparent coefficient, in glass, may be obtained readily by means of a glass bulb (of known volume) having a stem graduated in terms of the bulb's volume. This is filled to a certain point up the stem. It can then be immersed in a bath the temperature of which can be adjusted to any desired value, and the apparent volume at each temperature can be read off.

The real or absolute expansion is usually determined by comparing the *density* of the liquid at one known temperature with its density at 0° C. or at any other known temperature. As density is the mass of a unit volume it follows that as the volume of a given mass increases, its density decreases. Fig. 32 illustrates a form of apparatus by means of which this measurement may be made. The liquid to be tested is placed in the large U-tube, each limb of which is surrounded by a

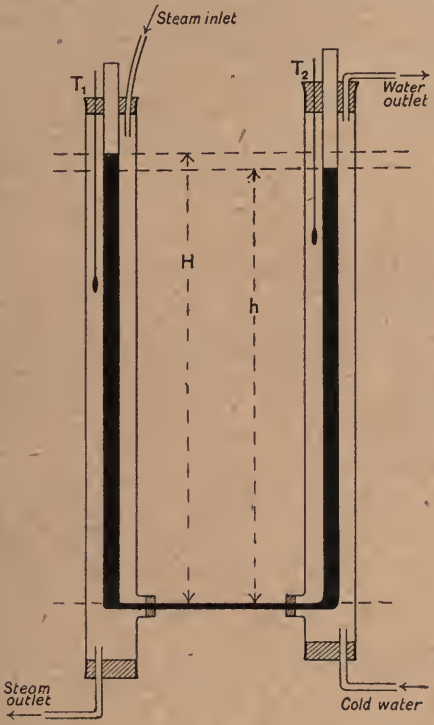


Fig. 32

jacket through which we can run cold water or steam or water at any desired temperature. The U-tube is open to the atmosphere and if both limbs are at the same temperature the liquid will be at the same level in each. If we pass ice cold water through one jacket and steam through the other then the density of liquid in the hot limb will be less than that in the cold limb and therefore we shall get a difference in level since a longer column of hot liquid will be needed to balance a given column of cold liquid. We then measure the heights of the columns $H$ and $h$ and note the temperature of the two jackets.

The heights $H$ and $h$ are inversely proportional to the densities which we may call $D_0$ and $D_t$.

The densities are inversely proportional to the volumes.

Therefore the heights are directly proportional to the volumes.

That is to say $H : h =$ volume at the higher temperature : volume at the lower temperature.

Therefore the coefficient of expansion between the temperatures chosen

$$= \frac{H - h}{h(\text{difference in temperature})}.$$

There have been several elaborations of this principle of measurement notably by Regnault and Callendar: but the fundamental principle is the same and the elaborations aim at producing greater accuracy.

**Peculiar behaviour of water.** If we look at Fig. 31 again we notice that as the temperature of water is increased from 0° C. the volume of the water *decreases* and becomes a minimum at 4° C. after which it increases again. Water is unique in this respect and the temperature at which the water has its least volume is known as the *temperature of maximum density*, namely 4° C. or 39·2° F. The unit of mass on the metric system is one gramme, which is the mass of a cubic centimetre of water at 4° C.

The immediate effect of this peculiar behaviour of water is the preservation of animal and vegetable life in lakes and ponds in winter time. The water below the ice will never fall below this temperature of 4° C. or 39·2° F. because at any other temperature higher or lower it will be lighter bulk for bulk and will therefore remain on top. As a pond cools down (it should be noted that this cooling will only take place at the surface) the water at the top will contract and sink until the whole pond is at 4° C. On further cooling the surface water will become lighter and will remain on the top and so will ultimately freeze. But the water below the ice will be at 4° C. Water and ice are bad conductors of heat and thus the pond will never become frozen to any great depth. It is well known that an ice coating on a pond should be flooded each night if it is desired to get thick ice on the pond.

The table given below shews how the density and the volume of water changes between the temperatures of 0° C. and 8° C.

| Temperature | Density | Relative volume |
|---|---|---|
| 0° C. | 0·99987 | 1·00013 |
| 2° C. | 0·99997 | 1·00003 |
| 4° C. | 1·00000 | 1·00000 |
| 6° C. | 0·99997 | 1·00003 |
| 8° C. | 0·99989 | 1·00012 |

# CHAPTER VIII

## EXPANSION OF GASES

As we saw in Chapter III the volume of a gas depends upon the pressure to which it is subjected. It therefore follows that in considering how volume changes with temperature we shall have to be careful to keep the pressure of the gas constant.

Charles found that gases expand uniformly and that as far as he could ascertain all gases have the same coefficient of expansion, namely 0·00366. As a matter of fact later experimenters have found that this is not strictly true, but it is sufficiently near the truth for our purpose.

Gases expand much more than do solids or liquids under equal conditions and we have therefore to be more careful and particular about our definition of the coefficient of expansion. We must remember that the *coefficient of expansion of volume* of a gas is *the increase in volume of a unit volume at* 0° *C. when heated from* 0° *to* 1° *C.*

We had better look at the importance of this. Let us suppose for example that that coefficient of expansion was $\frac{1}{10}$th. Now a volume of 1 at 0° C. would become 1·1 at 1° C., and 1·2 at 2° C. and so on. But if we take the volume of 1·1 at 1° C. and to find its volume at 2° C. we were to take $\frac{1}{10}$ of 1·1, viz. 0·11, and add this on to the original volume we should get a volume of 1·21 at 2° C.

This does not agree with the result we get by working from 0° C. So that if we are given that a certain gas has a volume of 1·1 at 1° C. and we are asked to find its volume at 2° C. we must first find what its volume would be at 0° C. and calculate from that point.

In cases where the coefficient is small we need not bother to find the volume at 0° C. since the error caused would be quite negligible for practical purposes. We have adopted this view already in our examples on the expansion of solids, but in the case of a gas it will be necessary to work from the temperature of 0° C.

**Charles' Law.** Charles' law states *that if a given mass of a gas be kept at a constant pressure and heated, the increase in the volume will be directly proportional to the increase in the temperature.*

If we represent the volume of a given mass of gas at constant pressure by $V_0$ at 0° C. and by $V_t$ at some temperature $t$° C. then according to our definition the coefficient of expansion $K$ will be given by

$$K = \frac{V_t - V_0}{V_0 (t - 0)} = \frac{V_t - V_0}{V_0 \times t},$$

i.e. the change in volume per unit volume at 0° per degree C.

$$\therefore \; V_t - V_0 = V_0 \times K \times t,$$

$$\therefore \; V_t = (V_0 \times K \times t) + V_0,$$

or

$$V_t = V_0 (1 + Kt).$$

Therefore we can easily find the volume at 0° C. and from that we can find the volume at any other desired temperature.

*Example.* A given mass of a certain gas is 12 c.c.

at a temperature of 15° C.; what will it be at 60° C., the coefficient of expansion being 0·00366?

Firstly we find the volume at 0° C.

$$V_{15} = V_0 (1 + \cdot 00366 \times 15),$$

$$12 = V_0 (1 + 15 \times \cdot 00366),$$

$$\therefore V_0 = \frac{12}{1 \cdot 0549} = \underline{11 \cdot 375 \text{ c.c.}}$$

Then we find the volume at 60° C. from

$$V_{60} = V_0 (1 + \cdot 00366 \times 60),$$

$$\therefore V_{60} = 11 \cdot 375 \times 1 \cdot 2196$$

$$= \underline{13 \cdot 875 \text{ c.c.}}$$

**Experimental verification.** Charles' law may be verified and the coefficient of expansion of a gas determined by the dilatometer method similar to that described in the previous chapter.

A bulb of known volume having a graduated stem can be arranged as shewn in Fig. 33. The bulb and part of the stem can contain air or any other gas and this is shut off from the outside air by means of a small pellet of mercury $P$ which also serves as an index. If the volume of the bulb is fairly large compared with the stem the errors due to the exposed part of the stem will be very small, but the range of temperature which can be covered will not be very great. This should be

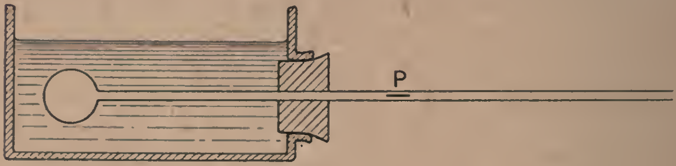


Fig. 33

determined by a preliminary experiment. Then the bath is heated up to the highest permissible temperature and readings are taken, as the bath cools, of temperatures and volumes. These can be plotted graphically and coefficients can be calculated from the various readings. The volume at 0° C. can be determined by experiment or can be obtained from the graph.

Any bulb and stem may be readily calibrated by filling with mercury, and then weighing the mercury required. Similarly the volume per inch of tube can be determined by measuring the length of any pellet of mercury in the tube and then weighing it. From the density of the mercury and its mass the volume is calculated since density is the mass of a unit volume.

There are again many more refined and elaborate devices for the verification of Charles' law, but if the principle of this is understood, the refinements can be appreciated quite readily by the intelligent student.

**Variation of Pressure with Temperature.** We all know that if we confine a gas to a given space and heat it the pressure of that gas increases. Such pressure plays the all-important part in internal combustion engines and in the use of explosives. We have all witnessed the disasters to our air balloons in bygone days when they got too near to the fire.

Regnault shewed that if the volume of a given mass of a gas was kept constant and its temperature increased the increase in the pressure was directly proportional to the increase in temperature.

He found moreover that the coefficient of increase of pressure—namely *the increase in the pressure of a unit pressure at 0° C. when heated 1° C.*—was the same as the coefficient of increase in volume, ·00366 or $\frac{1}{273}$.

A simple form of apparatus for the verification of this law is shewn in Fig. 34. A bulb which contains the gas *G* is immersed in a bath *B* the temperature of which can be varied at will and determined by the thermometer *T*. The bulb is connected by a fine bore tube to one of the limbs of a U-tube—similar to the apparatus used for the verification of Boyle's law (page 43). By raising or lowering the right-hand limb *R* the mercury in the left-hand limb can be kept at the same position for various temperatures of the bath. The actual pressure of the gas at each temperature will be the atmospheric pressure in inches or centimetres of mercury plus or minus the *difference* in the levels of the mercury in *L* and *R* in inches or in centimetres—the volume of the gas being kept constant at each temperature by the adjustment of *R*.

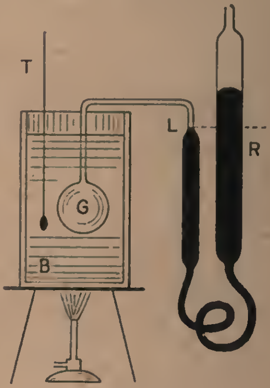


Fig. 34

**Absolute zero of temperature.** If, instead of using a mercury thermometer for the measurement of temperature, we use a gas thermometer—either on the constant volume or on the constant pressure principle—we should find a theoretical minimum temperature below which we could not use it. That is to say if we assume for a moment that the law of Charles and the corresponding pressure-temperature law hold good for all temperatures we should find that at a temperature of − 273° C. gases would have no volume and would exert no pressure. This temperature is called the *absolute zero of the perfect gas thermometer.*

Now it is not considered possible to annihilate matter at all, so that we must feel that there is a way out of this mystery. It lies in the fact that gases change into liquids before they reach that temperature and after that they no longer follow Charles' law.

According to the Kinetic Theory of Gases (page 8) the pressure of a gas is caused by the agitation or bombardment of its molecules. Therefore if the gas exerted no pressure its molecules must be stationary. It is further suggested that as a body contains more and more heat the movement of its molecules is increased and *vice versa.* Therefore if we can reduce a gas to such a temperature that it exerts no pressure there will be no molecular movement and no heat. That temperature would therefore be the lowest possible or the *absolute zero* of temperature.

The temperature of – 273° C. has never been reached in practice although in recent times the temperature of – 269° C. has been obtained.

Fig. 35 shews a volume-temperature graph, volumes being plotted vertically and temperatures horizontally. If we get readings of the volume of any mass of a gas between 0° C. and 100° C. and then produce the graph backwards (assuming Charles' law to hold good) until the volume is zero we find that the temperature for this condition is – 273° C.

It will be quite clear to our readers that if this point, – 273° C., were made the origin of the graph, that is to say if it were both a zero of temperature and volume, we could say that the volume was directly proportional to the temperature calculated from this zero.

