4.

REFRIGERATION.

Just as water always tries to find its own level, so heat is always endeavouring to find a common temperature level, the transference of heat being always from the body at a higher temperature to the body as a lower temperature. To refrigerate anything, therefore, it is necessary to withdraw heat from it at a rate greater than it can absorb heat from its surroundings until the desired temperature depth has been reached, whereafter the refrigerating effect must continue at a rate *equal* to the inflow of surrounding heat. Also, the heat withdrawn must eventually be discharged to the surroundings—there is nowhere else for it to go. Hence the refrigerant must at one moment be colder than the body to be cooled, and then (having extracted heat therefrom) be put in such a state that it can reject heat to its surroundings. That is, it must be heated until its temperature exceeds that of its surroundings. Hence the paradox that cooling can only be achieved by the expenditure of heat.

The heat may be applied directly (as in absorption machines) or in the form of work (compression machines) but in either case it must be rejected to the surroundings (circulating water) along with the heat taken from the cold body. Clearly, the greater the amount of heat withdrawn from the cold body for a given quantity applied, the more efficient the machine, and the ratio between these two variables is known as the Co-efficient of Performance.

In the early forms of refrigerating machines, namely, the air compression type, the air was compressed in a cylinder, the heat of compression extracted by circulating water and the air re-expanded, doing work, with consequent fall in temperature. These machines were necessarily bulky and of such low mechanical efficiency that only a proportion of the work applied became effective for refrigeration, and vapour compression machines with a much greater Co-efficient of Performance have taken their place.

As is well known, the vapourisation (condensation) of any given fluid takes place at a temperature dependent on the pressure to which it is subjected. Hence, by varying the pressure the condensing point can be controlled, within limits to be considered later, at will.

This property is exploited in vapour compression machines in which a liquid with a low boiling point at moderate pressures is vapourised by heat from the body to be cooled and then compressed to such a pressure that its boiling (condensing) point is above that of the available circulating water, whereupon it rejects its latent heat and again becomes liquid.

The temperature of this liquid is now approximately that of the circulating water and, therefore, incapable of any refrigerating effect; but as soon as the pressure is reduced, say, by throttling through a regulating valve, the boiling point falls and the fluid instantly begins to vapourise. The necessary latent heat of formation to bring this about is drawn from the remainder of the fluid itself, with the result that a mixture of vapour and liquid at a low temperature passes to the evaporator. In the evaporator heat begins to flow in from outside and the temperature of the fluid ceases to drop as soon as the heat drawn from the two sources—external and internal—is sufficient to keep pace with the rate of vapourisation.

Although the above cycle diverges in certain notable features from a reversed Carnot cycle, yet in the ideal case the refrigerating cycle is simply that for a reversed heat engine. Ideally, therefore, the maximum thermal efficiency of a refrigerator like that of a heat engine, is dependent only on the difference of the absolute temperatures employed. Where the object is external work for a minimum expenditure of heat, the greater the range of temperature the greater the efficiency, but in the refrigerator where the object is a maximum transference of heat for a minimum expenditure of work, the *smaller* the range of temperature the greater the efficiency. From another point of view the refrigerator may be considered as a machine for pumping heat from a lower to a higher temperature level, and the smaller this temperature difference (or " head ") the more heat can be pumped for a given outlay of energy. And this is the main reason why vapour machines are more efficient than air machines, because in the vapour machine the major exchanges of heat take place in the latent zone, i.e., at constant temperature, and the temperature " head " of the cycle is thereby greatly reduced.

Unfortunately, in practice, the temperature difference in the cycle unavoidably increases as the surroundings become hotter, thus causing the efficiency of the machine to fall away when refrigeration is most in demand. Moreover, this effect is intensified when CO_2 is used as the working fluid by reason of its low critical temperature. As the critical temperature of a fluid is approached the latent heat of condensation diminishes rapidly and becomes, *at* the critical temperature, zero—that is to say, that above this temperature the vapour will not liquefy, however much it is compressed. In the case of CO_2 this occurs at a temperature little, if at all, above the temperature of tropical sea-water. Consequently, as the temperature of the circulating water rises, increasing difficulty is experienced in obtaining complete liquefaction of the fluid and a growing proportion makes the circuit of the cycle as vapour. This amounts, in a measure, to a reversion to the conditions of the cold air refrigerator, and naturally involves a drop in the co-efficient of Performance.

