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## Thermodynamics and Refrigeration.

BY MR. G. JAMES WELLS (MEMBER).

READ

*Monday, February 3, 1913.*

CHAIRMAN: MR. J. CLARK (MEMBER).

CHAIRMAN: We have a very important paper before us to-night on "Thermodynamics and Refrigeration" by Mr. Wells. From a very casual reading I am assured that it is an excellent paper on the subject, and I now have pleasure in calling upon Mr. Wells to read it.

THE MEASUREMENT OF HEAT is naturally a matter of some difficulty, since heat cannot be handled in the same manner as coals, etc., and this difficulty compels the adoption of indirect methods. The *intensity* or relative *hotness* of bodies is spoken of as *temperature*, and the scale of temperature is based upon the difference between the "hotness" of "melting" ice and boiling water under the pressure of 14.7 lb. per square inch. The unit of "quantity" is the increment of heat

necessary to raise unit mass of water through one degree of temperature at maximum density. The measurement of heat is obviously indirect, since it is based upon the effect produced upon some substance.

FLOW OF HEAT can only take place from a body at high temperature to another at a lower temperature. There must be a difference of temperature or "head," or heat flow cannot take place. Exactly as a difference of head is requisite for the flow of water, so heat flow depends upon a temperature head, and water can only naturally flow from a higher towards a low level, so heat can only flow from a high temperature level to a lower level of temperature. A pump is necessary in order to raise water from a well to a higher level, and similarly a "heat" pump is necessary to extract "heat" from a body at a temperature below its surroundings.

SPECIFIC HEATS.—Bodies have different capacities for heat, so that the quantity of heat required to change unit mass one degree of temperature varies very widely. The quantity requisite in the case of water is used as the unit, and the unit for other substances is expressed in terms of that unit. Thus the specific heat of iron is = 0.114, which means that one unit of heat will raise one pound of iron  $8.77^{\circ}$ , although it will only raise one pound of water one degree. This ratio varies according to the circumstances under which the heat is received.

The fundamental equation is—

$$\left. \begin{array}{l} \text{Total quantity of heat} \\ \text{involved in any} \\ \text{operation.} \end{array} \right\} = \left\{ \begin{array}{l} \text{Change of internal} \\ \text{energy.} \end{array} \right\} + \left\{ \begin{array}{l} \text{External} \\ \text{work.} \end{array} \right\}$$

EFFECTS OF HEAT UPON MATTER.—Generally the condition of matter is dependent upon the temperature and pressure to which it is subjected. A familiar example is water, which at temperatures below  $32^{\circ}\text{F}$ . is a solid; at temperatures between  $32^{\circ}$  and  $212^{\circ}$  it is a liquid; and at temperatures above  $212^{\circ}$  it is a gas. If, however, the pressure of the atmosphere be artificially increased or decreased, the temperatures at which the change of state will occur will be varied. As refrigerating engineers—unlike steam engineers—have to do with materials in each of the three conditions, i.e., solid, liquid and gaseous, it is necessary to consider at length the phenomena of change of state, and the quantities of heat involved in the process.

The terms *vapour* and *gas* have somewhat similar meanings, although there is a difference, which should be appreciated. A



*vapour* is the gas into which a liquid is changed by evaporation. Every gas is probably the vapour of some liquid. The term *vapour* is especially applied to the gaseous condition of substances usually met with in the solid or liquid state; whilst the term *gas* is applied to substances ordinarily found only in the gaseous state.

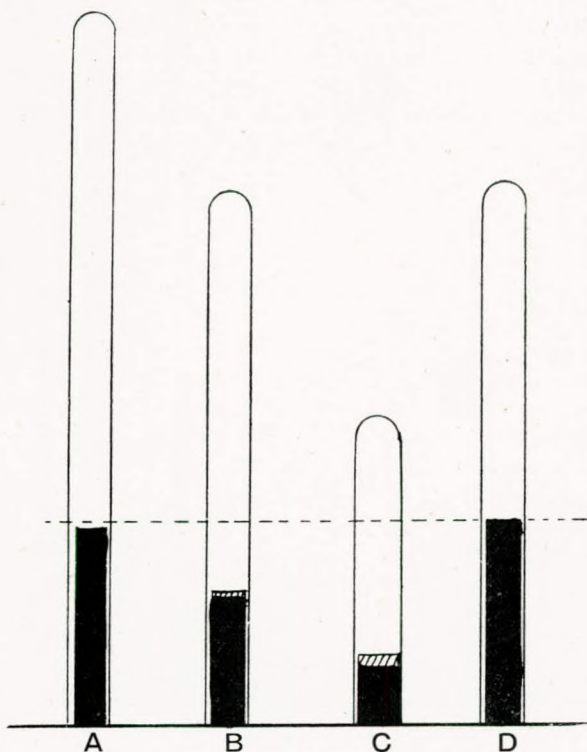


FIG. 1.

The change of state is accompanied by the *evolution* or *absorption* of heat. Thus water requires the *supply* of a definite amount of heat in order to be *evaporated*, or *vaporized*, but when the vapour is condensed then heat is given up. Hence refrigerating machines are possible if the designer arranges matters so that the substances to be *cooled* supply the heat necessary for vaporization, and the heat so taken up is subsequently

given up to some other substance by the vapour and so reduced again to the liquid state.

An experiment which illustrates the laws of vaporization most simply is possibly that illustrated in Fig. 1, in which a long tube A, closed at one end, is filled with pure mercury and a small quantity of ether is added, when the tube is inverted with its open end below the surface of the mercury in the deep tube B. When the tube is at its lowest position C the ether will be noted above the mercury, but the height of the mercury column will be lower than that of the barometer by a definite amount, depending upon the temperature. If now the tube be raised, the quantity of the liquid ether will be reduced, until—

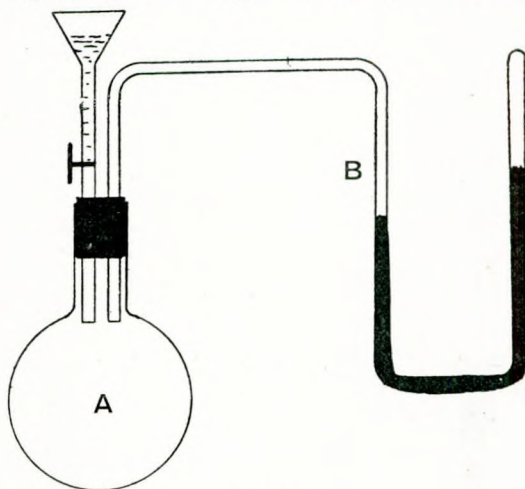


FIG. 2.

if the tube is long enough and the original amount of ether not too great—it entirely disappears. During the *progress* of vaporization, the height of the mercury will remain *stationary*, but it will *increase* afterwards if the tube be *raised*. Conversely, if the tube be *depressed*, the mercury will fall until some liquid ether *appears*, afterwards it will remain *stationary*, but the quantity of liquid ether will *increase*.

If by some device the *temperature* can be changed, then the same series of phenomena are again noticed, except that at any stage during vaporization the pressure will be increased and the amount of liquid diminished. This effect is best shown quantitatively by the apparatus shown in Fig. 2, where



A is a glass globe fitted with a means of introducing a definite quantity of some liquid into it, also with a manometer B. If into A is passed some perfectly dry air, then the manometer B will show the pressure. Now if the liquid be admitted by drops, it will at once disappear, being immediately *vaporized* with an increase of pressure shown by a farther *fall* of mercury in the left hand leg of the manometer. After a definite number of drops have been evaporated, the mercury *ceases* to fall, and the liquid falls to the bottom of A.

Next if the temperature be *increased*, then this liquid will be reduced or disappear, and be accompanied by an increase of pressure. On the other hand, if the temperature be reduced there will be a precipitation of liquid and a fall of pressure.

From these results it is evident that for a *given temperature there is a corresponding pressure, which is the maximum possible for the vapour "at that temperature."*

If the globe A in Fig. 2 be exhausted of all gases, air, etc., then the same phenomena is again evident, and Dalton showed that—

(i) *The mass of vapour which can be contained in a given space is the same whether this space be empty or filled with gas.*

(ii) *When a gas is saturated with a vapour, the pressure of the mixture is the sum of the pressures of each component.*

LIQUEFACTION OF GASES.—It follows from these considerations that if the volume of a mass of vapour in a state of saturation be *reduced, without change of temperature*, some of the vapour must collapse into the liquid state. The amount liquefied will be proportional to the reduction of volume, since the final volume will be saturated.

Also, if a mass of saturated vapour be *cooled at constant volume* a portion of the vapour must be liquefied corresponding to the difference between the saturation densities at the higher and lower temperatures.