From this we have adopted another temperature scale—called the Absolute scale—having the temperature of – 273° C. as its zero and being equal to the Centigrade scale reading + 273. Thus 0° C. = 273° A.,

$$57^\circ \text{ C.} = 57 + 273 = 330^\circ \text{ A.},$$

and $$-38^\circ \text{ C.} = -38 + 273 = 235^\circ \text{ A.},$$

and so on. Charles' law may now be stated thus:

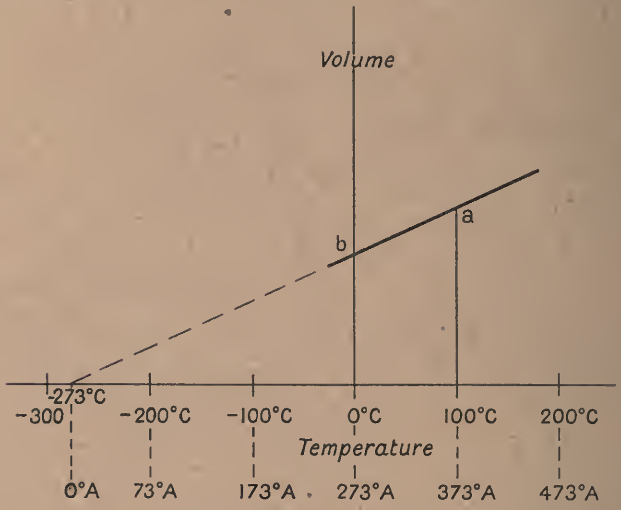


Fig. 35

*that the volume of a given mass of a gas kept at a constant pressure varies directly with the absolute temperature.*

Thus if $V_1$ be the volume at $T_1^\circ$ Absolute, and $V_2$ be the volume at $T_2^\circ$ Absolute, then

$$\frac{V_1}{V_2} = \frac{T_1}{T_2} = \frac{t_1^\circ \text{ C.} + 273}{t_2^\circ \text{ C.} + 273}.$$

In the same way it can be seen that if the volume is kept constant the pressure will vary directly as the absolute temperature:

$$\frac{P_1}{P_2} = \frac{T_1^\circ \text{ A.}}{T_2^\circ \text{ A.}}.$$

Finally if we consider possible variations of each of the three quantities pressure, volume and absolute temperature, we shall find that

$$\frac{P_1 V_1}{P_2 V_2} = \frac{T_1}{T_2},$$

when $P_1$, $V_1$ and $T_1$ are the pressure, volume and absolute temperature in one case, and $P_2$, $V_2$ and $T_2$ those in the second case.

*Examples.* (1) Let us take the example on page 88. A given mass of a gas is 12 c.c. at 15° C.; what will it be at 60° C.?

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}, \quad \therefore \frac{12}{V_2} = \frac{15+273}{60+273} = \frac{288}{333},$$

$$\therefore V_2 = \frac{12 \times 333}{288} = \underline{13{\cdot}875 \text{ c.c.}}$$

We see that it is much easier to solve the problem this way.

(2) A mass of air has a volume of 24 c.c. at a temperature of 27° C. and a pressure of 30″ of mercury. What will be its volume at 77° C. and a pressure of 20″ mercury?

$$\frac{V_1 P_1}{V_2 P_2} = \frac{T_1}{T_2},$$

$$\therefore \frac{24 \times 30}{V_2 \times 20} = \frac{300}{350},$$

$$\therefore V_2 = \frac{24 \times 30 \times 350}{20 \times 300} = \underline{42 \text{ c.c.}}$$

**Absolute-Fahrenheit scale of temperature.** Before concluding this chapter it may be well to point out that the absolute zero of temperature on the Fahrenheit scale would be – 459·2°. By adding 459·2 to any Fahrenheit reading we shall get an Absolute-Fahrenheit scale. This scale could be used for the above calculations.

For example: If a certain gas has a volume of 12 c.c. at 59° F., what will be its volume at 140° F.?

$$\frac{V_1}{V_2} = \frac{T_1\text{° A.}}{T_2\text{° A.}},$$

and using the Absolute-Fahrenheit scale $T_1$ is

$$459{\cdot}2 + 59 = 518{\cdot}2°$$

and $T_2$ is

$$459{\cdot}2 + 140 = 599{\cdot}2°,$$

$$\therefore \frac{12}{V_2} = \frac{518{\cdot}2}{599{\cdot}2},$$

$$\therefore V_2 = \frac{12 \times 599{\cdot}2}{518{\cdot}2} = \underline{13{\cdot}875 \text{ c.c.}}$$

EXAMPLES

1. A certain mass of air has a volume of 50 cubic inches at 16° C., what will be its volume at 0° C. and at 100° C., the pressure being constant?

2. A certain mass of air has a volume of 3 cubic feet when the temperature is 27° C. and the pressure is 15 lbs. per square inch: what will be its volume when the temperature is 227° C. and the pressure is 150 lbs. per square inch?

3. A certain mass of a gas at a temperature of 59·8° F. has a volume of 36 cubic feet, the pressure being 20 lbs. per square inch. If the temperature be increased to 212° F. what must be the pressure in order to keep the volume the same?

4. The volume of a certain mass of gas is 8 cubic feet at 15 lbs. pressure and temperature 20° C. If the pressure be doubled find the temperature to which it must be heated so that its volume becomes 6 cubic feet.

# CHAPTER IX

## MEASUREMENT OF HEAT

One of the effects which heat may produce when given to matter is an increase in temperature. This effect is not inevitable, but generally speaking a body becomes hotter when it receives heat. An exception may be quoted at once. If we put a vessel of water over a furnace we shall find that the water will get hotter and hotter (as shewn by a thermometer placed in it) until it starts to boil. But we shall find that it does not get any hotter after that. We may increase the temperature of the furnace as much as we please but the thermometer will not rise beyond the boiling point. Of course the water will boil away more quickly, and the heat is being used to produce this change of the state of the liquid.

However, whenever heat is given to a substance which is neither at its boiling point nor melting point an increase in temperature will follow. It is readily conceivable that if two equal quantities of a substance are given equal quantities of heat they will be equally affected so far as temperature increase is concerned. It is also conceivable that if a certain quantity of heat be given to a substance and it produces a certain increase in its temperature, twice the quantity of heat will produce twice the increase in temperature. For all practical purposes this is true (just as a pint of liquid will rise to twice as great a level in a cylindrical vessel as half a pint) but actually it is not strictly the case. We shall, however, assume that it is, since the very small error involved is of little or no account in engineering practice.

**Unit of Heat.** A unit quantity of heat energy is defined as that quantity necessary to raise the temperature of a unit mass of water through one degree of temperature.

Thus on the British system of measurement a unit of heat is the heat necessary to raise the temperature of 1 lb. of water through 1° F. This is called a *British Thermal Unit* and is commonly used by mechanical engineers.

The quantity of heat necessary to raise the temperature of 1 gramme of water through 1° C. is the unit of heat on the metric system of measurement. This is called a *Calorie*.

These units are not equal of course: and since there are 453·6 grammes to the pound and $\frac{5}{9}$ of a degree Centigrade to the degree Fahrenheit it follows that there are 252 calories to the British thermal unit.

It will be noted that water is chosen as the standard substance. We shall see presently that different substances require different quantities of heat per lb. to produce one degree rise in temperature.

Every unit mass of water will require a unit of heat for every degree its temperature is raised: and conversely, on cooling, every unit mass will give out a unit of heat per degree fall in temperature. Thus the heat necessary to raise the temperature of 3 lbs. of water from 60° F. to 212° F. will be $3 \times (212 - 60)$, viz.

3 × 152 or 456 B.TH.U. The heat given out by 4·5 lbs. of water cooling from 60° F. to 32° F. will be 4·5 × (60 – 32), viz. 126 B.TH.U. That is to say the heat required or yielded by any mass of water $M$ when it undergoes a change of temperature from $t_1°$ to $t_2°$ will be

$$M \times (t_2° - t_1°) \text{ units.}$$

The units will be calories if $M$ is in grammes and $t_1$ and $t_2$ are Centigrade; and they will be British thermal units if $M$ is in lbs. and $t_1$ and $t_2$ are Fahrenheit.

**Specific Heat.** If we take equal masses of iron and copper and heat them to the same temperature and then plunge them into two equal vessels of water at the same temperature, we shall find that the vessel into which we plunged the iron will become a little hotter than the other one. This suggests that the iron must have given out more heat than the copper. The heat given out must have been received by the water: and its temperature would rise. In the same way if we take equal masses of other different substances at equal temperatures and plunge them into separate equal vessels of water we shall find that these different substances give out different quantities of heat.

*The quantity of heat necessary to raise the temperature of a unit mass of a substance through* 1° *is called the specific heat of that substance.*

The specific heat of copper, for example, is 0·094. That is to say 0·094 *British thermal unit* of heat will raise the temperature of 1 *lb.* of copper through 1° *F.* It also means that 0·094 *calorie* of heat will raise the temperature of 1 *gramme* of copper through 1° *C.*

The following table gives the specific heats of some substances:

| | |
|---|---|
| Silver | 0·055 |
| Copper | 0·094 |
| Iron | 0·112 |
| Mercury | 0·033 |
| Glass | 0·19 |
| Turpentine | 0·43 |
| Aluminium | 0·21 |
| Lead | 0·031 |
| Water | 1 |
| Ice | 0·502 |
| Hydrogen (constant pressure) | 3·402 |
| Air (constant pressure) | 0·2427 |
| Air (constant volume) | 0·1715 |

The fact that water has such a high specific heat compared with most other things is not generally appreciated by the man in the street. He is always inclined to think that a kettle absorbs as much if not more heat than the water it contains, and may even advocate the use of thinner kettles. Let us consider how much heat will be absorbed by a kettle made of copper, weighing 2 lbs., and containing 3 lbs. of water when heated from 70° F. to 212° F.

Firstly, the kettle:

1 lb. of copper heated through 1° F. will require 0·094 unit of heat,

therefore 2 lbs. of copper heated through 1° F. will require $2 \times 0{\cdot}094$ units of heat,

therefore 2 lbs. of copper heated through $(212 - 70)°$ F. will require $142 \times 2 \times 0{\cdot}094$ units of heat.

That is to say the kettle will absorb 26·7 *units*.

Secondly, the water:

1 lb. of water heated through 1° F. will require 1 unit of heat,

therefore 3 lbs. of water heated through 1° F. will require 3 units of heat,

therefore 3 lbs. of water heated through $(212-70)°$ F. will require $3 \times 142$ units of heat.

That is to say the water will absorb 426 *units.*

Thus we see that the total heat absorbed by the kettle and the water is 452·7 units of which only 26·7 units are taken by the kettle.

**Water Equivalent.** We could have taken it in a simpler way than this. Since 1 lb. of copper only absorbs 0·094 unit of heat for each degree rise in temperature, we can say that 1 lb. of copper is only equivalent to 0·094 lb. of water, since 0·094 lb. of water would absorb 0·094 unit for each degree increase. Therefore we could say that the kettle—viz. 2 lbs. of copper—was *equivalent to* $2 \times \cdot094$, viz. 0·188 lb. of water, so far as the absorption of heat is concerned. We could then take it that the kettle and the water were together equivalent to 3·188 lbs. of water, and if 3·188 lbs. of water are heated from 70° F. to 212° F. the heat required will be $3\cdot188 \times (212-70)$, viz. 452·7 units, which agrees with the previous answer.

Thus we can say that the mass of any substance multiplied by its specific heat is the *water equivalent* of that substance. This is of some assistance to us in our experiments connected with the measurement of heat.

**Measurement of Specific Heat.** The substance whose specific heat is to be determined must be weighed, and it is heated in some way or other to some known or measurable temperature. It is then dropped into a vessel containing a known quantity of water at a known temperature. The "mixture" is thoroughly stirred and its temperature is taken. From these particulars the specific heat of the substance may be calculated.

It will be seen at once that there are certain practical difficulties connected with this experiment. Precautions must be taken to avoid loss of heat as the substance is being dropped into the water; and again, precautions must be taken to prevent loss of heat from the water to the surrounding air.

The vessel containing this water is usually called a *calorimeter* and generally consists of a cylindrical copper vessel which is suspended inside a similar but larger vessel by means of three silk threads. The surfaces are kept well polished and the calorimeter losses are thus reduced to a minimum. In addition to this it is usual in important measurements to arrange that the first temperature of the water in the calorimeter shall be as much below the temperature of the surrounding air as the second temperature is above. In this way we get a slight gain balancing off a slight loss.

The arrangement for heating the substance generally takes the form of a steam jacket $J$, $J$ as shewn in Fig. 36. The substance $S$ is suspended inside and a thermometer $T$ is fixed near it. The heater is fixed on an insulating base with a sliding shutter which has the effect of opening or shutting the heater. The calorimeter is placed directly beneath the centre of the heater. When the jacket is heated and its temperature has been noted, the shutter is opened and the substance is lowered into the calorimeter as speedily as possible. The calorimeter and its contents are then removed, stirred, and the temperature read.

Let us suppose that the following results were obtained.

Mass of calorimeter empty 45 grammes.

Material of calorimeter, copper of specific heat 0·094.

(N.B. Only the inside vessel should be weighed as the outer vessel does not absorb any heat.)

Mass of water in calorimeter 132 grammes.

Original temperature 15° C.

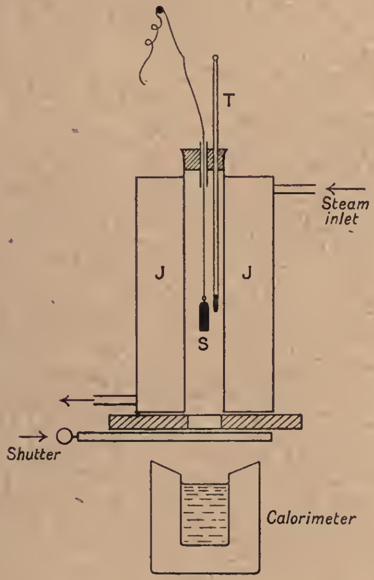


Fig. 36

Mass of substance in calorimeter 116 grammes.

Original temperature of substance in heater 92° C.

Final temperature of "mixture" 22° C.