Supercharging.—The fall of efficiency under the foregoing conditions can be counteracted to some extent by increasing the initial pressure of the vapour, either by the addition of gas to the machine, or by decreasing the clearance volume of the compressor. The greater part of the extra heat so applied is extracted by the circulating water, and the vapour brought down to the same temperature as before, but its pressure being higher, its potential refrigerating effect is increased. For example, it is found that with circulating water temperature at 90°F., evaporator pressure 400 lbs./in.^{2} and compression pressure (*a*) 1,000 lbs./in.^{2} and (*b*) 1,500 lbs./in.^{2}, the state of the fluid after expansion will be roughly (*a*) 10 per cent. liquid, (*b*) 65 per cent. liquid. The temperature of the mixture in each case being about 16°F.

This is curious. Before expansion the fluid is a vapour; after expansion, part of it is liquid and the whole is at a much lower temperature than before, yet no appreciable heat has been discharged to the surroundings, for the throttle expansion process is very nearly a constant heat operation, and the total heat of the fluid is, therefore, the same as before. The explanation is that the fluid in the neighbourhood of the critical temperature ceases to behave either as a true liquid or a true vapour. The density of the liquid is so much reduced by the high temperature, and that of the vapour so much increased by the high pressure, that the two densities become equal, and the fluid exhibits properties inapplicable to either condition. It would seem that as the pressure is decreased the specific heat of the fluid changes—*in*creases. The internal heat remaining the same the temperature of the fluid therefore falls, and continues to fall until it passes through the critical temperature, whereafter liquefaction continues until equilibrium is reached as regards the internal heat of the substance and the sensible and latent heats corresponding to the lower pressure. But whatever the precise interpretation of the internal changes which take place during this operation, the result is a matter of observation, and can be clearly seen on entropy charts.

Entropy Charts.—These charts, which have been prepared for CO_2 and other refrigerant fluids, are built up from experimental observations. They consist of families of intersecting curves of constant pressure, dryness, volume,* total heat (or temperature) and entropy, referred to ordinates of either temperature or total heat and entropy. Entropy is simply a function of heat change and absolute temperature—a mathematical conception which facilitates calculation, particularly in the graphical form. The construction and use of such charts are described in text books, and it is only to be added here that they are indispensable for rapid calculation and a great aid to a proper understanding of the working cycle.

Pre-cooling.—Another device for increasing the refrigerating effect in tropical conditions which has recently received attention

* The volume lines are omitted in some charts.

and is now being fitted to the majority of new naval refrigerators is known as pre-cooling.

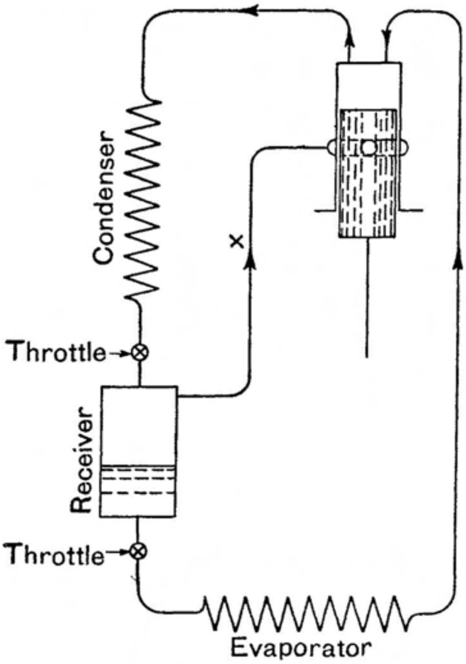


FIG. 1.