An example will give definite meaning to these two processes of liquefaction. Take a vessel containing saturated ammonia vapour at a temperature of  $5^{\circ}$  Fahr., and suppose its volume be 10.78 cubic feet, and that its temperature falls to  $-5^{\circ}$  Fahr. required the amount of ammonia liquefied, and the heat given up.

At  $5^{\circ}$  Fahr. one pound of  $\text{NH}_3$  vapour occupies 8.472 cubic feet, and the total heat is 554.1 B.Th.U., at  $-5^{\circ}$  Fahr. the volume of one pound is 10.78 cubic feet, and the total heat is 553.8.

Assuming that the vessel does not change its volume, it contains at  $5^{\circ}$  Fahr.  $\frac{10.78}{8.47}$  lb. of ammonia vapour, and the total heat of this mass is  $= \frac{10.78}{8.47} \times 554.1 = 1.273 \times 554.1 = 705.2$  B.Th.U.

At  $-5^{\circ}$  Fahr. the weight of ammonia vapour  $= \frac{10.78}{10.78} = 1$  lb. and 0.273 liquid at  $-5^{\circ}$  Fahr. Hence the heat remaining in the vapour latent is . . . . . 594.4 B.Th.U.

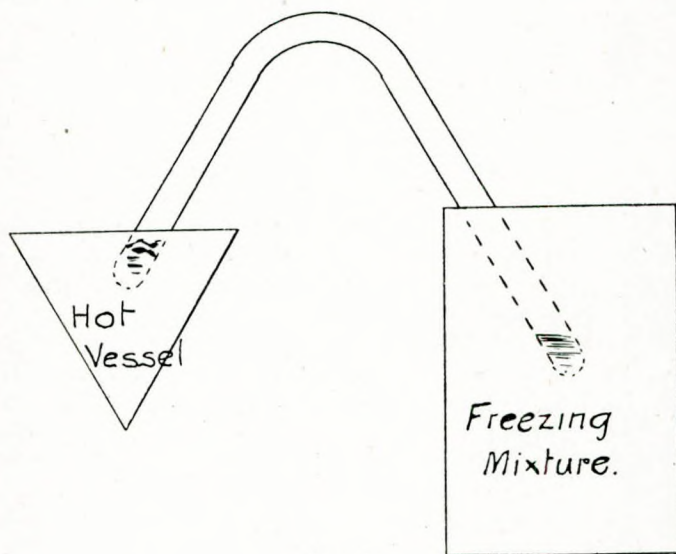


FIG. 3.

Latent in 1 lb. of vapour at $-5^{\circ}$	. . . . .	= 594.4 B.Th.U.
Sensible in 1 lb. of vapour at $-5^{\circ}$	. . . . .	= -40.57 "
And sensible in 0.273 lb. of liquid at $-5^{\circ}$	. . . . .	= -11.06 "
		= 542.77 "
so that heat rejected is $705.22 - 542.77 = 162.45$ B.Th.U.		

In the second case, the temperature remaining constant, imagine the vessel so constructed that its volume is reduced from 10.78 to 8.47 cubic feet or 2.31 cubic feet; but since the



temperature is unchanged the density of the gas is also unchanged, so that as 8.47 cubic feet is the volume of 1 lb. of vapour at 5° Fahr., there will be  $\frac{2.31}{8.47}$  lb. or 0.273 lb. of vapour precipitated (as in the previous case) as liquid. Since the latent heat at 5° Fahr. is 583.9, the quantity of heat rejected will be =  $0.273 \times 583.9 = 159.23$  B.Th.U.

A large number of experiments are possible to illustrate this phase of the subject. Of these Faraday's apparatus, Fig. 3, may be noticed as being one of the earliest systematic inquirers in this subject. It consists of a strong bent glass tube, one

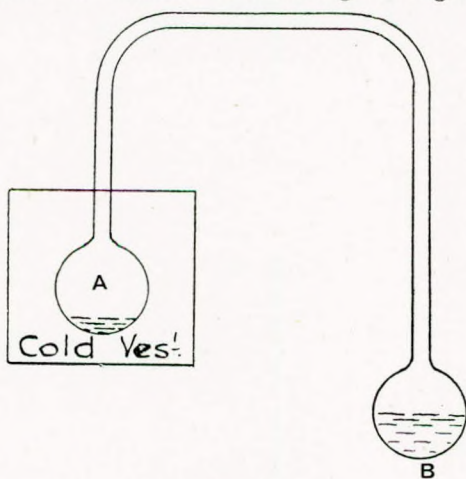


FIG. 4.

end of which contains the materials for the evolution of the gas ; the other end is plunged into a freezing mixture. The pressure produced by the evolution of the gas combined with the cold produces liquefaction of the gas, and the liquid accordingly collects in the cold end of the tube.

Wollaston's Cryophorous (Fig. 4) consists of a tube with a bulb at each end, containing water sufficient to partially fill one bulb. The water is passed entirely into the bulb B, whilst the other bulb A is plunged into a freezing mixture. The cold condenses the vapour in A, thus promoting vaporization in B, and in a short time ice needles will be seen in B, due to the intense cold consequent upon the evaporation of the water.

LAWS OF EBULLITION.—A liquid is said to be in ebullition

when it gives off vapour of the same pressure as the atmosphere above it.

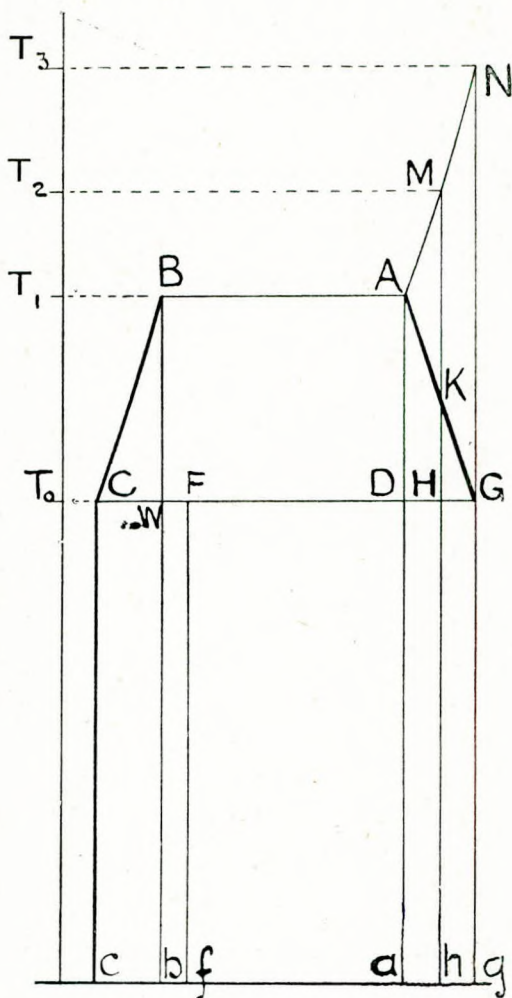


FIG. 5.

- (i) The temperature at which ebullition commences is definite for each liquid, at the ordinary pressure.
- (ii) The temperature of ebullition rises or falls as the pressure increases or diminishes.



- (iii) The temperature remains constant during ebullition.
- (iv) The pressure of the vapour given off during ebullition is equal to that of the external air.

This is merely a restatement of the principles already in part emphasized in the preceding discussion of the phenomenon of change of state, and do not call for detailed discussion again.

TEMPERATURE-ENTROPY CHART.—Probably the most powerful means of comprehending thermo-dynamics is the temperature-entropy diagram, which will always be associated with the name of the late J. Macfarlane Gray. On this diagram energy is represented by an area in terms of *heat-units*, its co-ordinates being “temperature” and “entropy.” This

latter quantity may be defined as being  $\frac{Q}{\Theta}$ ; where  $Q$  is a quantity of heat expressed in heat units, and  $\Theta$  is absolute temperature. Whilst temperature is measured from a zero, it will be noticed that “entropy” is only measured as a difference, no actual zero being imaginable. In tables of entropy it is given as the amount between  $32^{\circ}$  and any other temperature.

Such a diagram (Fig. 5) may be drawn for any particular substance, and where constant volume and pressure lines are drawn upon it, its physical state is completely specified by the locus of its state point under all conditions, thus it becomes a graphical representation of the behaviour of the substance during any sequence of changes of condition. Most problems relating to volume, pressure, temperature, entropy, internal energy, heat supplied, heat rejected, etc., may be readily determined by means of such a chart, using a piece of tracing paper, a pencil, straight edge and a planimeter; and when completed the sheet may be filed away as a record.

HEAT ENGINES are machines for the conversion of heat energy into mechanical work, and depend upon the utilization of the change of volume of the working fluid, in consequence of the effect of the heat supplied. Engineers are in the habit of estimating the work done in foot lbs. by means of the Pee-Vee diagram, in terms of pressure and volume, and in consequence are apt to lose sight of the fact that heat-units are also a suitable and convenient unit of work. In all heat engines some cycle of heat changes is imposed upon the working fluid, and in such cycles the locus of the “state point” traces out a closed loop on the temperature-entropy, so that the heat exchanges are revealed.