The *water equivalent of the calorimeter*

$$= 45 \times 0{\cdot}094 = 4{\cdot}2 \text{ grammes.}$$

Therefore the total equivalent mass of water

$$= 132 + 4 \cdot 2 = 136 \cdot 2 \text{ grammes.}$$

Therefore the heat received

$$= 136 \cdot 2 \times (22 - 15) = 953 \cdot 4 \text{ units.}$$

Now this heat must have been given out by 116 grammes of substance cooling from 92° to 22°, that is, through 70°.

Therefore the heat which would be given out by 1 gramme cooling through 1°

$$= \frac{953 \cdot 4}{116 \times 7} = 0 \cdot 117.$$

Therefore the specific heat of the substance = 0·117.

In all heat measurements our results are determined from the following fact:

*Heat received by calorimeter and water = heat given by substance inserted.*

There is no need for us to express any of this as mathematical formulae. The fundamental ideas are quite simple, and the examples can be and should be worked out from first principles.

**Calorific value of fuels.** It is often very important that engineers should know how much heat is given by burning a known quantity of different kinds of fuel. As we have said before we buy fuel for the heat energy which we can get out of it, and the cheapest fuel is that which will give the greatest amount of heat for every shilling which we pay for it.

The number of heat units per unit of mass of fuel is called the *calorific value* of that fuel.

One of the methods of determining this value is by the use of the Darling calorimeter, the main ideas of which are illustrated by Fig. 37.

A known mass of the fuel is placed in a small crucible *C* which is placed inside a bell jar *B*. This jar is fastened down to a special base plate. The products of combustion can only leave the jar through the outlet at the bottom of the base-plate, and this outlet *R* is like a watering-can rose with very fine holes. A supply of oxygen—which, of course, is necessary for the combustion of the fuel—is admitted at the top of the bell jar and its rate can be regulated by means of a regulator.

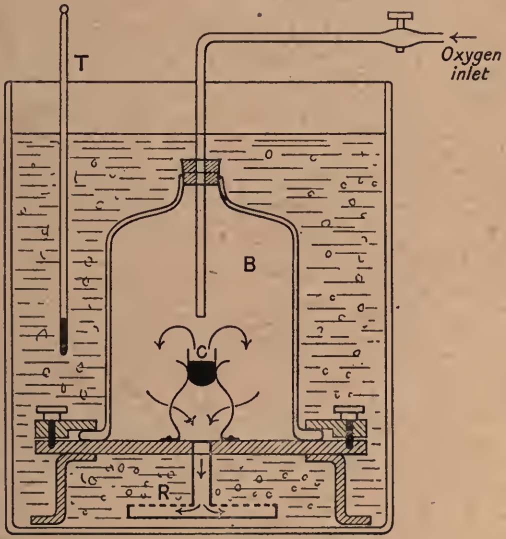


Fig. 37

The bell jar and its attachments thus form a small furnace and this is immersed in an outer vessel containing a known quantity of water at a known temperature.

The fuel is then ignited (this being done by means of a small piece of platinum wire heated by an electric current) and the flow of oxygen is regulated so that the "flue gases" formed by the burning fuel bubble slowly up through the water. Thus they give out their heat to the water.

When the fuel has completely burned itself out the water is allowed to flow inside the jar so that we can be quite sure that all the heat generated has been absorbed by the water. The temperature is then taken and the calorific value is calculated as shewn below.

Mass of water = $Mw$ lbs.

Water equivalent of calorimeter: Bell-jar, etc. = $Mc$ lbs.

(This *water equivalent* is usually given by the makers of the calorimeter, but of course it can be calculated or determined by experiment. In this case a record would be kept for future use.)

Total equivalent mass of water = $Mw + Mc = M$ lbs.

Original temperature of water = $t_1$° F.

Final temperature of water after fuel has been burned = $t_2$° F.

Therefore *heat received by water* = $M \times (t_2 - t_1)$ B.TH.U.

Mass of fuel burned = $P$ lbs.

Therefore if $M(t_2 - t_1)$ B.TH.U. were given by the combustion of $P$ lbs. $\frac{M(t_2 - t_1)}{P}$ British thermal units would be given by 1 lb. in burning.

And this is the calorific value of the fuel.

The results could all be taken with metric units, if desired, and the calorific value in *calories per gramme* could be determined.

The following table shews the calorific values of some fuels in British thermal units per lb. of fuel.

| | | | |
|---|---|---|---|
| Methylated alcohol | 11,320 | Steam coal ... | 15,600 |
| Benzol ... ... | 17,750 | Bituminous coal | 14,600 |
| Petrol ... ... | 20,000 | Coal gas (London) | 500 B.TH.U. per cubic foot |
| Paraffin oil... ... | 19,000 | | |

**Two values for the Specific Heat of a Gas.** The reader has already noted that two values are quoted on page 98 for the specific heat of air. It has been found that if the volume is kept constant the gas absorbs less heat per degree of temperature than it does if it is allowed to expand at constant pressure. This is an interesting and important matter to engineers. The explanation is to be found in the fact that if the gas expands it has to do work in pushing back the surrounding atmosphere, just as if it were pushing back a piston in an engine cylinder. This work is done at the expense of some of the heat which is being given to it and therefore we have to give it more heat to raise its temperature through each degree than would be necessary if it was not expanding. The additional heat represents the work which the gas is doing in expanding.

The methods for the determination of these specific heats are of a very refined order, and the details cannot be dealt with in this little volume.

## EXAMPLES

1. Find the heat necessary to raise the temperature of 3·5 lbs. of water from 59° F. to 212° F. If the same amount of heat be given to 17·5 lbs. of iron at 59° F. to what temperature would it be raised? The specific heat of iron = 0·112.

2. 4·8 lbs. of copper at 177° F. are plunged in 3 lbs. of water at 60° F. and the resulting temperature of the mixture is 75·6° F. What is the specific heat of the copper?

3. A copper calorimeter (sp. heat ·094) weighs 0·2 lb. and contains 0·75 lb. of water at 50° F. What is the water equivalent of the calorimeter and the total equivalent weight of water of calorimeter and contents? It is found that when 2·5 lbs. of iron at some unknown temperature are placed in the calorimeter the temperature rises to 60° F. How much heat did the iron give out and what must its original temperature have been? Sp. heat of iron = 0·112.

4. If all the heat given by 0·02 lb. of coal of calorific value 15,600 B.TH.U. per lb. were given to a glass vessel containing 3 lbs. of water at 60° F. (the glass vessel weighing 2·7 lbs. and having a specific heat of 0·19) to what temperature would it be raised?

5. A mass of 200 grammes of copper of specific heat 0·1 is heated to 100° C. and placed in 100 grammes of alcohol at 8° C. contained in a copper calorimeter of 25 grammes mass: the temperature rises to 28° C. What is the specific heat of the alcohol?

6. 3·5 lbs. of water at 200° F. are mixed with 5 lbs. of water at 60° F. the cold water being poured into the hot which is contained in a copper calorimeter of 1 lb. weight and specific heat 0·1. Find the temperature of the mixture (*a*) neglecting the calorimeter, (*b*) taking the calorimeter into account.

# CHAPTER X

## FUSION AND SOLIDIFICATION

The third important effect of heat upon matter is that known as a change of *physical* condition such, for example, as the change of a substance from the solid to the liquid form. If such a change is effected without producing any change in the chemical constitution of the substance it is called a *physical change of state.* When heat is given to ice it changes to water (which is chemically the same thing) and if more heat be given it will ultimately change again to steam, which again has the same chemical composition.

When heat is applied to coal chemical changes take place, and the same applies to many other substances. But if no chemical change is produced then the physical change is produced: and we shall only consider such change in this volume.

**Melting Point of a Solid.** The temperature at which a solid melts—that is to say changes into the liquid form—is called the *melting point* of that solid. Different substances have different melting points as the following table shews.

| | |
|---|---|
| Ice | 0° C. |
| Aluminium | 600 |
| Antimony | 440 |
| Bismuth | 265 |
| Brass | 1015 |
| Carbon | 3500 |
| Copper | 1050 |
| Gold | 1250 |
| Iridium | 1950 |
| Iron (wrought) | 1600° C. |
| Iron (cast) | 1100 |
| Lead | 325 |
| Mercury | – 39·5 |
| Platinum | 1700 |
| Silver | 1000 |
| Steel | 1350 |
| Tin | 231 |
| Tungsten | 3200 |
| Zinc | 420 |

The melting point is usually a well-defined temperature though there are some substances like glass, for example, which become plastic and slowly change to the fluid state. It is difficult to determine the exact melting point of such a substance.

The *solidifying point* or *freezing point* of a liquid is that temperature at which it changes from liquid to solid. This temperature is the same as the melting point. That is to say, ice melts at 0° C. and water freezes at 0° C.

**Heat required to melt a solid.** In order to melt a solid it is not enough to heat it to its melting point. Additional heat must be given when this temperature is reached and it will be found that *such heat does not produce any increase in temperature* until the whole of the solid is melted. If some ice be placed in a vessel and the vessel be heated over a furnace it will be found that

(*a*) the temperature of ice will increase if it were below 0° C. at the start:

(*b*) when it reaches 0° C. it will remain stationary until every particle of ice is melted:

(*c*) when the ice is all melted then the temperature of the water will rise.

During this experiment the ice and water must be kept thoroughly stirred.

The same thing exactly applies to the melting of any other substance though equal masses of different substances do not all require the same quantity of heat energy to melt them *after the melting point has been reached.* In this respect ice requires more heat than is required by any of the metals given in the above list. The reader must think this over carefully and see that he understands exactly what is meant.

**Latent Heat of Fusion.** *The quantity of heat necessary to change a unit mass of a solid* AT ITS MELTING POINT *to liquid* AT THE SAME TEMPERATURE *is called the latent heat of fusion of that substance.*

For example the latent heat of fusion of ice (on the British system of measurements) is 144. That is to say 144 B.TH.U. of heat are required to change 1 lb. of ice at 32° F. into 1 lb. of water at 32° F. Conversely when 1 lb. of water at 32° F. freezes to ice at the same temperature it must give up 144 B.TH.U. of heat.

On the metric system the quantity of heat necessary to melt 1 gramme of ice at 0° C. and change it to water at 0° C. is 80 calories.

The latent heat of fusion of a few substances is shewn below.

*Latent heat in British thermal units per lb. of substance.*

| | | | |
|---|---|---|---|
| Ice ... | 144 | Bismuth | 23 |
| Zinc ... | 51 | Sulphur | 17 |
| Silver | 38 | Lead ... | 9·6 |
| Tin ... | 25·6 | Mercury | 5 |

An interesting experiment, which illustrates how melting points may be determined and demonstrates at the same time the fact that heat is absorbed or yielded by a substance in changing its physical state, may be performed by placing some paraffin wax, or better still some naphthalene, in a boiling tube and heating this tube in a water bath. The bath should be heated until all the wax has melted. A thermometer should then be placed in the liquid formed and the bath allowed to cool. Readings of the thermometer should then be taken at regular intervals of time—say every half-minute. It will be noted that the thermometer falls steadily to a certain temperature after which it remains stationary (or in some cases it may even rise again slightly) for several minutes. During this stationary period it will be noted that the wax is solidifying, and when it has all become solid the temperature will start to fall again.

Fig. 38 gives two graphs (one for wax and the other for naphthalene) shewing how the temperature falls with

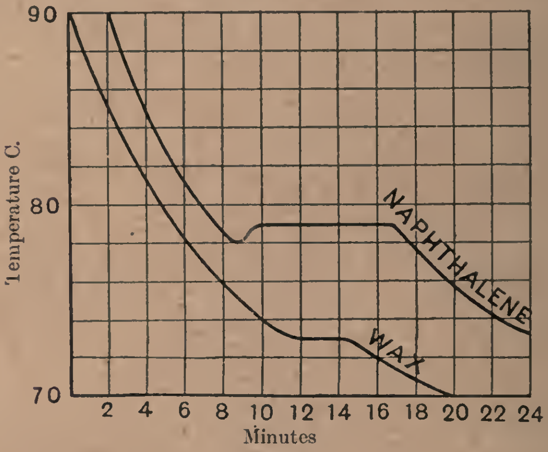


Fig. 38

the time. The melting point is that temperature at which the cooling temporarily ceases. The explanation lies in the fact that on solidifying the substance gives out heat, and this heat suffices to prevent the temperature from falling. In the case of substances with a more defined melting point than wax the heat given out on solidification will cause the temperature to increase. This is shewn on the naphthalene graph. It should be pointed out that the melting point of the naphthalene is given by the horizontal part of the graph.

We may also compare, roughly, the latent heat of each substance by noting the length of time during which the temperature remains practically constant. The longer the time the greater must be the quantity of heat given out. Of course, the reader will see that such comparison could only be made if equal masses of substances were used and allowed to cool under equal conditions. This in turn would mean that only substances with approximately equal melting points could be compared in this way. From our curves we can see that the naphthalene has a greater latent heat than the wax.

**Change of volume with change of state.** It is found that some substances, like water, increase in volume in passing from the liquid to the solid state. That is to say a given mass of the substance will have a greater volume in the solid state than in the liquid state *at the same temperature.* We say that such substances *expand on solidification.* Other substances contract on solidification.