The essential feature of this appliance (Fig. 1) is that the throttle expansion process is carried out in two stages, two expansion valves being fitted in series. In the first stage the fluid (whether liquid, or in the intermediate state described under supercharging) is expanded into a vessel called a receiver, to a pressure and temperature intermediate between that of the condenser and the evaporator. Here, partial vaporisation and condensation take place, and the vapour so formed is led back to the compressor and drawn into the cylinder towards the end of the suction stroke, through a belt of ports in the compressor liner. The remaining liquid passes through the second valve and vaporises in the evaporator in the ordinary way. The fall in pressure and temperature here is small compared with the drop between condenser and receiver, so that only a small further amount of self-vaporisation takes place, and practically the whole of the liquid is available for cooling the brine.

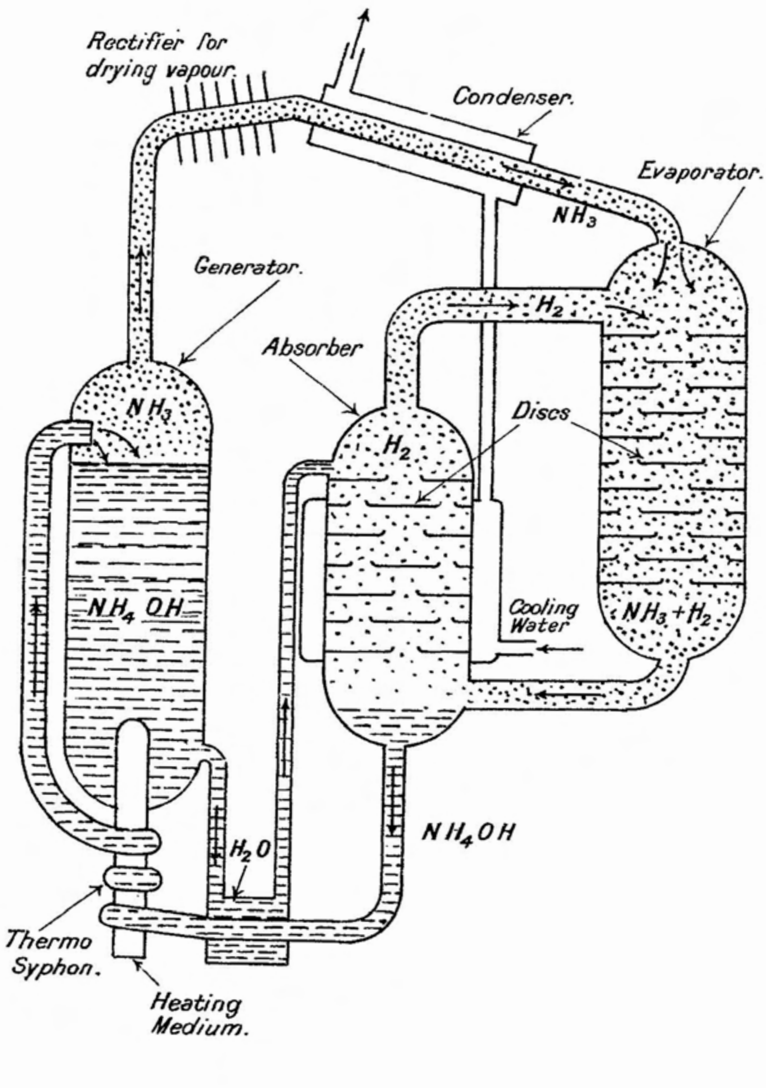
As a basis for comparison with an ordinary cycle, let it be assumed that an equal weight of vapour is drawn from the evaporator in each case. Then the effect of pre-cooling can be seen by a comparison of Figs. 2 and 3.

Fig. 2.—Without precooler. Work done by compressor is *ABCD*. At the regulating valve the vapour follows some such line as *EF*, *i.e.*, it is partially vapourised and only a fraction $\frac{FB}{AB}$ remains as liquid.

ELECTROLUX REFRIGERATOR.

DIAGRAMMATIC ARRANGEMENT.

FIG. 4.



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Refrigerating effect is therefore proportional to $FB \times$ Latent Heat of the liquid.