HEAT PUMPS are heat engines reversed. Heat engines receive heat at a *high* temperature and reject it at a low temperature; whilst heat pumps receive heat at a low temperature and reject it at a higher temperature. Heat engines overcome external resistance in virtue of the natural flow of heat from the hot body towards the cold body, but since heat cannot flow "uphill," external work must be done on the pump, in order to force the heat flow. This external work must be done by some form of heat engine, thus heat is the source of energy employed to produce cold.

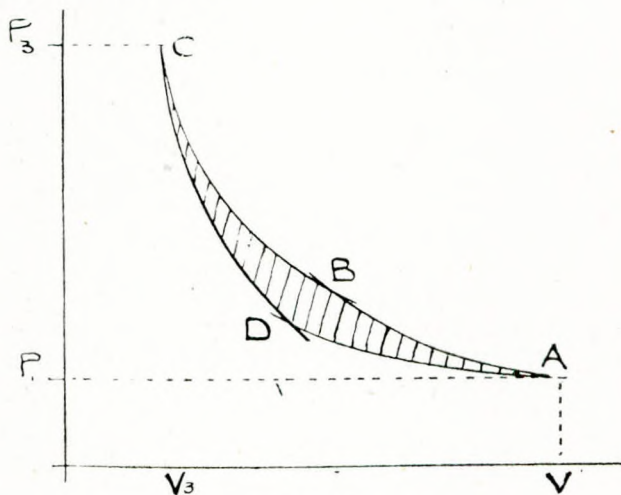


FIG. 6.

CARNOT'S CYCLE is the cycle of operations first described by Sadi Carnot and which is ideally perfect. In this cycle all the heat supplied is at the temperature  $T_1$ , and all the heat is rejected at the lower temperature  $T_2$ . No heat is lost by radiation, absorption, that is spent in warming up cylinder, piston, valves, etc., but the difference between the heat supplied and rejected is wholly converted into mechanical work. It is reversible, for if the state point move in the opposite direction, heat is supplied at the lower temperature  $T_2$ , and rejected at the higher  $T_1$ , thus acting as a heat pump.

DIAGRAMS OF THE CARNOT CYCLE are shown in Fig. 6 Pee-Vee, and Fig. 7 temperature-entropy, when the working fluid is air, or other gas which remains a gas during the whole cycle.



The cycle is carried out as follows: Starting with the piston at A, the air is compressed adiabatically to the point B, where its temperature has reached the upper temperature  $T_1$ , when the air is compressed at constant temperature until the point C is reached. During the stage BC heat is being *rejected* at  $T_1$ , so that the temperature remains constantly at  $T_1$ . From C to D the air expands adiabatically until the lower temperature  $T_2$  is reached, when the air is then expanded isothermally until the original point A has again been reached, so completing the cycle of changes. The area of the figure ABCD is the

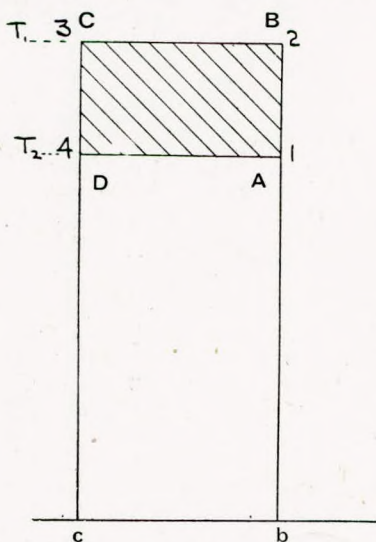


FIG. 7.

work done *on* the gas during each cycle; the figure BCcb is the heat rejected, and ADcb is the heat received. Let the work done on the gas =  $W$  units of heat = area ABCD;  $Q_1$  = heat received = area ADcb; and  $Q_2$  = heat rejected = area BCcb. The co-efficient of performance is the ratio—

$$\frac{\text{heat received}}{\text{work done in driving engine}} = \frac{Q_2}{W} = \frac{Q_2}{Q_1 - Q_2}$$

From Fig. 7  $Q_1$  = area ADcb =  $T_2 \times bc$ ;

$$Q_2 = \text{,, BCcb} = T_1 \times bc;$$

hence



$$\text{co-efficiency of performance} = \frac{T_2 \times bc}{(T_1 - T_2)bc} = \frac{T_2}{T_1 - T_2}$$

Assuming that in such a heat engine the upper limit of temperature to vary between  $32^\circ$  and  $100^\circ$  Fahr., whilst the lower limit of temperature to lie between  $-80$  and  $30^\circ$  Fahr., then the value of the co-efficiency of performance would be as in the following table.

TABLE I.

Lower Limit of Temperature in deg. Fahr. ( $T_2$ ).	Upper Limit of Temperature. Deg. Fahr. ( $T_1$ )							
	32	40	50	60	70	80	90	100
30	245	49	24.5	16.3	12.2	9.8	8.2	7.0
20	40	24	16.0	12.0	9.6	8.0	6.8	6.0
10	21.3	15.6	11.7	9.4	7.8	6.7	5.9	5.2
0	14.4	11.5	9.2	7.7	6.6	5.8	5.1	4.6
-10	10.6	9.0	7.5	6.4	5.6	5.0	4.5	4.1
-20	8.45	7.3	6.3	5.5	4.9	4.4	4.0	3.7
-30	6.9	6.1	5.4	4.8	4.3	3.9	3.6	3.3
-40	5.8	5.2	4.7	4.2	3.8	3.5	3.2	3.0
-50	5.0	4.5	4.1	3.7	3.4	3.1	2.9	2.7
-60	4.3	4.0	3.6	3.3	3.1	2.9	2.7	2.5
-70	3.8	3.5	3.2	3.0	2.8	2.6	2.4	2.3
-80	3.4	3.2	2.9	2.7	2.5	2.4	2.2	2.1

The co-efficient of performance improves very rapidly as the upper and lower temperature limits approach each other. This is well shown by Fig. 8, in which three examples are shown, the upper limit  $T_1$  has been taken at  $40^\circ$  F., and the lower limits at  $20^\circ$ ,  $0^\circ$ , and  $-20^\circ$  F., the shaded areas, equal in each case, shows the work done on the fluid, and the areas in each case their the maximum amount of cooling possible in each case, and their relative magnitudes show clearly the enormous increase of efficiency possible if  $(T_1 - T_2)$  is very small. In the figures the areas are proportional to 40 units, then in Fig. 8a the unshaded area represents 960 units of refrigeration, and the co-efficient of performance is therefore (see p. 11).

$$= \frac{Q_1}{Q_1 - Q_2} = \frac{960}{1,000 - 960} = \frac{960}{40} = 24$$

which is the result shown in Table I,

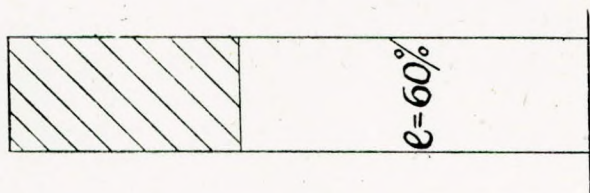


FIG. 8c.

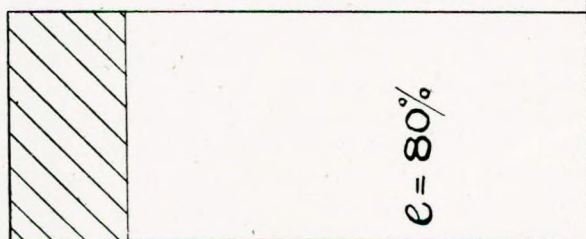


FIG. 8b.

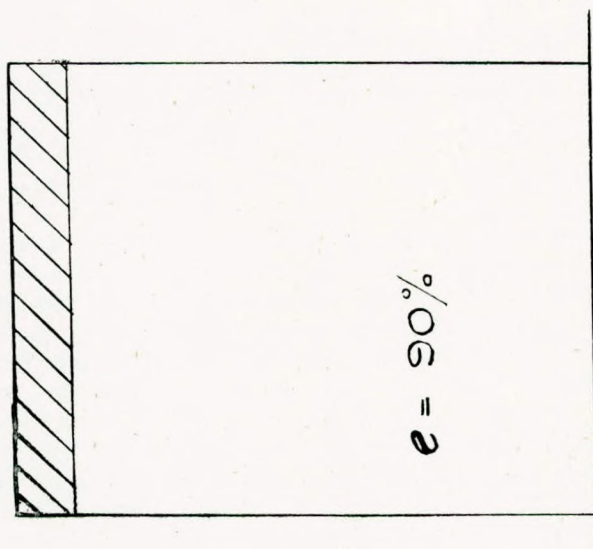


FIG. 8a.