This is important to engineers for many reasons. Firstly, whenever a casting is made we have a liquid changing to solid. If that substance contracts on solidification the chances are that we shall not be able to get a good casting—that is to say a well defined casting—because the metal will shrink away from the sand mould. If we can use a metal which expands slightly on solidification, or one which does not change in volume, we shall get sharp castings which will not need so much machining. Metals like copper and iron contract on solidification. Antimony and bismuth expand on solidification. Some alloys like *type-metal* (an alloy of lead, tin and antimony) expand on solidification. In fact that is the sole reason why this particular alloy is used for making type. Some readers may have seen castings which were ready for immediate assembling on being taken out of the sand. They are sharply defined, have smooth surfaces, and do not require any machining.

Secondly, if there is going to be any appreciable change of volume then account will have to be taken of this in the size of the pattern. The volume of the pattern will be the volume of the molten metal.

Again, especially in the case of larger castings, the metal nearer to the sand will solidify first, so that when the inner portions solidify stresses are produced due to internal contractions or expansions, and these may cause the casting to break.

It is well known that water expands on solidification. Water pipes are burst in winter time by that expansion. It is that same expansion which breaks up the soil for the farmer.

**Determination of the Latent Heat of Fusion of ice.** A calorimeter, of known water equivalent, containing a known mass of water at a known temperature is taken, and into this are dropped small pieces of *dry* ice (each piece must be carefully dried with flannel). This process is continued until the temperature of water has been reduced several degrees and when all the pieces of ice which have been introduced are seen to be melted the temperature is taken. The calorimeter and its contents are weighed again so that the mass of ice which has been melted may be determined. From this the latent heat may be calculated.

The heat given out = (total equivalent mass of water) × (fall in its temperature).

The heat received = (mass of ice × latent heat of fusion) + (mass of ice × rise in temperature from melting point to final temperature).

It will be seen that unless the temperature of the water is reduced to the melting point then the ice will receive heat firstly to melt it and secondly to heat the melted ice up to the final temperature of the water in the calorimeter.

Since the heat received = heat given out,

the latent heat is easily determined.

In performing the experiment it is well to start with the temperature of the water a few degrees above and to stop adding ice when it is the same number of degrees below the temperature of the room. The pieces of ice should be small and clean, and they should not be touched by the naked fingers.

**Solution: Freezing mixtures.** Whenever a solid dissolves in a liquid without producing any kind of chemical change the temperature of the liquid is reduced. A chemical change always generates heat: and thus when a solid is dissolved in a liquid and produces a chemical combination the liquid will be heated if the chemical change is greater than the physical change and *vice versa*.

A mixture of salt and pounded ice or snow falls to a temperature as low as − 22° C. or − 7·6° F., according to the proportions of ice and salt.

**Effect of Pressure on the Melting Point.** The temperature at which a solid melts is only slightly affected by pressure. Ordinary changes in atmospheric pressure do not produce any measurable effect upon the melting point, but if greater pressures be applied it is found that

(*a*) substances which expand on solidification have their melting points lowered by an increase in pressure, and

(*b*) substances which contract on solidification have their melting points raised by an increase in pressure.

That is to say ice can be melted by the application of great pressure, but of course the water so formed will be below the temperature of the freezing point and will freeze again at once when the pressure is released.

The making of a snowball; the freezing together of two colliding icebergs; the progress of glaciers, are all explained by this.

## EXAMPLES

1. How much heat would be necessary to heat up 3 lbs. of ice from a temperature of 10° F. to its melting point, to melt it, and to heat the water to the boiling point? The specific heat of ice is 0·5 and its latent heat is 144 on the British system.

2. Compare the quantities of heat necessary to melt 4 lbs. of each of the following substances *assuming that they are all at* 32° *F. to start with*: ice, silver and lead. See pages 107 and 109 for melting points and latent heats, and page 98 for specific heats.

3. A cavity is made in a large block of ice and into it is put an iron sphere at a temperature of 1000° F. The iron weighs 0·64 lb. and its specific heat is 0·112. How much water will be formed in the cavity?

4. How many heat units on the C.G.S. system would be given out by half a litre of water in cooling down from 15° C. and freezing at 0° C.? If this heat were given to 1 lb. of lead at 15° C. to what temperature would it be raised? (Melting point, 325° C.: specific heat, ·031: latent heat, 9·6.)

# CHAPTER XI

## VAPORISATION

Just as a solid may be changed to the liquid form by the application of heat so can a liquid be changed to the gaseous form. This change of physical state is called *vaporisation*, the reverse change (from gas to liquid) being called *condensation*.

Vaporisation can take place either by the process known as *evaporation* or by the process of *boiling* or *ebullition*. These processes differ from one another. Evaporation takes place at all temperatures but it only takes place from the *surface* of a liquid. If equal quantities of water are placed in different vessels—one an open shallow dish, the other a tall narrow flower vase, for example—and left over night in the same room after having been weighed, it will be found next morning that the shallow vessel has lost more weight than the other one. We all know how a cork in a bottle will prevent evaporation: how an imperfect cork is a useless thing in a scent or other spirit bottle.

Ebullition or boiling will only take place at one definite temperature for a given liquid *at a given pressure*, and it takes place throughout the whole mass of the liquid.

**Boiling Point.** We will deal with ebullition first. A liquid is said to be boiling when bubbles of vapour formed at the bottom of the vessel rise up throughout the mass of the liquid and "burst" into the space above. Such bubbles must not be confused with the more minute air bubbles which may rise up as soon as heat is supplied.

As soon as the liquid commences to boil *its temperature will cease to rise.* The temperature of the liquid when this happens will be the boiling point of that liquid: the temperature of the vapour in the space above will be the boiling point of that liquid which is formed by the condensation of the vapour. For example, if we boil some salt water we shall find that the temperature of the liquid is higher than that of the vapour above it. As we know, the vapour is steam and it will condense to water. Therefore the temperature of the vapour is the boiling point of *water*: but the temperature of the liquid is the boiling point of that particular sample of *salt water*.

As a general rule if the liquid is of the same chemical composition as the vapour above it we take the temperature of the vapour, because the boiling point of a liquid is slightly affected by mechanical impurities and by the material of the containing vessel.

**Effect of Pressure on the Boiling Point.** If we test the boiling point of a liquid on different days we shall find that it varies and that it is slightly higher when the barometer is higher. This suggests that the boiling point is affected by pressure. Complete investigation leads to the discovery that a given liquid may be made to boil at any temperature within wide limits and that an increase in pressure raises the boiling point of all liquids whilst a decrease in pressure lowers the boiling point.

The reader naturally enquires what is *the* boiling point of a liquid? The answer is that we must define the boiling point of a given liquid as the temperature at which it boils at *some definite pressure*, and that the boiling points of all liquids should be taken at that pressure. The pressure chosen for this purpose is the normal atmospheric pressure—that is to say the pressure of the atmosphere when the barometric height is 30 inches of mercury. This pressure is sometimes called a pressure of 1 atmosphere and is equivalent to 14·7 lbs. per square inch. Thus the boiling point of water is 100° C. or 212° F. when it is boiled in a vessel open to the atmosphere and the barometer stands at 30 inches.

If the water be boiled in a vessel which can be closed—like the boiler shewn in Fig. 39—it will be found that, as the steam pressure inside increases, the boiling point will rise as shewn by the thermometer. The pressure can be determined by means of a pressure gauge, either of a direct reading pattern or of the pattern shewn in the figure. This is a U-tube having fairly long limbs. Mercury is put into this and when it has the same level in each limb then the pressure of the steam must be equal to that of the atmosphere. As the steam pressure increases the mercury will be forced down the

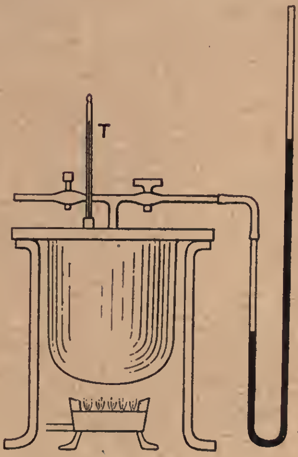


Fig. 39

left and up the right limb and the steam pressure will then be greater than the atmospheric pressure by an amount represented by the difference in level of the mercury in each limb. That is to say, if the difference is 6 inches and the atmospheric pressure is 30 inches then the steam pressure must be equivalent to that produced by a 36 inch column of mercury. Thus the relationship between the pressure of the steam and its temperature can be determined within the ranges possible with the apparatus.

Fig. 40 is an illustration of a converse experiment. It shews how water may boil at a lower temperature than 100° C. by reducing the pressure upon it. Some water is put into a round-bottomed flask and boiled. When it is boiling and steam is issuing freely we know that all the air has been driven out of the flask. The flame is removed and a cork with a thermometer is fitted. Then some cold water is squeezed out of a sponge on to the flask and it is noticed that the water inside at once begins to boil again. The colder the water in the sponge the more vigorous will be the boiling of the water inside the flask, but of course the thermometer will indicate a rapidly falling temperature.

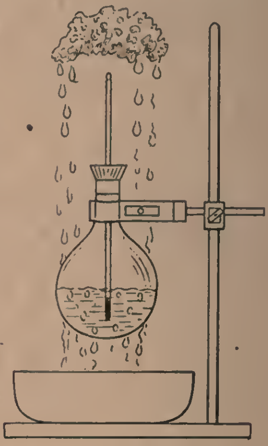


Fig. 40

Obviously the cold water will cause some of the steam inside to condense: this condensation will reduce the pressure: this reduction will lower the boiling point and the water will boil. There is always the risk of the flask breaking in this experiment, and it should be made of good quality glass, and of the shape shewn.

**Temperature of steam at different pressures.** The graph shewn as Fig. 41 indicates the temperature of

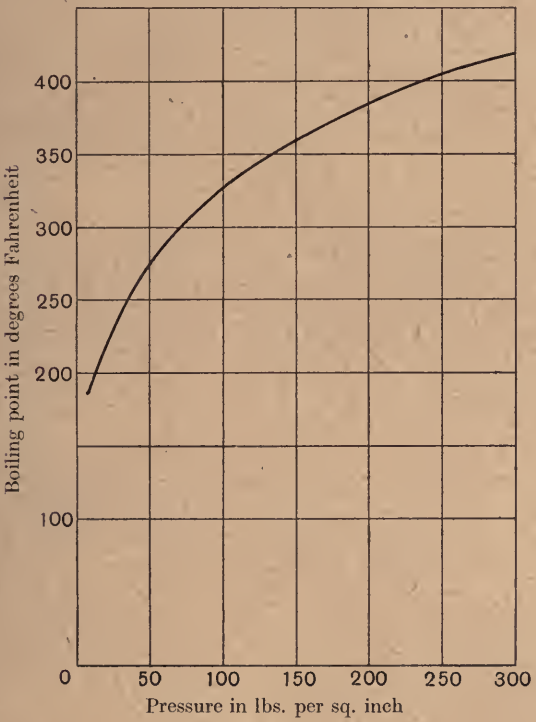


Fig. 41

steam at various pressures. At atmospheric pressure, 14·7 lbs. per square inch, the temperature of the steam is 212° F. At a pressure of 150 lbs. per square inch it is 358° F.: at 200 lbs. per square inch it is 381° F. and at 300 lbs. pressure it is 417° F. The average working steam pressures lie between 150 and 200 lbs. per square inch. Since the relationship between pressure and temperature can be obtained from the above graph, and since the relationship between the height of a place above sea level and the atmospheric pressure at that place compared with sea level pressure can also be obtained from a similar graph, it is quite obvious that height above sea level may be measured by finding the boiling point of water at various heights.

**Evaporation.** As we have said before this process goes on at all temperatures but only from the surface of a liquid. Our common experiences have taught us that some liquids evaporate much more quickly than others. We all know that petrol, scent, alcohol and benzoline will evaporate very quickly indeed, and we know the necessity for well-fitted stoppers for the vessels containing such liquids. We also know from our own experiences how water will evaporate or dry up more quickly on some days than on others. We know too that it is not entirely a question of temperature. We can think of hot close days in summer when water will not dry up at all. On such days the atmosphere is said to be *saturated* with water vapour: it cannot hold any more, and consequently no more evaporation of water can take place. That will not affect the evaporation of other liquids: but if the atmosphere could become *saturated* with petrol vapour (we hope that it never will) then even petrol would cease to evaporate. That indeed is the secret of the cork in a bottle. The space in a bottle above the liquid soon becomes saturated; and then the liquid cannot evaporate any more: but if there were no cork to the bottle then the vapour would go out into the atmosphere in a vain attempt to saturate that.

**Heat necessary for Evaporation.** Although this process goes on quietly and at all temperatures yet heat is necessary for its accomplishment. If a little alcohol, or petrol, or, better still, ether be poured on to the hand a sensation of cold will be experienced. Yet if the temperature of the liquid be taken it will be found to be the same as that of the room in which it is. The sensation of cold is brought about by the fact that the liquid absorbs heat more or less rapidly from the hand in proportion to its rate of evaporation. Thus the ether will feel colder than the alcohol, which in turn will feel colder than water—though in fact all three will have practically the same temperature*.

The rate at which they evaporate depends upon their boiling point and upon the condition of the space above them. A liquid with a low boiling point will evaporate much more quickly than one with a high boiling point—other things being equal. Nevertheless the liquid will require heat and the greater its rate of evaporation the more heat it will need. Some readers may have been unfortunate enough to have had their gums frozen prior to a tooth extraction. The "freezing" is produced by the rapid evaporation of ether absorbing much heat from the gum.