Fig. 3.—With precooler. Machine is now supercharged but 1 lb. still passes through the evaporator, the additional charge passing from precooler to the compressor cylinder at completion of suction stroke. The passage through the first regulating valve is represented by *EG* and the supercharge vaporises along *GK*. The 1 lb. cools to *H* and passes through second valve along *HM*. Refrigerating effect is now proportional to *MB* and work to *ABKLD*.

The output of the machine has therefore been increased, which is what is required. The work to be done by the compressor is necessarily greater than before, because the weight of vapour compressed is greater by the amount entering from the receiver, but this fraction being less depreciated in pressure partly compresses the charge drawn from the evaporator without the addition of external work. In the result, therefore, although additional power is required when pre-cooling, the co-efficient of performance is better in most conditions of working because the

Fig. 2.—Without precooler.

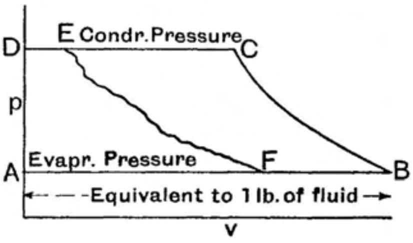
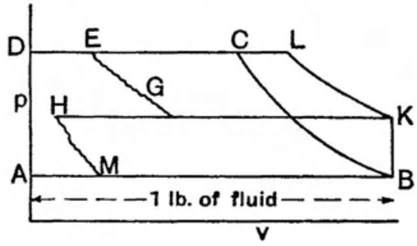


Fig. 3.—With precooler.



bulk of the vapour necessarily formed in liquefying the fluid is not uselessly degraded in temperature and pressure beyond the point necessary to bring this about. Expedients of this type can, of course, be obviated by using a working fluid with a critical temperature well above the hottest circulating water likely to be met with, and it may be asked why this is not more generally done. Other properties, equally important, however, have to be considered.

Choice of Refrigerant.—For mechanical reasons the saturated vapour pressure of the fluid corresponding to the highest sea water temperature must not be too high, nor that corresponding to the lowest brine temperature so low as to make it possible for air to leak into the machine. The specific volume within these pressure limits must be reasonably low if the machine is to be compact, while the importance of a high latent heat of vaporisation and a low specific heat of the fluid should have become clear from the discussion of the changes involved in the working cycle. Safety from fire, explosion and poisoning, together with security of supply and moderate cost, have also to be considered. Barely half-a-dozen fluids have been found to meet these requirements, with reasonable completeness, and of these, only two, NH_3 and CO_2, have received more than a restricted application.

The objectionable nature of ammonia vapour has hitherto precluded its use between decks in the Navy, but in other respects it is probably the most satisfactory of all refrigerants. The critical temperature is some 180° F. above the highest sea water temperature, the plant only slightly more bulky than one using CO_2, while the lower range of working pressures and other factors combine to give an improved Co-efficient of Performance. It is very widely used commercially, both ashore and afloat, for the large machines employed in the preservation of food in bulk, and it is also used in many of the small machines working on the absorption principle which have recently become so popular for shop and household use.

Absorption Machines.—The working basis of these machines is the property of all liquids, some more than others, to take a certain amount of gas into chemical combination with themselves. During this absorption, heat is given off and the new compound possesses less heat than the original component parts. To separate them again, a corresponding amount of heat must be supplied from an external source. The application of these effects to refrigeration is briefly as follows :—

NH_3 (say) and water, which have a great liking for each other, are allowed to unite and the resultant heat to dissipate. The cycle of operations is started by applying heat to the compound, whereupon the NH_3 is driven off as a vapour under pressure. The vapour is freed from particles of water by one or more drying devices, and then goes to a condenser where it is cooled and liquefied. From thence it passes through a regulating valve to an evaporator, where the pressure is reduced and the ammonia re-evaporated with heat drawn from the substance to be cooled. It is then again brought into contact with and re-absorbed by the water from which it was driven off. The resulting compound is returned to the generator by a small pump. The small pump employed for this purpose is the only moving mechanism in the machine, and in at least one type, the "Electrolux," even this is dispensed with.