Similarly in Fig. 8b the co-efficient of performance is

$$= \frac{Q_2}{Q_1 - Q_2} = \frac{460}{40} = 11.5;$$

and in Fig. 8c the co-efficient of performance is

$$= \frac{Q_2}{Q_1 - Q_2} = \frac{\left(\frac{2}{3}\right)440}{40} = 7\frac{1}{3};$$

in each confirming the corresponding figures in Table I. In these cases the quantity of refrigeration obtained has been increased no less than 327 per cent., by raising  $T_2$  from  $-20^\circ$  to  $20^\circ$  F.,  $T_1$  being kept at  $40^\circ$  F., the expenditure of work being kept at 40 units. The inference from this is plain, viz., the cooling water must be maintained at the lowest possible temperature, the working fluid must not have its temperature raised any higher than is necessary for the discharge of the heat, and the lower limit of temperature should be as high as permissible in order to obtain a co-efficient of performance as high as possible.

**REVERSIBILITY ESSENTIAL FOR PERFECTION.**—Many find some difficulty in realizing what reversibility actually means, but unless this conception is appreciated, the nature of the losses inevitably sustained in practice in all thermodynamic processes cannot be appreciated at their real value. Perhaps the simplest way of stating the condition of reversibility is to point out that any flow of gas or liquid through a throttle valve is an irreversible process, and any flow of heat by conduction or radiation is also irreversible.

The cycle in a heat engine may be completely reversible, and when it is so the engine will have maximum efficiency. To secure this characteristic, two conditions are necessary—

(1) The reception of heat from the source and the rejection of heat to the refrigerator must take place at temperatures not sensibly different from those of the bodies themselves.

(2) It is necessary that the expansive force of the fluid should be exactly balanced by the resistance which is being overcome.

**ANALOGY BETWEEN A HEAT ENGINE AND A WATER WHEEL.**—All analogies have limits, beyond which they fail, but if judiciously employed they are valuable aids to illustrate difficult points in a discussion.

A water wheel does work by utilizing the energy of falling water. The water must have a fall, that is, the passage from a high to a low level, and in order to utilize all the energy of the falling water, it is essential that the whole of the fall be performed by the agency of the wheel. If any of the water



be spilled from the wheel before the fall is complete, or any water pours on to the wheel, the corresponding difference of level is more or less completely wasted. If the water enters or leaves the buckets, so that there is *shock*, then there will be loss of efficiency. It is clear that to be reversible the water wheel must so act that if its motion be reversed in direction, it will raise the same weight of water from the lower to the upper level with the same torque exerted upon it, as the fall of the water would produce. This reversibility obviously depends upon (1) absence of loss by spilling, (2) freedom from loss by shock, eddies, etc., set up by irregularities in flow, etc., during the passage of the water from one level to the other.

Water Wheel.	Heat Engine.	Refrigerating Engine.
Water <i>must</i> enter exactly at H ; Water must leave exactly at the lowest level. Water must enter and leave without shock, etc.	Heat must be received exactly at $T_1$ . Heat must be rejected exactly at $T_2$ . The expansive action of the working fluid must continuously be exactly equal to the resistance overcome.	Heat must be received exactly at $T_2$ . Heat must be rejected exactly at $T_1$ . The effort exerted must continuously be exactly equal to the work required to compress the working fluid.

REFRIGERATING MACHINES.—In the Carnot Cycle so far considered, all the operations have been treated as though they are performed in the same vessel. This method conduces to simplicity of thought, but in practical machines each operation is performed in its own particular vessel, suitably arranged for the special function required. In Fig. 9 is represented the four separate organs of a refrigerating machine in their simplest form, showing their relative positions. The upper cylinder, in which the working fluid is compressed from  $T_2$  to  $T_1$ , the cooler, then receives heat from the fluid, lowering the temperature in the process, afterwards the cooled fluid expands in the expansion cylinder, the work so done assisting to drive the machine. The expenditure of energy during this process of expansion reduces the temperature of the working fluid to the lower limit, when it enters the fourth part of the machine, where it receives heat from, i.e., cools the substance contained in the surrounding envelope.

A variation from this arrangement usually met with in practice when dealing with liquid or vapour is to omit the expansion cylinder and replace it with a throttle valve, and as a consequence the action differs from the Carnot method, involving as it does an irreversible action entailing a loss of efficiency.

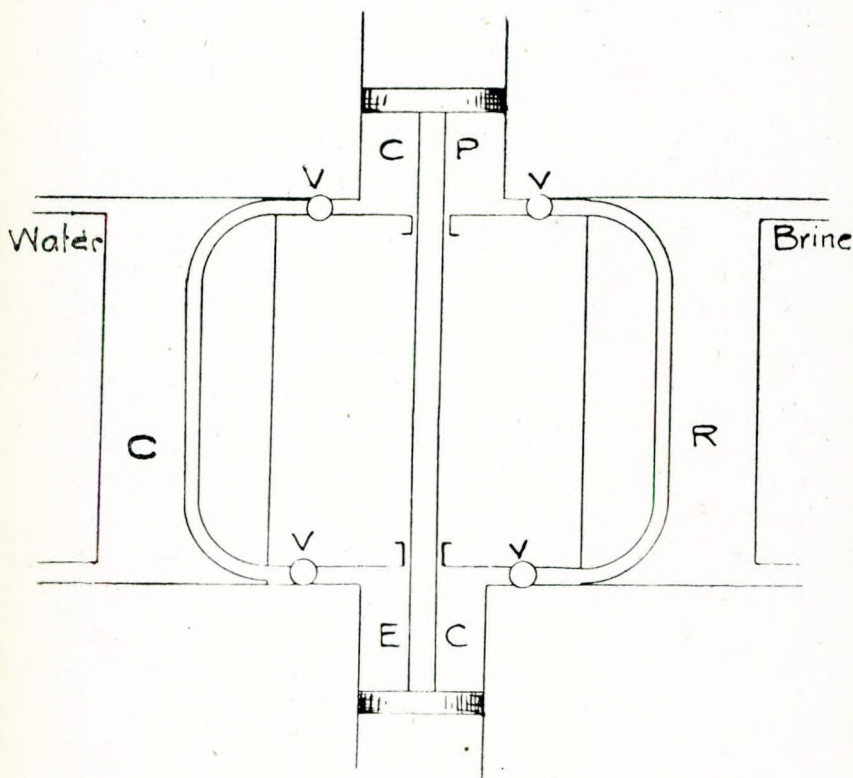


FIG. 9.

The gain, however, in simplicity far outweighs the thermodynamic loss.

The thermodynamical losses entailed are—

(1) The amount of work expended upon the working fluid in carrying it through the cycle is *increased*, by the amount lost in consequence of the absence of the expansion cylinder.

(2) The working fluid enters the refrigerator at a slightly *higher temperature*, because it has not been cooled by expansion.

so that the *net* amount of refrigeration is diminished for a given expenditure of energy.

### COLD AIR MACHINES

COLD AIR MACHINES belong to the group of refrigerating devices, in which the working fluid does *not change its state*, but remains in the gaseous condition throughout the whole cycle. There are two sub-divisions: (1) in which the same mass of air is made to pass repeatedly through the cycle of operations, and (2) those machines in which the air is discharged into the atmosphere at the end, and a new volume of air drawn in at the com-

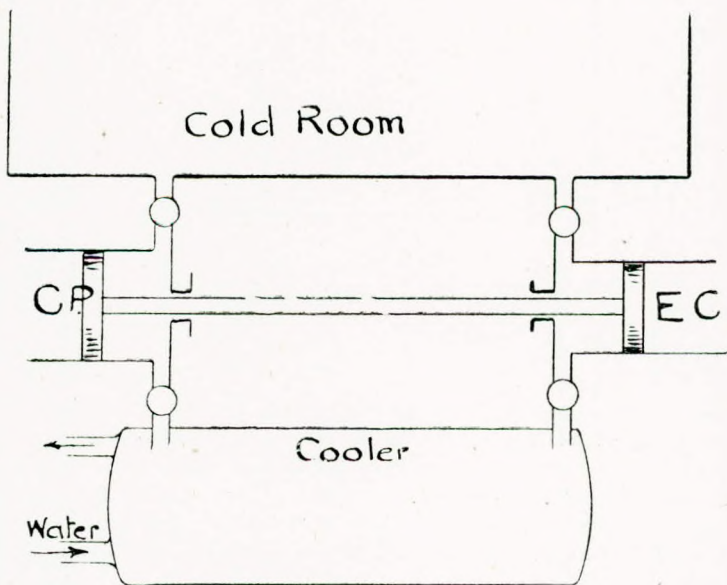


FIG. 10.

mencement of each cycle. The former are sometimes spoken of as the *closed* cycle, to distinguish them from the latter. It is obvious that the second group commence and end each cycle by a return to atmospheric pressure, whereas the former may work at pressure, continuously higher than that of the atmosphere.