The cooling effect produced by "fanning" the face is due to the fact that the fan is continually replacing

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* When a liquid evaporates the portion of liquid remaining will generally have its temperature diminished. How much it is diminished will depend upon the quantity of liquid, the rate of evaporation and the rate at which it receives heat from external sources.

the air near to the face with comparatively fresh and unsaturated air so that evaporation of the moisture on the face can proceed more rapidly. This evaporation can only take place by absorbing heat from the face: hence the cooling sensation. The same thing applies to the common method of finding which way the wind blows: that is by holding a moistened finger in various directions. That direction in which it feels coldest is the direction from which the wind is proceeding.

**Vapour Pressure.** Every kind of vapour exerts some pressure. The pressure which it exerts depends upon the amount of vapour present and upon the temperature. If the temperature is constant then as more and more liquid evaporates the pressure of the vapour will increase until the space is saturated with that vapour. Thus it follows that at a given temperature a particular vapour will exert a maximum pressure when the space is saturated.

But though a space may be saturated with one vapour it can hold other vapours. And the total pressure in any enclosed space will be the sum of all the pressures produced by the several vapours. (This is known as Dalton's law but it is only approximately true in most cases.)

If a space be saturated with vapour and the temperature be increased it will be found that the pressure increases—though not proportionately. It will also be found that when the vapour pressure is equal to that produced by 30 inches of mercury the temperature will be *the boiling point* of that substance.

And from this it has been shewn that a liquid will boil whenever the pressure acting upon it is equal to its saturated vapour pressure. Therefore we can boil a liquid at any temperature provided that we can adjust the pressure upon it to equal that of its saturated vapour pressure at that temperature. *The* boiling point of a liquid may therefore be defined as that temperature at which its vapour pressure is equal to that of 30 inches of mercury.

**Boyle's Law and Vapour Pressure.** If a saturated vapour occupies a definite volume and we reduce the volume, then if Boyle's law were to hold good the pressure of the vapour would be increased thereby. Actually however nothing of the kind occurs. The saturated vapour pressure cannot be increased except by an increase of temperature. We find on reducing the volume that some of the vapour *condenses*: but the pressure remains the same. Boyle's law does not hold good!

An experiment was performed by Dalton to illustrate this. He made an ordinary mercury barometer using a longer tube than usual and a longer cistern (Fig. 42, *A*). Then he introduced a drop of ether into the tube by means of a bent pipette. This rose to the top and immediately evaporated, the pressure of the vapour causing the mercury to fall a little (*B*). Then he introduced a little more ether and a further fall of the mercury resulted. So he continued until he noticed that the ether ceased to evaporate, shewn by the appearance of a layer of ether liquid on the top of the mercury (*C*). He then found that the introduction of more ether did not increase the pressure—the mercury remained at the same height—but simply added to the quantity of ether liquid floating on top of the mercury. Then he lowered the barometer down into the cistern (*D* and *E*) thereby diminishing the volume of the space above the mercury, but he found that the pressure was not altered—shewn by the mercury remaining at the same level. At the same time he noticed that the quantity of liquid ether above the mercury increased. Then he gradually withdrew the tube out of the cistern so increasing the volume of the space above the mercury.

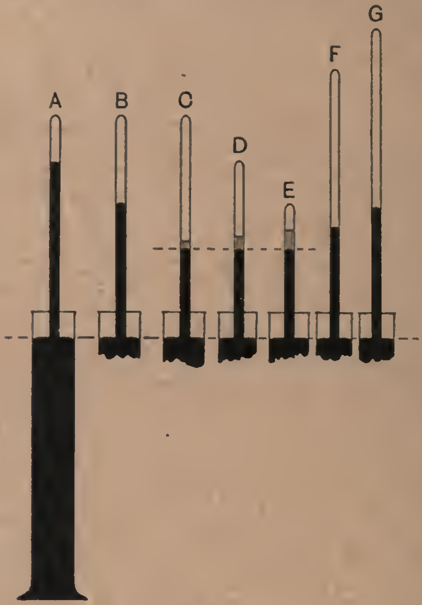

Fig. 42

But again he found that the pressure remained constant and that the quantity of liquid ether diminished. When he was able to get the tube high enough so that all the liquid ether had disappeared (*F*) then he found a slight drop in pressure shewn by the mercury rising (*G*).

He thus found that so long as a space is saturated with vapour that vapour will not obey Boyle's law:

that no change in pressure could be produced by altering the volume of the space *so long as the space was saturated.* He also found by further experiment that Boyle's law does not hold good even when a space is not saturated; but that the further the space is from saturation the closer does it follow the law.

**Temperature and Vapour Pressure.** An increase in temperature will cause an increase in pressure in either a saturated or an unsaturated space.

If a space be unsaturated a decrease in temperature will also cause a decrease in pressure, but if the temperature be lowered sufficiently (depending upon the vapour under experiment) the space will become saturated and some of the vapour will condense: but the pressure will decrease so long as the temperature is decreased.

Charles' law does not hold good: but it is approximately true in the case of non-saturated spaces; and the further the space is from saturation the closer does that space obey the law.

**Latent Heat of Vaporisation.** Heat is necessary to vaporise a liquid whether the process of vaporisation is that of evaporation or of ebullition. The number of units of heat required to change a unit mass of a liquid into the gaseous state *without a change in temperature* is called the *latent heat of vaporisation* of that liquid.

It has been found that this is not a constant quantity for a given substance: it depends upon the temperature at which vaporisation takes place. However, it is usual to speak of the latent heat of vaporisation of a substance as *the quantity of heat necessary to change a unit mass of the liquid at its normal boiling point to vapour at the same temperature.*

We are chiefly concerned with water and steam.

The latent heat of vaporisation of water—more commonly called the latent heat of steam—is 966 British thermal units per pound, or 537 calories per gramme.

This means that in order to change 1 lb. of water at 212° F. into 1 lb. of steam at 212° F. we have to supply 966 British thermal units of heat. Conversely when 1 lb. of steam at 212° F. condenses to water at the same temperature it gives out 966 British thermal units.

**Sensible Heat and Total Heat.** If we have 1 lb. of water at 60° F. and we wish to convert it to steam at atmospheric pressure we shall have to give it heat (1) to raise its temperature from 60° F. to 212° F. and (2) to convert it from water at 212° F. to steam at 212° F.

For this we shall require (1) $(212 - 60) \times 1$ units, and (2) $966 \times 1$ units, that is to say 1118 units in all.

The heat which produces a change in temperature is often called the *sensible heat*. In the case just quoted the *sensible heat* amounts to 152 units. The sum of the sensible heat and the latent heat is called the *total heat*.

**Determination of the Latent Heat of Steam.** In this measurement it is necessary to pass a known mass of dry steam into a calorimeter of known water equivalent containing a known mass of water at a known temperature. This steam will heat the water and from the increase in temperature we can easily find how much heat the water and the calorimeter have received. Now all this must have been given out by the steam and it gave it (*a*) in condensing, (*b*) in cooling down from water at the boiling point to water at the final temperature of the calorimeter. As we can easily calculate this latter amount, we have only to subtract it from the total heat received by the calorimeter and the remainder must represent the heat given out by the steam in condensing without change in temperature. We can then calculate how much a unit mass of steam would have given out and the latent heat of steam is determined.

The usual method is as follows:

Weigh the inner vessel of the calorimeter.

Partially fill with water and weigh again.

From this get the weight of the water.

Add to this the water equivalent of the calorimeter.

Take the temperature of the water.

Then allow dry steam to pass into the water.

When the temperature of the water has risen some 20 degrees shut off the steam, stir well, and take the final temperature of the water in the calorimeter.

Weigh again so that you may get the *mass of the steam condensed*.

Calculate the value of the latent heat of steam.

The chief points of importance in the performance of this experiment are (*a*) to be sure that the steam which is passed into the calorimeter is quite dry and does not carry any water particles with it; and (*b*) to prevent loss of heat due to radiation from the calorimeter. The steam may be made dry by using some kind of a steam dryer such as that shewn in Fig. 43. The loss of heat can be reduced to a minimum by arranging that the temperature of the water in the calorimeter shall be as much below the temperature of the room at the beginning of the experiment as it is above it at the end. Thus the loss and gain of heat will approximately balance.

There is nothing difficult about the calculations. The only point which is likely to be overlooked is that the heat given out by each unit mass of steam in condensing down to the final temperature is the total heat, and that this is the sum of the sensible heat and the latent heat.

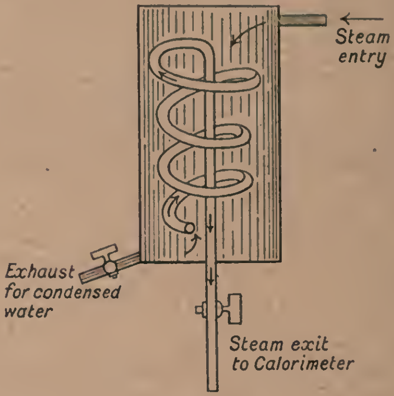

Fig. 43

**Variation of Latent Heat of Steam with Temperature.** Regnault found that the latent heat of steam was not a constant quantity. He found that as the temperature at which the steam is produced increases (due to increased pressure upon the water) the latent heat decreases and *vice versa*.

It has been shewn that the variation is approximately as follows: for each degree F. above the boiling point (212°) the latent heat of steam is diminished by 0·695 B.TH.U. per lb. of steam, and for each degree F. below the boiling point the latent heat is increased by 0·695 B.TH.U. per lb. of steam.

Thus at a temperature of 300° F. the latent heat of steam will be 966 less 0·695 unit for each degree above 212°. That is to say the latent heat will be

$$966 - (88 \times 0{\cdot}695) = 966 - 61{\cdot}16 = 904{\cdot}84.$$

Similarly at a temperature of 180° F. (that is under reduced pressure) the latent heat of steam would be

$$966 + \{(212 - 180) \times 0{\cdot}695\} = 988{\cdot}24.$$

On the metric system of units the variation is 0·695 *calorie per gramme* for each degree *Centigrade* above or below the boiling point (100° C.).

**Pressure and Temperature of Saturated Steam.** Although we know that an increase in pressure causes an increase in temperature of the steam above boiling water yet no definite law connecting these quantities has been expressed. Certain empirical formulae have been deduced to enable one to calculate the pressure at some known temperature or *vice versa*, and these formulae are often used for the purpose. It is more usual, however, for engineers to use tables which have been drawn up from the formulae. These tables shew at a glance the value of the pressure for any temperature. The graph shewn in Fig. 41 is plotted from such a table.

**Pressure and Volume of Saturated Steam.** Again there is no simple law connecting the pressure and the volume of saturated steam. This will be discussed again in the chapter on Thermo-dynamics.

**Hygrometry.** Hygrometry is the measurement of the amount of water vapour present in the air. The actual amount of water vapour present in a given mass of air is called the *absolute humidity* of that air. This is determined by passing a known volume of the air through some previously weighed tubes containing some substance (like calcium chloride) which will readily absorb all the water vapour. The tubes are again weighed and the increase represents the amount of water vapour which was present in that particular sample of air.

The absolute humidity of the air varies from day to day. But so far as our sensations are concerned we may easily be led into errors in this respect. In the early morning or after sunset we might assume that there is more vapour in the air than at noon, whereas the converse might be true. Or in other words it does not follow that, because the air is saturated on one occasion and not on another, the actual amount of vapour present is greater.

When the air feels "dry" more vapour is necessary to saturate it. When it feels "moist" it is saturated or nearly saturated. Further when the temperature is high more vapour will be necessary to produce saturation than when it is low. Thus it is quite possible that the absolute humidity on an apparently "dry" day in summer is greater than on an apparently "moist" day in winter.

The ratio of the quantity of water vapour actually present in a given volume of air to the quantity which would be necessary to produce saturation at the same temperature is called the *relative humidity*.

Thus when the relative humidity is 1 the air is saturated and the smaller the relative humidity the further is the air from saturation.

**The Dew-point.** The temperature at which the amount of vapour actually present would produce saturation if a volume of the air were cooled at constant pressure is called the *dew-point*. This temperature will always be lower than the air temperature unless the air be saturated or supersaturated, in which case rain will be falling. Dew may be regarded as "local" rain: the word local being used to indicate the immediate neighbourhood of blades of grass, etc., which become very cold at night due to excessive radiation of heat (see p. 148).

Instruments used to determine the dew-point are called *Hygrometers.* There are several different forms and the principle consists in cooling down some surface to which a thermometer is thermally connected until a film of dew appears. The temperature is read, and the cooling process discontinued. When the film disappears again the temperature is read again and the mean of these readings is the dew-point.

So far as the dew-point of the atmosphere is concerned these readings must be taken out of doors, otherwise the dew-point found is simply that of the air in the room in which the experiment was performed and this would afford no index of the atmospheric conditions.

The wet and dry bulb hygrometer is very commonly used though its users do not bother as a rule to find the dew-point. The instrument consists of two similar thermometers placed side by side. One of these has some muslin round its bulb and some cotton wick attached to this muslin dips into a vessel of water. The water runs up the wick and so keeps the muslin moist. This moisture evaporates, absorbing heat from the thermometer which therefore records a lower temperature than the dry bulb thermometer. Clearly the lower the dew-point the more rapid will be the evaporation of the water on the muslin and the lower will be the wet bulb thermometer reading. This reading is *not* the dew-point: but tables have been drawn up by means of which the dew-point may be obtained from the readings of the two thermometers.