It will be seen, therefore, that machines of this type are particularly suitable for household use since the only outside requirements are circulating water, which can be taken from a tap, and electric current to drive the motor and supply heat; in practice the two are commonly operated by a single lever.

"Electrolux" Refrigerator.—This is a particularly interesting example, not only on account of the absence of all moving mechanism, but because even the regulating valve is omitted. The indispensable drop in pressure to promote the circulation of the working fluid (although the *total* pressure in all parts of the machine is necessarily the same) is obtained by an ingenious application of Dalton's Law. Dalton's Law, it will be recalled, states that the pressure exerted upon the interior walls of a vessel containing a mixture of gases and/or vapour (provided

they have no chemical action on each other) is the sum of the pressures which would be exerted if each of the gases occupied the vessel alone.

The plant (*see* diagram Fig. 4) consists essentially of a generator, condenser, evaporator and absorber. The generator is, once for all, partly filled with water containing a percentage of NH_3 in absorption. An inert gas, hydrogen, is then added until the pressure in the apparatus is such that condensation of the NH_3 will take place at normal circulating water temperatures. The apparatus is then hermetically sealed. On the application of heat, the NH_3 dissolved in the water is driven off as vapour, passes through a rectifier to separate the water vapour from the ammonia vapour, and is then liquefied in a condenser. The liquid ammonia then flows to the upper part of the evaporator and is met by hydrogen which is continuously transmitted from the absorber. The ammonia flows over a number of discs in the evaporator and vaporises under the influence of the heat drawn from the cold cupboard. The vapour so formed diffuses into the hydrogen, without combining with it, and the mixture, being heavier than the pure hydrogen, begins to sink, and becoming progressively heavier as evaporation of the ammonia proceeds, continues to fall until it reaches the bottom of the evaporator. From thence the mixture flows away through a pipe to the absorber, where it is met by a shower of water, practically free of NH_3, coming from the generator by gravity and trickling over discs in the absorber. This water absorbs the NH_3 in the mixture of ammonia and hydrogen. The remaining hydrogen, being lighter than the mixture, rises and again finds its way to the evaporator, while the compound of liquid ammonia and water is returned to the generator by means of a thermo-syphon. The source of external heat thus performs two functions: first lifting the ammonia liquid from a lower to a higher level, and then splitting it up into its component parts to continue the cycle independently.

Summarising, it will be seen that there are three separate but intersecting circuits—water, hydrogen and ammonia; the ammonia, as it comes in contact with the others, forming in turn a compound with the water and a mixture with the hydrogen. The circulation of the liquids is promoted by external heat and gravity, and that of the gases by gravity. The fall in the vaporising temperature of the ammonia as it passes from the condenser to the evaporator, due to the drop from total pressure to partial pressure, should also be noted.

Naval and Commercial Applications.—Refrigeration, which was first introduced into the Navy for the preservation of food and cordite, has recently been extended to maintaining habitable conditions in those spaces on board ship where collective protection against gas attack is required, and for normalising the temperature of electrical storage batteries and living spaces in submarines. The production of ice for medical and other purposes in the tropics is also claiming greater attention than formerly, and recently the need has arisen for the cooling of water and chemicals required for the development of aerial photographs in aircraft carriers. But in the nature of things the naval applications can never attain to the almost ubiquitous nature of the commercial.

Besides the production of ice and the cooling of buildings, it is not so generally realised that commercial refrigeration is involved in one or more of the essential processes in the manufacture of explosives, beer, chocolate, artificial silk and many other substances. Its paramount importance, however, is, of course, for the preservation of food—fruit, dairy produce, fish and meat. In this field, refrigeration has fostered the growth and specialisation of the population of England until it would now be impossible, financially and practically, to breed or import alive sufficient animals to replace our receipts of chilled and frozen meat from overseas. Conditions, indeed, have become so artificial that it must be recognised that refrigeration is essential to the continued prosperity of the food producing countries and the maintenance of our own.