THE OPEN CYCLE AIR MACHINE.—In Fig. 10 is shown in



outline the essential features of the open cycle air machine. Drawing in air from the cold room, compressing it to a pressure of some four atmospheres it is cooled down to about  $65^{\circ}$  F. in the cooler, it is expanded in the expansion cylinder down to atmospheric pressure and delivered into the cold chamber at a temperature from  $-60^{\circ}$  F. to  $-120^{\circ}$  F. depending upon the conditions of working. The cold room is therefore chilled by removing a small portion of its atmosphere each stroke, and returning it at a temperature much lower than that of the chamber itself.

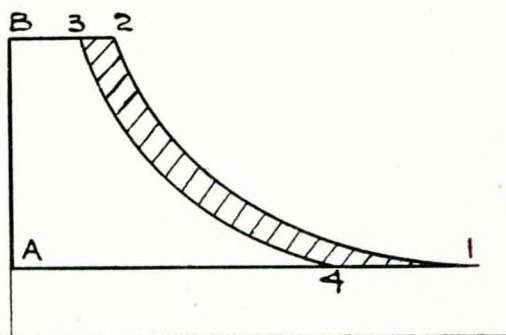


FIG. 11.

In Fig. 11 is shown the ideal indicator card (combined compression and expansion diagrams) for this type of machine. The area 1,2 A. B. represents the work done on the air in the compression cylinder, and the area AB34 the work done by the air in the expansion cylinder. The air is compressed from a pressure  $p_1$  to the pressure  $p_2$ , where it is delivered to the cooler. During compression its temperature will have increased, so that in the cooler its temperature falls, that is, heat is abstracted at constant pressure, resulting in a reduction of volume from B. 2. to B.3. The ideal condition of compression would be isothermal, and therefore the compression cylinder is water-jacketed, in the dry compression method, whilst in the wet system cold water is injected into the compression cylinder itself to reduce the rise of temperature during compression, by abstracting the heat due to compression. The law of compression is

$$PV^n = \text{constant};$$

where  $n$  has a value between unity and 1.408, dependent upon

the efficiency of the cooling device adopted. The value of  $n$  would appear to be from 1.29 to 1.3.

The cooler is supplied with a current of water entering at a temperature of about 60° F., and the air is cooled down to about 65° F. before entering the expansion cylinder. Its volume is reduced, so that the expansion cylinder has usually a proportionally smaller volume than the compression cylinder,<sup>1</sup> the final pressure is sensibly equal to that of the atmosphere.

ANALYSIS OF COLD AIR OPEN CYCLE MACHINE.—An examination of tests upon this type of machine results in a co-efficient of performance not exceeding  $\frac{3}{4}$ , which compares very unfavourably with the theoretical possible values shown in table. An examination of the details at once shows the source of serious losses, due to deviations from the ideal thermodynamical conditions discussed.

(1) Heat is rejected to the cooling water in the cooler with a maximum temperature difference of 196°, hence a great loss must occur.

(2) Heat is received by the working fluid under a temperature head of 138°, with a consequent loss of heat.

ABSORPTION MACHINES form a class in which the working fluid changes its state alternately from the liquid to the vapour, and back again to the liquid, in consequence of the application of high-temperature heat at one stage in the cycle. In the practical application, one kind of machine uses ammonia vapour and water: the arrangement of the parts of the machine are shown in Fig. 12 in diagram form. Heat is supplied by means of steam through the coil, thus heating the solution of ammonia in the generator G. The ammonia gas passes through the coil in the condenser C, where it is condensed, giving up its heat to the cold water circulating through the condenser. The condensed liquid passes away through the regulating valve V into another coil, where it evaporates, absorbing the heat required from the brine circulating through this second vessel. It is evaporated at a low pressure, and consequently at a low temperature, so that the brine circulating in this vessel is cooled to a temperature considerably below 32° F. The cold gas passes into vessel A, where it is absorbed by the dilute solution received from the generator, after evaporation. In the process

<sup>1</sup> The relative proportions naturally vary, but in some published data the ratio of volumes appear to be about 1.7.



the strong ammonia solution rises to the top in the generator G; the weaker falling to the bottom is allowed to pass by a suitable check valve into the absorber A, where it meets the gas coming from the brine vessel. After the gas is absorbed, the liquor is again pumped into the generator, thus completing the cycle of operations. In the process of absorption a large quantity of heat is given out, so that the absorber must be cooled by circu-

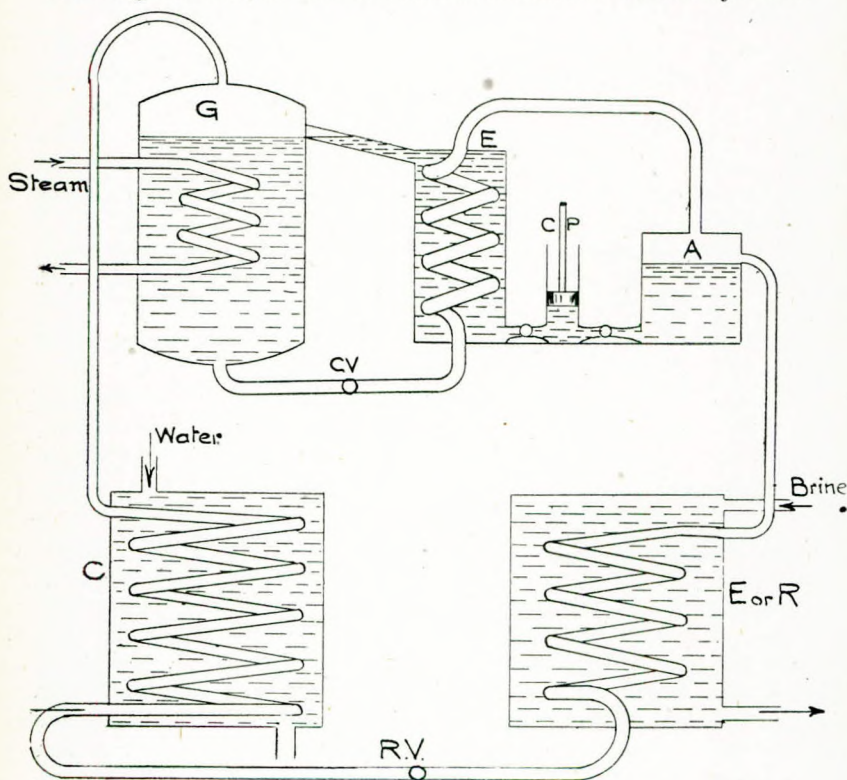


FIG. 12.

lating water. The interchanger or economizer E cools the weak hot liquor on its way to the absorber, because the liquor in the absorber must be comparatively cold for absorption to take place. The strong cool liquor is pumped into this vessel on its return to the generator; thus the heat is, as it were, interchanged from the one to the other, thus effecting a notable economy of heat in the process.



The apparatus may be divided into two parts, one in which the pressure is low, and the second where the pressure is high. The low pressure portion is the evaporator and the absorber, and is cut off from the high pressure side by the pump and regulating valve.

It should be noticed that the absorbing substance takes the place of the pump, producing a state of low pressure while the process of evaporation is going on.

In this process the heat diagram is not readily applicable, because the chemical reaction during absorption involves work not *mechanical*. Consequently the efficiency of this process must be calculated by noting the expenditure of heat in separating the gas from the concentrated liquid, and the work done in operating the pump, whilst the work done in cooling may be found by noting the temperature change and weight of brine cooled.

#### WATER VAPOUR ABSORPTION MACHINES.

Similar classes of machines are employed in which water vapour is the working fluid. At low temperatures the pressure

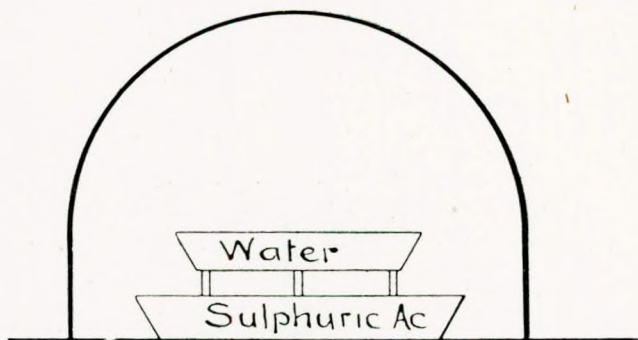


FIG. 13.

must be very low ; hence refrigerators of this type are frequently spoken of as " Vacuum " machines, being based upon the well-known " Leslie " experiment, Fig. 13, in which water is frozen in a vacuum, some sulphuric acid being present to absorb the water vapour.

In this type of machine the vacuum pump is an accessory and not an essential feature, being required only to remove the

atmospheric air present in the first instance, and later, the air introduced with the water, which would accumulate and so destroy the vacuum, and slowly reduce the refrigerating effect of the machine to zero.