This instrument is generally quoted in the daily meteorological reports and the readings of the dry and wet bulb thermometers are given. The man in the street understands that if the difference of the readings is great the air is dry and there is no immediate prospect of rain; whilst if the wet thermometer is nearly as high as the dry thermometer he had better be provided with an umbrella. For once in a way the man in the street is on the right path.

## EXAMPLES

1. 10 lbs. of steam at 212° F. are condensed into a large vat of ice at 32° F. How much ice will be melted, assuming that the temperature of the vat remains at 32° F. all the time?

2. Steam is condensed by allowing it to pass through a large length of coiled tube in a vessel containing 120 lbs. of water. The original temperature of the water was 59° F. and after 15 minutes it was found to be 130° F.: how much steam was condensed?

3. How much heat would be necessary to convert 12·5 lbs. of ice at 32° F. to steam at 212° F.? Give the answer in British thermal units *and* in calories.

4. If a boiler receives 120 B.TH. units of heat per minute through every square yard of its surface, the total surface being 6 sq. yards, and if its temperature be 280° F. while it is fed with feed water at 110° F., what weight of steam would you be able to draw off regularly per hour? (The latent heat of vaporisation at 280° may be calculated as shewn at top of page 129.)

5. Steam is admitted into a water cooled condenser through which 20 gallons flow per minute. The water on entering the condenser is at 60° F. and on leaving has a temperature of 100° F. How much steam is being condensed per minute?

# CHAPTER XII

## TRANSMISSION OF HEAT

There are three modes by which heat may be transmitted from one point to another. The first is by *conduction* and it is in this way that heat is transmitted through solids. If one end of a metal bar be heated the other end will soon become hot provided that the bar is not very long. The heat seems to pass from molecule to molecule from the warmer end to the colder end and will continue to pass so long as there is any difference of temperature between the ends.

The process is comparatively slow: it is not to be compared with the speed of light or sound or electricity, or of heat transmitted by another process called radiation.

Different substances conduct differently. In general terms we all know that silver is the best conductor of heat—as it is of electricity—though it is quite possible that most of us do not know quite what we mean when we say it. One reader may be thinking that the heat travels more rapidly along silver than along anything else: another may be thinking that it is not so much a question of speed as of quantity—that is to say that more units of heat can pass at the same speed: another may think that both speed and quantity must be taken into account.

If two equal rods of copper and bismuth be coated with wax and one end of each be put in a Bunsen flame it will be found that the wax melts more quickly along the bismuth at the start but ultimately more wax is melted on the copper than on the bismuth bar.

The point of this experiment is that the specific heat of the bismuth being less than that of the copper a smaller quantity of heat is required to raise its temperature. Thus its wax starts to melt before that on the copper. But since more of the copper's wax is melted ultimately it follows that at corresponding points along each bar the temperature of the copper was higher than that of the bismuth and that more heat units per second were passing along the copper bar than along the bismuth bar.

**Thermal Conductivity.** In order to compare conductivities of different substances it will be necessary to measure the quantity of heat which is transmitted through equal distances, equal cross sectional areas, in equal times and with equal differences of temperature at the extremities of the equal distances.

The *thermal conductivity* of a substance is the quantity of heat which passes in unit time through a unit length having a unit cross sectional area when the temperature at each end differs by one degree.

It is fairly evident that the quantity of heat which will pass through any length will be directly proportional to the difference in temperature at the ends, directly proportional to the area of cross section, directly proportional to the time and inversely proportional to the length.

If the thermal conductivity of the substance be known then the quantity of heat passing in any known time, along any known length of known cross sectional area with a known difference of temperature between the ends may be calculated.

**Conductivity of Wire Gauze.** If a spiral of copper or silver wire be placed over the wick of a lighted candle, as in Fig. 44 (*a*), the flame will be extinguished at once due to the fact that the copper conducts away the heat so rapidly that the temperature is lowered below the temperature of ignition. If however the spiral be heated first and then placed over the lighted candle wick the flame will not be extinguished.


(*a*) (*b*)

Fig. 44

In the same way if a piece of fine wire gauze be placed over a Bunsen burner, as in Fig. 44 (*b*), and if the gas be lighted *below* the gauze it will be found that it does not burn above the gauze. If the gauze be raised and lowered it will be found that the flame rises and falls with it. Of course gas is coming through the gauze and this can be lighted in the ordinary way. If the gas is extinguished and then turned on again the gas can be lighted *above* the gauze and it will not burn below. A yet more striking experiment is to soak a piece of cotton-wool in alcohol and place it on a piece of wire gauze. The gauze is then brought down over a lighted flame and the alcohol will burn—*but it* *will only burn below the gauze*, and if the piece of cotton wool be picked up from the gauze "the flame" will not come with it.

The explanations for all these simple experiments lie in the fact that the gauze is a good conductor of heat: that it conducts heat away rapidly in all directions over its surface and having a large surface exposed to the air keeps comparatively cool. Thus the temperature on the other side of the gauze from that on which the flame is playing is lower than the temperature of ignition of gas or alcohol as the case may be.

**Miner's Safety Lamp.** It is generally known that in most coal mines there is so much inflammable gas evolved from the coal that the presence of a naked flame would cause a disastrous explosion. The property of wire gauze as shewn above was used by Sir Humphry Davy in the design of a safety lamp for use in such mines. The main idea of the lamp is that the flame (a small oil flame) can only receive its supply of air through some fine wire gauze, and further it is surrounded by gauze.

Now although the inflammable gases may go in with the air supply and burn inside the lamp yet the flame cannot strike back through the gauze.

The lamp serves too as a danger signal. If there is much gas burning inside the lamp the miner knows that the proportion of inflammable gases is too great at that place and he should immediately report the fact so that better ventilation be secured.

Further, if the air is foul the lamp will burn less brightly and it may even go out altogether.

In most mines every lamp is lighted and tested, by being lowered into a well of coal gas, before it is given to the miner. It is also locked so that he cannot uncover the flame.

**Conduction in Liquids.** With the exception of the molten metals, liquids are comparatively bad conductors of heat. Liquids are always heated from below: we never think of putting the furnace at the topmost part of a boiler. An experiment may be performed in a manner shewn in Fig. 45, where we have a tall vessel of water with a number of thermometers projecting from it at various depths. When some cold water is put into this vessel all the thermometers will read alike. If a pan containing some burning coals or some other source of heat be applied to the *top* of the water it will be found that the various thermometers are only very slightly affected even after a considerable lapse of time. On the other hand we know that if the source of heat be applied to the bottom of the vessel the whole of the water will become hotter in a comparatively short time.

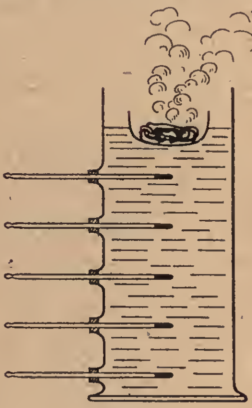

Fig. 45

We know also that if the same experiment were performed with a solid block of metal there would be no appreciable difference between top heating and bottom heating.

**Convection.** When the water is heated at the bottom the lower portion receiving heat expands and therefore becomes lighter bulk for bulk than the water above it. Consequently it rises, colder water descending to take its place. This, in turn, is heated, expands, becomes lighter and rises. In this way we get the water circulating in the vessel; warm and light water continually rising whilst the cooler and heavier water sinks to take its place. As the warm water rises it gives out some of its heat to the surrounding colder water. Thus we see that the particles of water move and all the upward moving particles are carrying and distributing heat. This process of transmission of heat is called *convection* and the currents of water set up are termed *convection currents.*

This can be shewn very effectively by means of a simple experiment illustrated in Fig. 46. A vessel of water (this may be a flat lantern cell so that it can be placed in a lantern and projected upon a screen) has two thick wires leading down to a small coil of thin wire at the bottom. Two or three crystals of potassium permanganate are dropped down to this spiral and they will dissolve colouring the water at the bottom. A current of electricity is then passed through the spiral which becomes warm. This warms the coloured

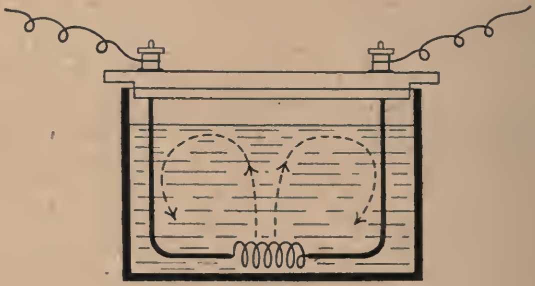

Fig. 46

water which then rises and we can see the convection currents by watching the paths of the coloured streams, which follow the courses shewn by the dotted lines in the diagram. The process will continue until all the water is uniformly hot and uniformly coloured.

This principle is the basis of heating by hot water circulation. The circulation takes place quite naturally and Fig. 47 illustrates a simple system of such heating. The boiler—or more properly, heater—is placed at the lowest part of the building and the hot water rises whilst the colder water descends to take its place. The method is sometimes called central heating—that is to say one fire will provide the heat for all the rooms and corridors. The system is often used in large buildings, theatres, churches, educational institutions and the like, but is not often met with in private houses in this country. In America it is the general rule.

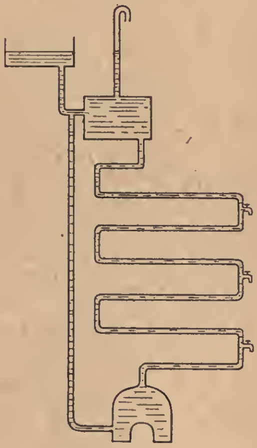

Fig. 47

Its general efficiency, economy and cleanliness deserve that it should meet with wider favour than it does: though it seems highly probable that electric heating will prove to be too strong a rival as soon as electrical energy is more universally adopted.

**Convection Currents in Gases.** Gases are also bad conductors of heat, and heat may be transmitted through gases by convection. When heat is applied to a gas the portion in the immediate neighbourhood of the source of heat expands, becomes lighter and tends to rise. Since this expansion is greater than in the case of liquids the convection current will be set up much more quickly and it will move with a greater velocity. The existence of these convection currents is readily shewn in many ways.

In an ordinary dwelling room where there is a fire the heated lighter air ascends the chimney. This is useful in that it carries the smoke and soot: but it has the serious drawback of carrying up a tremendous proportion of the total heat energy of the fire. This is one of the causes of the overall inefficiency of steam engines: so much of the total energy of the furnaces is carried up the flues by the air convection currents.

From another point of view these flue convection currents are useful for they assist in the promotion of proper ventilation. If air is ascending the chimney fresh air must be drawn into the room at the same rate. This may come through special ventilator ducts, or through open doors and windows, or—as is too often the case—through the cracks and joints of imperfectly fitting doors and windows. This fresh air is not only necessary and beneficial to any occupants of the room but it is also necessary for the proper burning of the fire.

A simple illustration of this is shewn in Fig. 48. The apparatus consists of a small box which is provided with two tubes or chimneys as shewn and a glass front. A candle placed under one of the chimneys represents a fire. When the candle is lighted convection currents will circulate in the directions shewn by the arrows.

This can be seen quite clearly by holding a piece of smouldering brown paper over each tube in turn: in one case the smoke will be drawn down: in the other it will be blown up. If the left-hand chimney be corked up the flame will burn less brightly and will be extinguished as soon as it has exhausted the oxygen supply in the box.

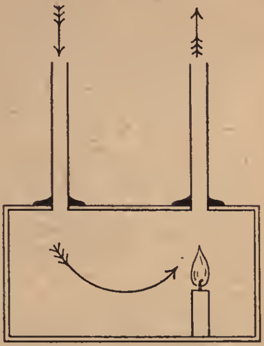

Fig. 48

Fig. 49 illustrates a method of room or hall ventilation which depends upon convection currents—as indeed all systems of "natural ventilation" (as opposed to forced ventilation by power fans) do. An air inlet is provided near to the floor and in front of this a radiator is fixed. The radiator may be hot water,

Fig. 49

steam or electric. The air about this radiator expands and rises and fresh air is drawn in through the inlet. Outlets are provided round the tops of the walls: the outlet shewn being a hinged flap which acting like a valve will only allow air to pass out. An advantage of this system is that the fresh air is warmed on entering the room. The circulation of the convection currents will be demonstrated further by the blackening of the wall above and behind the radiator at an earlier date than that of the other walls.

**Radiation.** Conduction and convection of heat are processes which require material mediums for the heat transference. We know however that heat can be transmitted from one point to another without the aid of matter: the heat energy which we receive from that great source of energy the sun is transmitted through millions of miles of space. This process of transmission is called *radiation*, and it takes place with the velocity of light, namely 186,000 miles per second. But the process is not confined to vacuous spaces for radiation can take place through matter and it can do so without necessarily raising the temperature of that matter.

To account for these facts the generally adopted theory is briefly as follows. A hot body is said to be in a state of vibration. These vibrations are transmitted as such by means of a hypothetical medium termed the aether of space. This medium is assumed to be weightless: to pervade all space and the interior of all matter: and to be highly elastic since it can transmit the vibrations with an enormous velocity. The theory fits in with all observed facts and it serves for the transmission of light as well as of heat.

According to this the fact that heat energy can be transmitted through air, or rock salt, without producing any appreciable increase in temperature, is explained by the assumption that the heat does not travel as heat but as vibrations which will be transmitted like waves through the aether. When these waves fall upon any matter they may be reflected; they may pass through as waves; they may be absorbed; or some or all of these possibilities may take place.

If the matter becomes hotter then we say that some of the waves are being absorbed and they give up their energy in the form of heat. If the matter does not become hotter then the waves are either being reflected or transmitted.

**Reflection and Absorption of Heat.** A simple experiment is illustrated by Fig. 50. Two metal plates

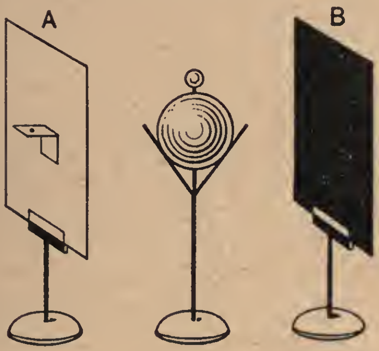

Fig. 50

*A* and *B* of the same size and material are placed at equal distances from a source of heat such as a red hot iron ball. The plate *A* is polished whilst *B* is covered with a coating of lamp-black or some dull black paint. From the back of each plate a small tongue of metal projects and on each of these tongues a small piece of yellow phosphorus is placed. In a very short time the phosphorus behind the black disc will ignite—but the phosphorus behind the polished disc will not ignite at all.

This is only one experiment of many which can be performed to shew that light polished surfaces are good reflectors of heat (as they are of light) whilst dark and rough surfaces are bad reflectors but good *absorbers*. A fireman's polished brass helmet reflects the heat: a guardsman's helmet does the same thing. Light coloured clothing is cooler to wear in summer time than is dark clothing, since the latter is a bad reflector and a good absorber of heat.

**Transmission and Absorption of Heat.** Heat may be reflected from mirrors in exactly the same way as light. If an arc lamp be placed at the focus of a concave mirror the reflected beam—like a searchlight beam—will consist of both light and heat waves. If this beam falls upon another concave mirror it will be converged to the focus. The temperature of the air through which this beam passes will not be appreciably altered: nor will it be affected at the focus. But a piece of phosphorus placed there will ignite immediately. It is only when the heat waves fall upon some substances (most substances be it said) that they give up their energy as heat. Fig. 51 illustrates this.

If such a beam as that mentioned above be allowed to pass through a strong solution of alum it will be found that most of the heat waves have been stopped and the phosphorus placed at the focus of the second mirror will take longer to ignite if indeed it ignites at all. The solution of alum will get hot. If a solution of iodine in carbon bisulphide be substituted for the alum it will be found to stop practically all the light but will allow the heat to pass through as will be shewn by the ignition of the phosphorus.

Rock salt will transmit the heat waves readily. Glass behaves rather remarkably: it will transmit the heat waves if they proceed from a source at a high temperature but it stops them if they come from a low temperature source. It is this property which makes glass so valuable for greenhouse purposes. The heat waves from the sun pass through readily enough and give up their energy to the plants inside; but after sunset when the plants are giving out heat instead of receiving it the glass will not transmit the heat waves and thus acts as a kind of heat trap.

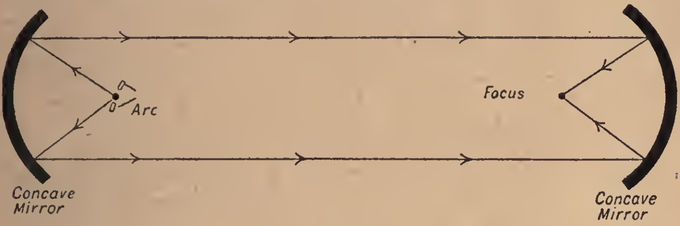

Fig. 51

**Radiation from different surfaces.** Different surfaces having the same temperature radiate heat at different rates. One simple experiment to illustrate this may be performed with two equal cocoa tins from which the paper covering has been stripped. One of the tins should be painted a dull black (a mixture of lamp-black and turpentine will serve for this purpose) and through the lid of each a hole should be made large enough to take a thermometer. The tins are then

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filled with boiling water and it will be found that the blackened vessel cools much quicker than the bright vessel. Readings of the two temperatures can be taken at equal intervals of time and "curves of cooling" can be plotted.

The usual methods of comparing the radiating properties of different surfaces are by means of a thermopile and galvanometer. The two constitute a sort of electrical thermometer which is much more sensitive than any expansion thermometer. The principle of this thermopile will be taken in the electricity course, but it may be stated here that when the temperature of the exposed thermopile face increases a current of electricity is set up which causes the needle of the galvanometer to be deflected. The greater the temperature the greater will be the current and the consequent deflection of the needle.

Fig. 52 shews a thermopile being used with a "Leslie cube" which is simply a metal cube in which water may be boiled. The faces of the cube may be treated in

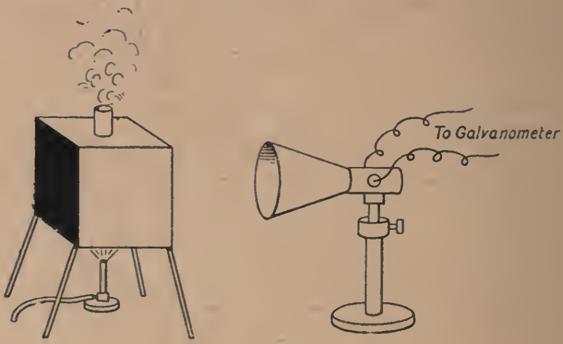

Fig. 52

different ways: or they may be made of different metals or covered with different materials. In this way a simple method is provided for heating a number of different surfaces to the same temperature. The thermopile is placed the same distance away from each face in turn and the permanent deflection of the galvanometer needle gives a measure of the rate at which the thermopile receives heat from each face. If it receives more heat per second in one case than in another then clearly its temperature will rise to a higher degree.

It will be found in general that polished surfaces do not radiate heat so well as dull surfaces and that light coloured surfaces are worse radiators than dark surfaces.

A polished metal teapot does not require a "tea-cosy": a dirty one does, for two reasons.

The "vacuum" flasks so largely used in these days depend upon this for their property of retaining the temperature of any liquids placed in them. They consist of a double walled glass vessel and the space between the two walls has the air driven out of it whilst a small quantity of quicksilver is vaporised inside. The inter-wall space is then sealed and the quicksilver condenses on the inside of the walls—forming a complete mirror coating. Thus the flask does not absorb the heat readily and what it does absorb it does not radiate readily. The absence of air from the space between the two walls of the flask prevents convection currents, but it is the non-radiating property of the silvered surface which is the main cause of the insulating property of the flask.

**Flame radiation.** The amount of radiation from a flame depends very much upon its nature. The luminosity of a candle flame depends upon the presence of solid particles of carbon within it, and the same applies to the old-fashioned batswing gas flame. If the gas of a burner be mixed with air before ignition—as in the case of a Bunsen burner or a gas stove or the burner of an incandescent gas—the solid particles of carbon do not exist in it for any appreciable time and very little light or heat is radiated. At the same time this flame is *hotter* than the batswing flame and can raise the temperature of substances to a greater degree. A gas mantle placed over such a flame becomes hotter and gives out more light and radiant heat than it would if it were placed over the batswing flame.

**Formation of Dew.** After sunset the earth radiates some of the heat it has received during the day, and a fall of temperature results. If the night be cloudy then the clouds reflect and radiate heat back again so that the fall in temperature is not very great. If the night be clear the heat is radiated into space and the temperature falls much more.

The earth thus becomes cooled and often to a temperature below the dew-point (see p. 130). Dew is generally deposited upon blades of grass whilst it is not noticeable upon bare earth or stones because the blades of grass are excellent radiators and become very cold and are also bad conductors so that they do not receive any heat from the earth by conduction.

Straw is an excellent radiator and a bad conductor and because of this it is possible to freeze water during the night in hot regions of India and other places by putting some water in a shallow vessel and standing it upon a heap of straw.

# CHAPTER XIII

## THERMO-DYNAMICS

In Chapters IV and V we pointed out that heat might be considered as a form of energy, and we shewed some of the methods by means of which other forms of energy could be changed into the form which we call heat. The most primitive method of generating sufficient heat to kindle a fire consists in causing friction to be developed rapidly between two dry pieces of wood —preferably and most easily by bending one piece into the form of a rough brace and using one end as a "bit" in the vain endeavour to bore a hole in the other piece. The operator will not be successful in boring but he will soon find that the "bit" will ignite. The energy which is converted into heat energy is the mechanical energy of the operator.

Experiments have been performed by means of which the relationship between the amount of mechanical work expended and the quantity of heat produced has been ascertained.

**Mechanical Equivalent of Heat.** The amount of mechanical work which must be done so that when it is all converted into heat it will produce one unit of heat is called the mechanical equivalent of heat. Many different kinds of experiments have been performed by various experimenters and the results obtained are all in close agreement.

On the British system of units it has been found that in order to produce one British thermal unit of heat by the expenditure of mechanical energy, 778 foot-lbs. of work must be done.

On the metric system 4·2 joules (or $4·2 \times 10^7$ ergs) must be done in order to generate 1 calorie.

**Method of Determination.** Count Rumford and Dr Joule were the experimentalists whose names are most generally associated with the determination of the mechanical equivalent of heat. Rumford's experiments were performed by boring cannon with sharp and blunt borers. In the latter case more work had to be done in the boring operation and proportionately more heat was developed. Dr Joule's apparatus consisted of a paddle arrangement which he rotated in a special calorimeter containing a known mass of water at a known temperature. The paddle wheel was made to rotate at a uniform rate by means of an arrangement of falling weights. In order to prevent the water from turning round with the paddle, some fixed arms projected inwards from the wall of the calorimeter. The weights were allowed to fall through a known distance: they were then quickly wound up again *without* turning the paddle wheel and allowed to fall again: and this was repeated until an easily measurable rise of temperature was produced in the water. The total work done by the falling weights was then calculated, and the amount of heat generated was determined by the product of the total equivalent weight of the water and calorimeter and paddles and the increase in temperature.

From this the work done per unit of heat generated was readily ascertained.

A favourite laboratory method of making this determination is that in which the apparatus shewn in Fig. 53 is used.

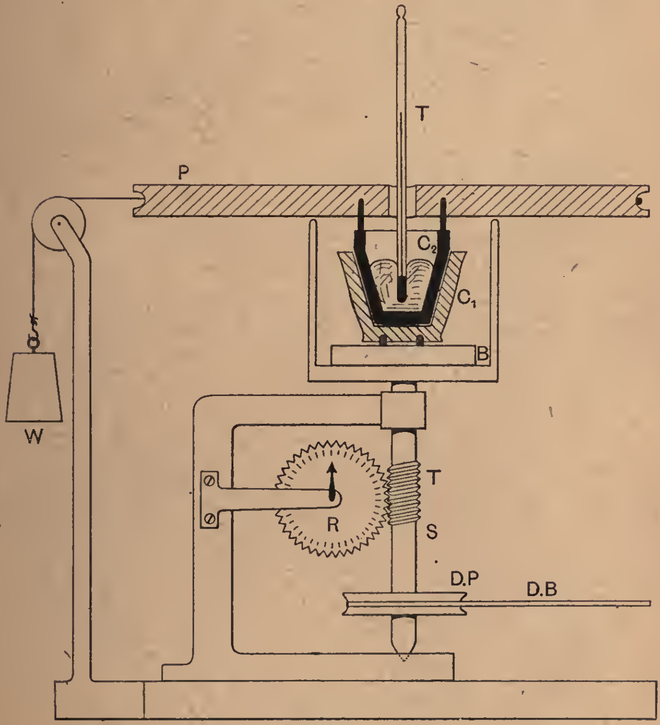

Fig. 53

The "calorimeter" consists of two brass cones $C_1$ and $C_2$ which can revolve on one another about a vertical axis. If $C_1$ is fixed $C_2$ can be turned round by means of a weight $W$ on a piece of string which is fixed to a large wooden pulley $P$ at the top of the apparatus. On the other hand if $C_1$ be rotated in the opposite direction to that in which the weight would rotate $C_2$ it can be seen that at a certain speed of rotation the tendency of the weight to fall could be exactly balanced. If the speed of $C_1$ were increased then $W$ would rise: if it were decreased $W$ would fall. Thus if we rotate $C_1$ at such a speed that $W$ remains stationary it follows that the work which we do per revolution must be exactly the same as if the weight had fallen through such a distance that it turned $C_2$ through one revolution. And it therefore follows that the work done per revolution when we keep $W$ stationary is given by the product of $W$ and the circumference of the pulley $P$.

This is the method by means of which the work which is done in overcoming the friction of the cones is determined. The outer cone $C_1$ is held by two pins projecting from an insulating base $B$. This in turn is fixed to a vertical spindle $S$ which can be rotated by means of a belt $DB$ which passes round a small driving pulley $DP$. In order to make it easy to count the total number of revolutions there is a worm thread $T$ on the spindle and this engages with a toothed wheel $R$ having, say; 100 teeth, every ten of which are marked. A fixed pointer on the supporting arm of the toothed wheel serves as recorder. The inner cone $C_2$ is fixed to the top pulley by means of two projecting pins.

The cones (both of them) are weighed and their water equivalent is determined. The inner cone is then partially filled with *mercury* and the whole weighed again in order to get the weight of mercury. The water equivalent of the mercury is then calculated and the sum of the two water equivalents gives the total water equivalent of the cones and the mercury.