To convert the machine into one of continuous action it is obvious that the sulphuric acid must be in a separate chamber, so that heat may be applied to evaporate the water, and concentrate the acid for use over again. Such a machine was made in 1878 by Windhausen, and employed by the Aylesbury Dairy Co., being described by Dr. J. Hopkinson in 1882. This machine produced 12 tons of ice in 24 hours, and its action was

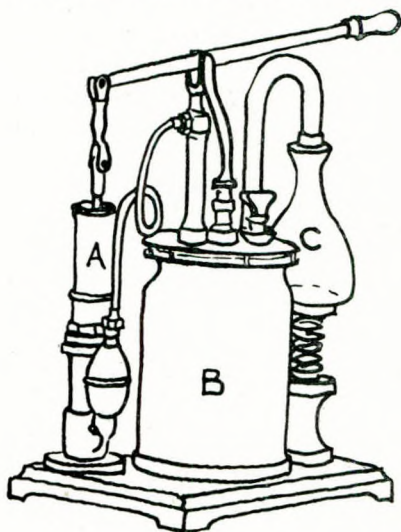


FIG. 14.

extremely rapid, six blocks each 650 lb. being formed in about an hour from the start. The ice is, however, not clear, so that except in small domestic machines this type has disappeared. Fig. 14 shows such a machine by the Pulsometer Company, in which the air pump (A) produces a vacuum in the apparatus, so that the water vapour is rapidly absorbed by the acid in the vessel (B), so that the water in C is frozen. After use several times the dilute acid in B must be replaced by fresh strong acid, the activity of the weakened solution may be restored by heating it, thus driving off the water absorbed.

## THE VAPOUR COMPRESSION PROCESS.

This class of machine is by far the most important commercially, embracing, as it does, by far the largest number of

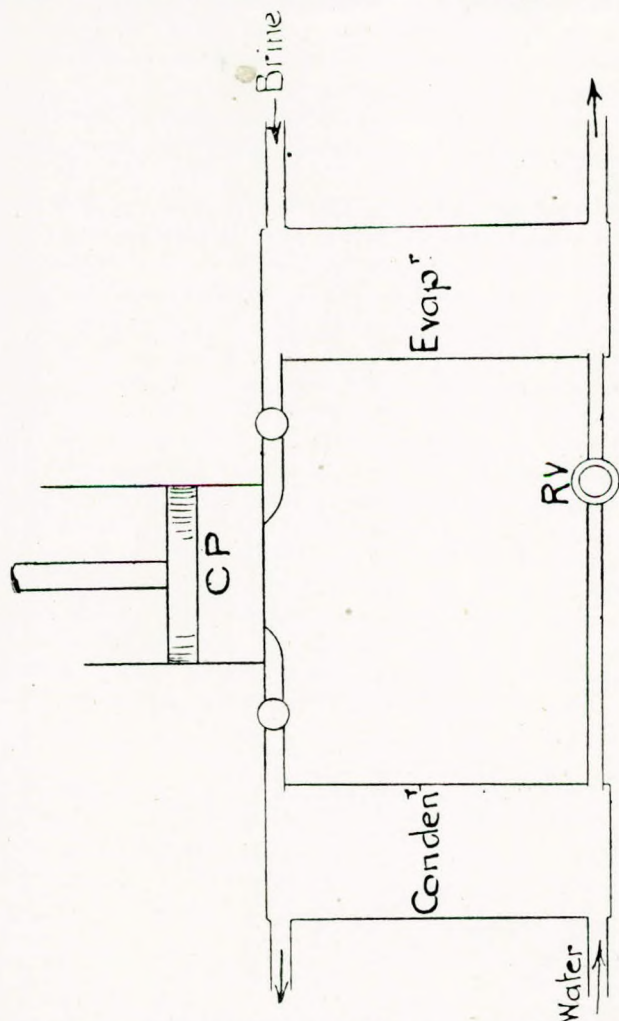


FIG. 15.

machines now on the market. It allows a very high co-efficient of performance to be reached, approaching closest to the thermodynamic ideal of perfection.



In diagram form Fig. 15 represents this type. The vapour from the refrigerator R is compressed by the compressor pump CP, and condensed in the condenser, the liquid returning to the refrigerator by way of the throttle valve V. In passing through the valve V the part of the liquid becomes gaseous, and the mixture of liquid and vapour passes into R, where the heat from the brine flows into the cold mixture of liquid and vapour, which completes the re-evaporation of the refrigerant, which is again in its initial state, and ready to pass through the cycle again.

Any liquid which can be practically liquefied and vaporized may be employed as the refrigerant, but for practical and commercial reasons the substances used are either carbonic acid or ammonia, although water, sulphurous acid, and sulphuric ether have been and are occasionally employed.

In machines using water, a vacuum must be maintained, but the water vapour is *not* absorbed, but may be discharged by the pump into the atmosphere (Windhausen), other water taking its place. The inspection of the table or chart for water will show that the volume of vapour to be removed will be at low temperatures exceedingly great, entailing a large pump with the corresponding charges for its operation, to say nothing concerning its bulk. For temperatures below 32° F. it is obvious that the water would freeze, hence brine must be employed, when the machine will become bulkier and less efficient.

THE CHOICE OF A LIQUID to use in a compression machine depends upon (i) thermodynamic and (ii) practical considerations. The following table illustrates some of these points in a clear, concise form.

	Temperature.	Pressure in lb. per sq. in.	Lat. Heat.	Volume of lb. in cub. ft.	Volume per 1,000 B.T.U. of Refrigeration.
			B.T.U.		
Water . . . . .	32° F.	0.085	1,092	3,416	3,129
Sulphurous Acid . . . . .	32° F.	22.50	164.2	3.4	20.71
Ammonia . . . . .	32° F.	61.80	568	4.8	8.45
Carbonic Acid . . . . .	32° F.	535.00	99.8	0.17	1.703

The volume swept out by the pump is comparatively trifling

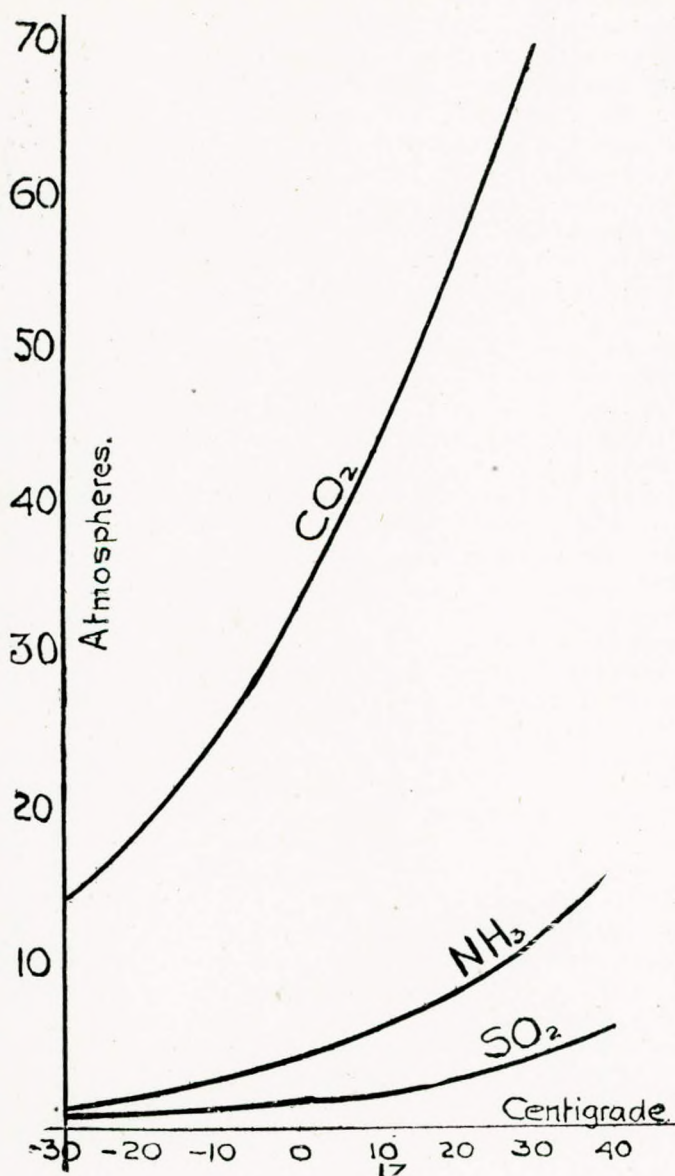


FIG. 16.

with any of these refrigerants compared with water, so that the water-vapour machine is obviously out of court.