Mercury is used because it has a small specific heat and is a good conductor. Thus we can get a greater rise in temperature than we should get if we used water: and in this way we reduce the possible errors of temperature reading.

The temperature of the mercury is taken, and then the spindle is rotated at such a speed that $W$ remains steady. This requires a little experience and some preliminary trials are necessary.

When the temperature has risen through a reasonable and readable range the rotation is stopped and the final temperature and the total number of revolutions are determined.

The mechanical equivalent is determined as follows:

*Heat*: Mass of the cones $= M_c$ lbs. Specific heat of cones $= S_c$.

Water equivalent of cones $= M_c \times S_c$ lbs.

Mass of mercury $= M_m$ lbs. Specific heat of mercury $= S_m$.

Therefore water equivalent of mercury $= M_m \times S_m$ lbs.

Therefore total water equivalent of cones and mercury $= M_c S_c + M_m S_m = M$ lbs.

Original temperature of mercury $= t_1$° F.

Final temperature of mercury $= t_2$° F.

Therefore units generated $= M(t_2 - t_1)$ B.TH.U. $= H$ units.

*Work*: Weight on the pulley string $= W$ lbs.

Circumference of pulley $= C$ feet $= \pi D$ feet, where $D =$ diameter in feet.

Number of revolutions $= N$.

Therefore total work done $= WCN$ foot-lbs. $= J$ foot-lbs.

*Relationship*: Since $H$ units of heat are produced by $J$ foot-lbs. of work therefore 1 unit of heat will be produced by $\frac{J}{H}$ foot-lbs.

Therefore the mechanical equivalent of heat $= \frac{J}{H}$ foot-lbs. per B.TH.U.

**Fundamental principle of the Heat Engine.** Just as mechanical work may be converted into heat so by proper arrangements heat may be converted into mechanical work. Any device by means of which this may be done is called a *heat engine*, and it would be well if we consider at this stage how such an engine does work at the expense of heat energy.

The thoughtful student might argue that in the case of a steam engine although heat energy is necessary to produce the steam which forces the piston along the cylinder yet the steam comes out of the exhaust as steam and has not given out any heat except that necessary to warm up the piston and cylinder in the first instance. Such argument however would be wrong, for it can easily be shewn that heat is given out by the steam as it expands in the cylinder, *and the energy of the steam engine is represented by the energy given out during this expansion.*

Let us imagine that we have a tall cylinder and that it is fitted with a piston which when loaded with a number of weights sinks down into the cylinder and so compresses the air in it. If we then remove the weights one by one the air will expand and will do work in raising up the piston and the remaining weights. Now if the weights be removed in sufficiently quick succession it will be found that the air is cooled by its expansion. We therefore conclude that some of the heat energy of the air has been converted into the mechanical work necessary to lift the weights, and therefore the temperature of the air must be reduced.

On the other hand if the air be compressed it will be found that its temperature rises and we conclude that the mechanical work done in compression is converted into heat. Probably all our readers know how hot the end of a bicycle pump gets after a few rapid strokes of the piston.

But—to return to our tall cylinder with its weighted piston—after we have compressed the air and so heated it, if we allow it to cool down again to the temperature of the surrounding air and then allow the piston to rise once more we shall again find that the air is cooled. The point here aimed at is that though we may produce heat by compression yet if we allow it to disappear we shall nevertheless take heat away again on expansion. Work must be done on the air in compressing it: that work is changed to heat and the temperature of the air rises. Work must be done by the air in expanding and it is done at the expense of some of the heat energy of the air which is thereby cooled.

The reader may remember that in our chapter on specific heat we stated that the specific heat of a gas is greater if the volume of the gas be allowed to change as it is heated than it is if the volume of the gas be kept constant during heating. The reason for this is now obvious. If when heating a gas it expands it *must* be doing work. The gas need not be actually pushing a piston along a cylinder, but as it expands it must be pushing air away from it and therefore must be doing mechanical work. The energy for this must come from somewhere: it comes from the heat energy of the air and so the air would be cooled. Therefore to keep the air up to its temperature more heat would have to be given to it than would have been necessary had the air not been expanding.

The reader will be able to see that the difference between the amount of heat necessary to raise the temperature of a given mass of gas through a certain range without any change in volume, and that necessary to produce the same temperature change when the gas is expanding, will represent the amount of energy which is changed from heat energy to mechanical energy.

In the case of the steam engine if we measure the quantity of heat energy in each lb. of steam as it enters the cylinder and again as it leaves, the difference will represent the amount of energy which each lb. of steam gives out to the engine as mechanical energy. If we know the number of lbs. of steam per minute which are passing through (an easily determined quantity), then we have at once the means of calculating the mechanical energy given per minute by the steam, and from that the horse-power. This, of course, does not give the horse-power which the engine will yield: that will depend upon the efficiency of the engine.

**Effect of compression and expansion on saturated steam.** We saw on page 124 that when a space was saturated a change of volume did not affect the pressure if the temperature remained constant. We are now in a position to see that unless the change in volume is effected very slowly indeed the temperature will be increased on compression and this increase might be sufficient to convert the space into a non-saturated one (or a superheated one). Indeed in the case of steam this is the case, for if saturated steam be suddenly compressed in a space from which no heat can escape the consequent rise in temperature is such that the space becomes superheated—that is to say instead of the compression producing condensation of the steam in the cylinder as we should expect it to do from Dalton's experiments on saturated spaces (page 124), enough heat is developed to raise the temperature sufficiently to render the space hot enough to be able to hold even more water vapour.

On the other hand if saturated steam be allowed to expand, doing the full amount of work of which it is capable during the expansion, it loses so much heat that, notwithstanding the increased volume, condensation takes place.

When this happens in the cylinder of an engine the condensed water accumulates. This is called *priming*. In all steam engines working expansively means are taken to prevent this condensation—such, for example, as surrounding the cylinder with a steam jacket.

If superheated or non-saturated steam be used then, of course, this condensation will not occur if the steam is sufficiently far from saturation.

**Isothermal and Adiabatic expansion.** If the volume of a given mass of gas be changed without any change of temperature it is said to be changed *isothermally*. From what we have seen above it follows that such isothermal change of volume can only be produced provided that heat is taken from or given to the gas. As it is compressed then heat must be taken from the gas in order that its temperature shall not rise. As it is expanded heat must be given to it to prevent the temperature from falling. Boyle's law, for example, is only true for an isothermal change: it states that the temperature must be kept constant. The curve which we plotted to shew the relationship between pressure and volume of a gas at constant temperature is called an isothermal curve connecting pressure and volume.

If, on the other hand, the gas be contained in some vessel which will not permit it to receive or lose heat, then as it is compressed its temperature will rise and as it expands its temperature will fall but the quantity of heat will remain constant. Such a change is said to be *adiabatic* or *isentropic*. Boyle's law is not true for adiabatic expansion or compression. On compression the temperature will be raised and therefore the gas will occupy a greater volume at a given pressure. On expansion the gas will be cooled and the volume will be less than it would be at a given pressure. Fig. 54 shews the difference: the curve *IBL* is an isothermal or Boyle's law curve shewing the relationship between pressure and volume: the curve *ABC* is the adiabatic curve for the same mass of gas. The point *B* is the starting point and if the gas be compressed adiabatically its volume will not fall as much as it would if compressed isothermally, and *vice versa*. Thus the adiabatic curve is steeper than the isothermal curve.

For the same reasons it follows that if we compress a gas adiabatically the mean pressure necessary to produce a given change in volume will be greater than that necessary to produce the same change in volume if the gas be compressed isothermally. Therefore it follows that more work must be done to compress a gas adiabatically than isothermally and more work will be given out by a gas expanding adiabatically than isothermally.

**The Indicator diagram.** If we can plot a curve which shews the pressure on a piston at each position of its motion along a cylinder we can then get the mean pressure from the curve. If we know this mean pressure in lbs. per square inch and the area of cross section of the piston and the length of its stroke in the cylinder we can calculate the total work done upon it per stroke. If, further, we know the number of strokes which it makes per minute we can determine the rate of working or the horse-power yielded by the steam.

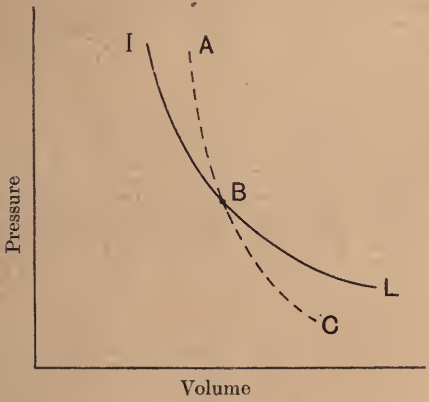

Fig. 54

Such a curve shewing the relationship between pressure and position of piston is called an *indicator diagram.*

If the pressure on the piston were constant through the full length of the stroke and then dropped suddenly to zero at the end, the diagram would be like that shewn in Fig. 55. The height $OA$ represents the steam pressure on the piston and the position of the piston in the cylinder is represented by such distances as $OM$, $OC$.

The point $C$ represents the end of the stroke. As the piston returns again to $O$ we are assuming that the pressure upon it is zero and when it reaches $O$ the pressure suddenly becomes $OA$ again.

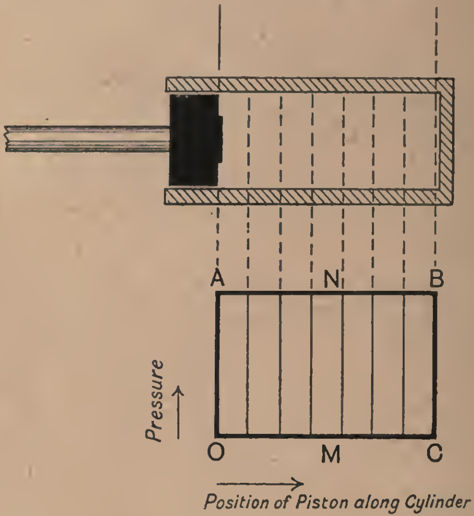

Fig. 55

If such conditions were possible and such an indicator diagram were obtained the horse-power of the engine concerned could be readily determined.

Let $A$ represent the area of the piston in square inches.

Let $P$ represent the average pressure* upon the

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* By this is meant the net average pressure or the average difference of pressure on each side of the piston.

piston—both journeys along the cylinder being considered. In this case the pressure is constant and is represented by $OA$ on our diagram. The return journey pressure is zero in this case.

Then $P \times A$ = total force in lbs. on the piston.

Let $L$ = length of stroke in feet.

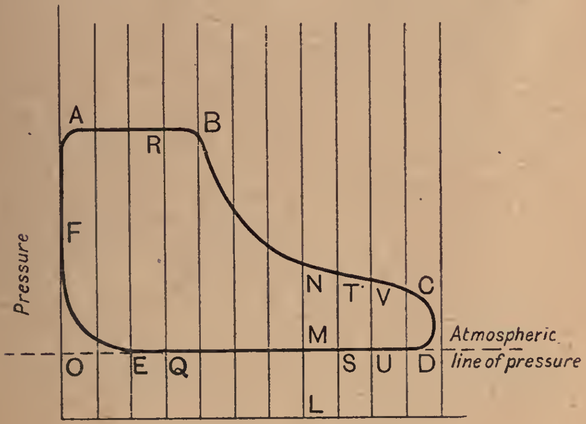
Then $PAL$ = force × distance = work in foot-lbs. for each journey of piston to and fro.

If $N$ = no. of to and fro movements per minute.

Then $PLAN$ = foot-lbs. per minute.

Therefore $\dfrac{PLAN}{33000} = \text{H.P.}$

Fig. 56 represents more nearly the actual relationship between the pressure and the position of the piston.



Position of Piston along cylinder

Fig. 56

The portion of the diagram $AB$ indicates that for the first part of the stroke the pressure is constant (practically, in fact, the boiler pressure). At the point $B$ the steam port is shut and the steam expands as the piston continues its motion, but the pressure falls as shewn by the curve $BC$. At the point $C$ the exhaust port is opened and the pressure falls rapidly to atmospheric pressure shewn at $D$ which is the extremity of the stroke. The piston then returns and when back again at the point $E$ the exhaust port is closed so that the small amount of steam left in the cylinder shall act as a cushion to assist the return of the piston. This steam becomes compressed as the piston approaches $O$ and the pressure rises as shewn by the curve $EF$. When the piston reaches $O$ the steam port is opened again and the pressure rises at once to the point $A$.

In order to find the indicated horse-power with the aid of this diagram it is clear that we shall need to find the average pressure on the cylinder during the complete to and fro motion of the piston. The net average pressure will be the difference between the average outward pressure and the average return pressure. On the outward journey when the piston is at $L$ the pressure is $LN$, on the return journey the pressure is $LM$ at the same position. Therefore the net or useful pressure is represented by the difference, namely $MN$. It will be seen that the net average pressure per complete cycle will be given by the average of such lengths as $FA$, $QR$, $MN$. Thus if a sufficient number of such ordinates be drawn at equal distances apart and their mean length determined—in terms of the pressure scale—we shall get the net average pressure at once.

If the engine were to exhaust into a condenser in which the pressure was less than the atmospheric pressure then the return part of the diagram $DE$ would fall below the position shewn: in which case it is clear that the net mean pressure would be greater.

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