Practically the strains put upon the machine is an important factor. With water the pressures are excessively low, being at the highest temperatures on the warm side much below a pound per square inch. Sulphuric ether at the ordinary working temperatures is also very low, the substance is very inflammable, and leakage would mean air finding its way into the machine, reducing its efficiency. Hence in modern practice the three last substances are mainly used.

Physically, the properties of the three substances are contrasted as regards pressures in Fig. 16, where it will be noticed that the pressures in the case of ammonia are such as engineers have usually to deal with, whilst with carbonic acid the pressures are very great, but light in the case of sulphurous acid. Chemically the carbonic acid has no reaction or solvent effect upon iron and brass, whereas ammonia attacks brass and copper. The chemical stability of the substances, their cost and thermodynamic qualities, are each factors in the problem of selection.

**THERMODYNAMIC EFFICIENCY.**—If it were possible to operate upon the Carnot cycle, then it would not matter which substance was employed, for all would be equally efficient so far as thermodynamic results are concerned. But the cycle actually employed differs from the Carnot in the omission of the adiabatic expansion, this stage being the substitution of the throttle valve, through which the liquid streams in place of the expansion cylinder. Obviously this means the loss not only of the work done during expansion, but also additional heat is carried forward into the refrigerator with a corresponding loss of refrigerating effect. Put  $L$  = latent heat of the vapour, and  $h_1$  and  $h_2$  the heat in the liquid at the temperature  $t_1$  of the condenser, and  $t_2$  of the evaporator. The heat the liquid carries over is  $h_1 - h_2$ , and this reduces the possible cooling effect from  $L_2$  to  $L_2 - (h_1 - h_2)$ ; the quantity  $h_1 - h_2$  is equal to  $s(t_1 - t_2)$ ; where  $s$  = specific heat of the liquid put  $t_1 = 62^\circ \text{F.}$ , and  $t_2 = 32^\circ \text{F.}$ , then—



	s.	$L_2$ .	$h_1-h_2$	Cooling Effect.	Loss per Cent.
Water . . .	1.00	1,092	30.0	1,062.0	2.74
Sulphurous Acid	0.32	164	9.6	154.4	5.85
Ammonia . . .	0.9	568	27.0	541.0	4.75
Carbonic Acid .	0.54	100	16.2	83.8	16.20
Area in Fig. 17 .		eCGg	eCBb	fFGg	

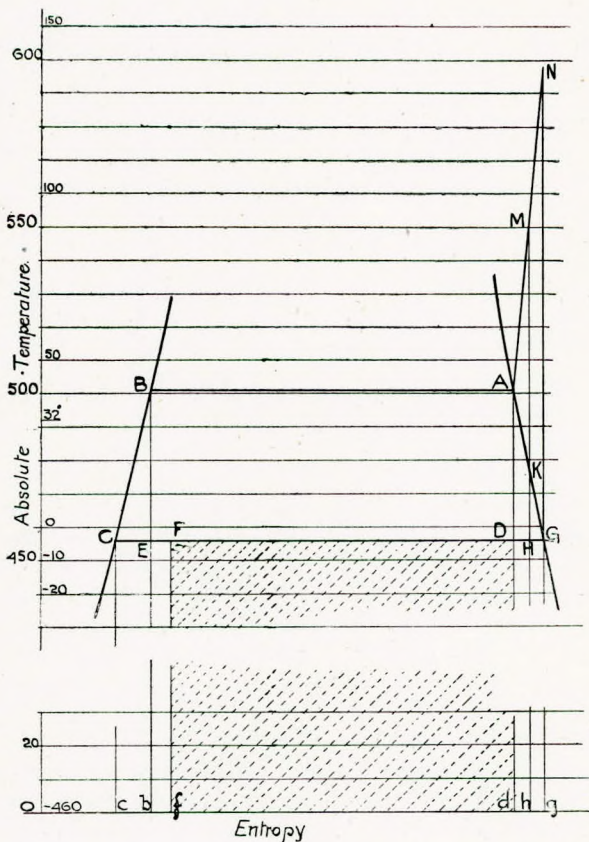


FIG. 17

In this comparison (seeing that water is out of the question) ammonia shows the least loss in consequence of the deviation from the ideal cycle.

THE ENTROPY DIAGRAM FOR VAPOUR COMPRESSION.—In the diagram, Fig. 17, the line AB is the condensation of the compressed vapour, BC is the cooling of the liquid as it passes to the evaporator, CD is the evaporation there, and DA the compression (adiabatic) of the vapour by the pump. The area  $bBCc$  is the quantity of heat carried over into the evaporator in consequence of the use of the throttle valve instead of an expansion cylinder. The net amount of heat extracted, is the area  $cCDd$  less the area  $cCBb$ ; and the effect of the physical qualities upon the efficiency previously discussed is represented by the

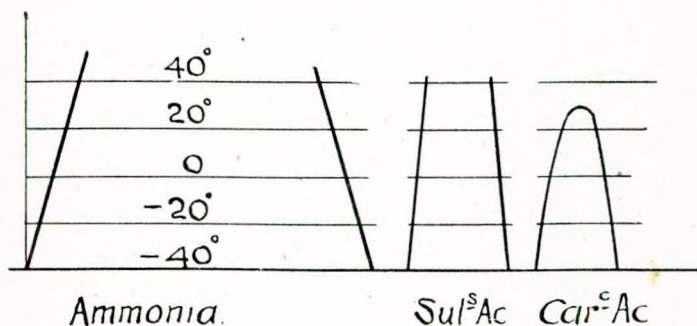


FIG. 18.

ratio of the areas,  $cCBb$  and  $cCDd$ . The area ABCD measures the expenditure of work done to perform the cycle. Next draw the line Ff so that the area  $cCFf$  is equal to  $cCBb$ , then the shaded area is the net cooling effect per pound of the working fluid performing the cycle. The co-efficient of performance is the ratio of  $fFDd$  to ABCD the work done on the compressor.

In Fig. 18 is shown for comparative purposes the entropy chart for the other substances from which the previous conclusion concerning the effect of the throttle valve upon efficiency is confirmed and needs no explanation.

WET OR DRY COMPRESSION is a point round which some argument may be still heard to-day, and possibly some light may be thrown upon it by the comparison of the heat diagrams illustrating the respective cycles. In Fig. 17 just considered is shown the diagram for *wet* compression, in which the sub-



stance at the end of compression is just "saturated" vapour. If the state point D had been at the instant compression commenced nearer G, say at H, then the compression line would meet and cross the saturation line at the point K, and would travel upwards to some point M, denoting that the gas is superheated. If the state point be at G, then the vapour contains no moisture at the instant compression commences, i.e., it is dry, and the compression line is then wholly within the superheated field and the compression is then said to be dry. Obviously in this last case the point N will be higher than M. Now the question is how far does the amount of wetness affect the efficiency of the process? By laying down the diagrams for these three cases (using ammonia) as illustrated, there the efficiency is measured by the ratios of the work done on compression and the heat extracted from the brine circulating in the evaporator.

Compression along the	Co-efficient of Performance	Additional area in Compression.	Additional Area of Refrigeration.
Line DA (wet) . . . .	9.65	—	—
.. HM (intermediate) . .	9.48	8.3	54.7
.. GN (dry) . . . .	9.17	9.3	45.6

As regards these figures it is evident that there is a little advantage possibly in the wet process over the dry, but it must be qualified by the fact that in practice, adiabatic expansion cannot be realized, whilst it is doubtful if either dry or wet compression can be always positively secured. The actual exchanges of heat that take place between the substance and the cylinder walls, covers, etc., are very complex, and remembering all the facts known concerning the formation of liquid, etc., it is more than possible that a moderate amount of superheat may be an advantage in reducing the loss due to these exchanges. This view is confirmed by the increasing use of dry compression. It should be noted that if the compression is unduly wet, the cooling effect would be reduced without any increase of efficiency, so that a little superheat should be aimed at as an indication that the throttle valve is not opened too wide.

CARBONIC ACID AND THE CRITICAL POINT.—The critical point is the temperature above which the substance cannot be



made to change from the gaseous to the liquid condition. This is shown by the sloping boundary lines in the entropy diagram, these lines evidently converging towards each other as the

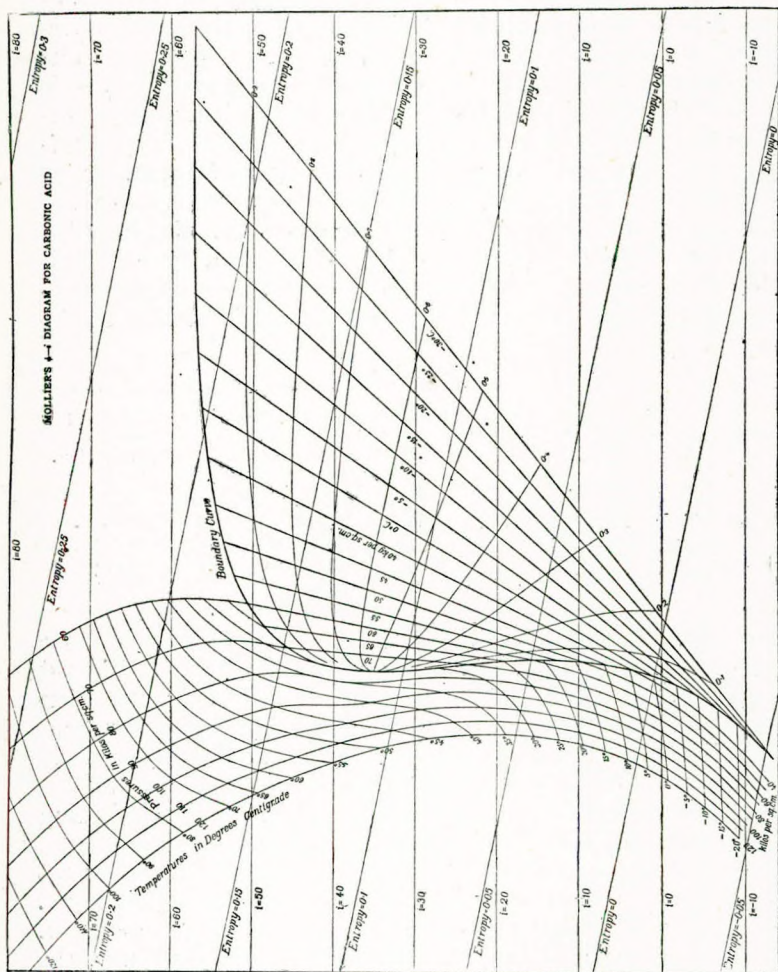


FIG. 19.

temperature is raised. This temperature need only be considered in the case of carbonic acid, for it is so high in the case of ammonia and sulphurous acid, as to lie beyond the range of temperature met with in refrigeration plants. For carbonic

acid it is about 88° F. When approaching the critical temperature the amount of the latent heat rapidly decreases, in proportion to the liquid heat, thus augmenting the loss due to the use of the throttle-valve. Also it is evident that the use of water at high temperatures (such as in the Tropics) must lead to a loss of efficiency.

Dr. Mollier has investigated the matter, and from his chart Fig. 19, it is easy to see exactly what happens in any given case. The units employed are the metric, but this will not affect the inferences to be drawn from it.

CHAIRMAN: I am sure we have all been delighted with Mr. Wells' exposition of the subject of his paper. His explanation of the entropy diagrams could not, I think, have been put clearer. It is a very fascinating subject and Mr. Wells has cleared up, at least in my mind, one or two points which had presented difficulties. I should be glad if some one would open the discussion.

Mr. ROBT. BALFOUR: I am glad to have been present to-night to listen to what has been a combination of unique paper and lecture. It has been one of those pleasures which is difficult to describe to those who have not been privileged to be present. Mr. Milton, in his Presidential Address to the Cold Storage and Ice Association, took for his subject the inter-relation of theory and practice, and paid tribute to the practical man who was the inventor of the steam-engine and, as we have heard to-night, we who are more concerned with the practical side of the subject of refrigeration are in a very great measure indebted to those who have studied the theory. It occurred to me that it was a pity Mr. Wells was not here some years ago to precede my own attempt to give the practical view of the subject. Mr. Wells appropriately refers to the great Carnot and to his ideal heat engine. In his famous essay on the Motive Power of Heat, Carnot introduced us to the cycle of operation and the principle of reversibility. In connexion with this subject, as in all cases where there is a problem to solve, it is necessary to have an ideal, and Mr. Wells has put before us most explicitly those ideal conditions laid down by Carnot and others. It is something to aim at, although we know that in practice we cannot get those ideal conditions owing to friction, radiation, etc. With regard to



compression machines, as Mr. Wells has rightly said, we are practically confined, as far as marine engineering refrigeration is concerned, to the carbonic anhydride and the ammonia anhydrous systems, these two substances being most in use to meet our conditions, which are somewhat different from land practice. The engineer must choose those substances which can be utilized in such a manner as to produce the greatest amount of work at the minimum cost. There are differences of opinion with regard to compressors of  $\text{CO}_2$  machines, but I was pleased to notice the unbiased way in which Mr. Wells treated the point. It seems to me that there is very little to choose between them. I was extremely interested in the graphical demonstrations given by Mr. Wells with regard to wet and dry compression—it is a subject now being dealt with at the Cold Storage and Ice Association. Personally I am inclined to favour wet compression. In dry compression with the superheated gases there is the trouble of producing overheating by carrying over the lubricant. I again thank Mr. Wells for the great pleasure he has given us, and I look upon his lecture as one of the best expositions of the subject we have ever had at the Institute.

MR. JAS. SHANKS: I had not the slightest idea on what lines the subject was to be treated to-night, and I assure you it has been to me a pleasant surprise. As Mr. Balfour has said, the science of refrigeration has had more to do with its progress than the work of the mechanical engineer, and it is necessary that all engineers should have some knowledge of the theory of refrigeration, because the successful working of the machinery is left to him. The paper has been especially interesting to me, because I have never had an opportunity of having the theta-phi diagram so clearly and lucidly explained. I have hurriedly looked through Professor Anderson's paper, referred to by the author. It is an excellent paper and goes thoroughly into the question of refrigeration in all its phases; but we needed a paper of the description we have had to-night to explain it and to understand it properly. I was particularly pleased to hear Mr. Wells' references to Mr. Macfarlane Gray's famous theta-phi diagram. Coming from such a source as this it warms our hearts to think of the great man we had in our midst a few years ago. The progress of refrigeration depends, I think, to a great extent on the marine engineer, and

for that reason this method of explaining the theory of refrigeration to our members will have a valuable effect, because I am sure that when marine engineers get a thorough knowledge of the theory it will be beneficial in every possible way. With regard to the question of wet and dry compression, Professor Anderson shows in his paper that wet compression is theoretically more economical than dry, yet in practice dry compression is the more economical. There are all kinds of theories and arguments put forward to account for it, but it is a fact, nevertheless, and for that reason dry compression has been largely adopted in America. We in this country use a medium partially saturated. It appears that we get better working of the machines so far as lubrication and wear and tear are concerned, and I believe, in view of that experience, Americans are gradually coming back to our degree of saturation of the gas. I should like to hear Mr. Wells' opinion on that point.

CHAIRMAN : Before asking Mr. Wells to reply to the questions which have been raised, I should like to say that there are one or two points in the paper which have specially appealed to me. One of these is in connexion with condensers. Mr. Wells has clearly and concisely explained the relationship of the vapour and the gas or air occupying the same space and having their own respective pressures according to the temperature. Of course that is a point which was impressed upon us in our youth, but it is astonishing how many truths seem to slip past us, because it is only of recent date that the condenser has really become known to the majority. Although Dalton's law was taught many years ago, somehow or other it did not seem to be fully apprehended generally until quite recently. I am sure the discussion has not been taken up so fully as it might have been owing to the difficulty of digesting what has been put before us, and, unfortunately, we were unable to obtain copies of the paper to study it before this evening.

Mr. WELLS : In the first place I should like to express my regret that pressure of many engagements prevented me from getting the paper ready in time for advance copies to be prepared. The only question raised, as far as I could gather, was that of wet and dry compression, and there I am quite in agreement with the speakers, whose remarks my own



limited practical experience bears out. Theoretically the wet method shows the greatest ratio of refrigeration for work expended, but it is not a serious difference. I think some of the difficulties are due to heat exchanges. It is a difficult thing to warm air, and comparatively easier to warm liquid. In the ordinary boiler tube there may be a difference of temperature between it and the water of 50 to 60 degrees Fahr., while the temperature of the gases may exceed that of the tube from 2,000° Fahr. to 500 at the far end. There is a great difference on the gas side and very little on the other, the particles of moisture acting as vehicles to carry the heat about, and where there are no such vehicles the heat is not so readily transmitted. It is much more difficult to warm up or cool down the dry gas than if there is a moist medium. I quite agree with Mr. Shanks that if the gas is highly superheated all the difficulties incident to high temperature working are experienced. There is a maximum temperature at which it is suitable to work, and the practical man aims at not exceeding such temperatures. If any of the members wish to contribute to the discussion in writing I should be very glad to consider any points raised.

Mr. ROBT. BALFOUR : There is a great difference of opinion as to the height of the liquid in the evaporator. Assuming a coil or series standing vertically, to what extent do you expect the liquid to be in that evaporator ?

Mr. WELLS : It is a question of how far along the evaporation line you have proceeded when the refrigeration is complete. I do not know that you can say anything definitely without having data.

Mr. BALFOUR : I presume it is a question of specific heat of the liquid versus the gaseous.

The meeting then concluded with a vote of thanks to the author, on the proposal of the Chairman.

