12TH OCTOBER, 1893.

*REFRIGERATING & ICE-MAKING MACHINERY,

WITH A

DESCRIPTION OF THE LINDE SYSTEM.

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THE intention of this paper is to lay before the Institution a description of recent practice in refrigerating, with a more particular description of that system which the author happens to be connected with. Before proceeding with the subject matter proper, a condensed *resumé* of the earlier appliances used may be given.

The purpose of all refrigerating apparatus is to abstract heat from some particular substance, whether gases, as the air contained in a room ; solids, such as meat, provisions, &c. ; or liquids, as for making ice, the temperature of the agent employed being necessarily below that of the substance to be cooled. In doing this it is apparent that provision must be made for the rejection or dispersion of the heat extracted, or for the renewal of the refrigerating agent, otherwise an equalisation of temperature must ensue, and no further cooling will take place.

In practical working if a machine is to maintain a continuous action, some arrangement has to be adopted, and a complete

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* Although this paper should have been published in Volume IX., it is inserted in this volume by special request, on account of its interesting nature.—ED.

plant for refrigerating consists of an apparatus by which heat is abstracted, combined with a contrivance for rejecting or carrying away that heat and the restoring of the agent to a condition such that it can again be employed.

The oldest method adopted for artificial cooling was that by the use of freezing mixtures, taking advantage of the law that when a substance changes its physical state, and passes from a solid to a liquid state, the force of cohesion is overcome by the addition of energy in the form of heat.

These liquids consisting of certain salts and water, acids, or ice, form liquids where the tendency to pass into a liquid form is so strong that heat is absorbed at a greater rate than it can be supplied from the surrounding substances, and the heat of the melting substances has to be drawn upon, with the result that the temperature falls to a point at which there is a balance, between the rate of melting and the rate at which external heat is supplied.

It was with a mixture of snow and salt that in the year 1726 Fahrenheit considered he had reached the limit of reduction in sensible temperature, and started the notation of his thermometer from 32 degrees F. below the freezing point of water. How far short of the truth he was has been shown by recent experiments when a temperature of actually $0.373°$ F. has been produced by the evaporation of solid nitrogen, and scientists are getting concerned as to whether the theoretical point of absolute temperature—$0.461°$—may not be actually reached and possibly proved to be wrong, the effects of which would be to upset all our present theories on thermo dynamics.

The use of freezing mixtures has never been satisfactorily worked commercially, the few apparatus designed and set to work having been abandoned on account of their expense in working and maintenance, nor is it likely they will ever be of practical value, except for laboratory purposes, where they are extremely convenient, and their further notice is, therefore, not required. There is, however, one form of this method of

refrigeration which has been, and is now, extensively applied, that is the use of ice, either natural or artificially made.   As is well known the melting point of ice is $32°$ F., and this tempera-ture remains constant so long as any ice remains ; any increase of temperature in surrounding substances merely hastens the melting process, the latent heat of the ice being drawn on. This latent heat being 142 6 B.T.U. per lb. of ice, a considerable power of abstracting heat is thus obtained, and utilized in the cooling of rooms, for preserving perishable articles, liquids, &c., but necessarily a freezing temperature can never be obtained in the surrounding substances, and the melting of the ice itself tends to produce a dampness in the atmosphere and on sur-rounding bodies, which has a very deleterious effect on articles it comes in contact with. For this reason, as well as the expense attending its use, ice refrigeration is rapidly giving way to more perfect systems, or in other words, to mechanical processes, though for special uses it may still be employed to advantage. From the, at one time, prevailing use of ice for this purpose, the power of refrigerating machinery has come to be rated in terms of given weights of ice melted per hour.

The attention of engineers and inventors having once been directed to the necessity of some mechanical method of abstract-ing heat, there has been a constant production of different systems and apparatus dating back from about 1755, when Dr. Cullen produced a machine using water evaporated under a nearly perfect vacuum, and followed by many others, the principal being :—Leslie, in 1810, with a machine using sul-phuric acid and water ; Hagen, in 1834, using a volatile spirit of cautchouc ; Dr. Gorrie, of New Orleans, in 1845, using air, and to whom belongs the credit of inventing the cold air machine ; Carré, in 1850, who invented the ammonia absorption process ; Harrison, Twining, and others, shortly after, using ether ; Dr. Kirk, in 1862, with an air machine adapted for making, ice, &c. ; Pictet, Linde, Windhausen, and others too numerous to describe in this paper, up to the present time.

All these apparatus can be classed under two general heads.

A. Machinery employing a permanent gas which having been compressed is cooled under compression, further cooled by doing work, expanding behind a piston, then this cooled gas is utilized for the extraction of heat.
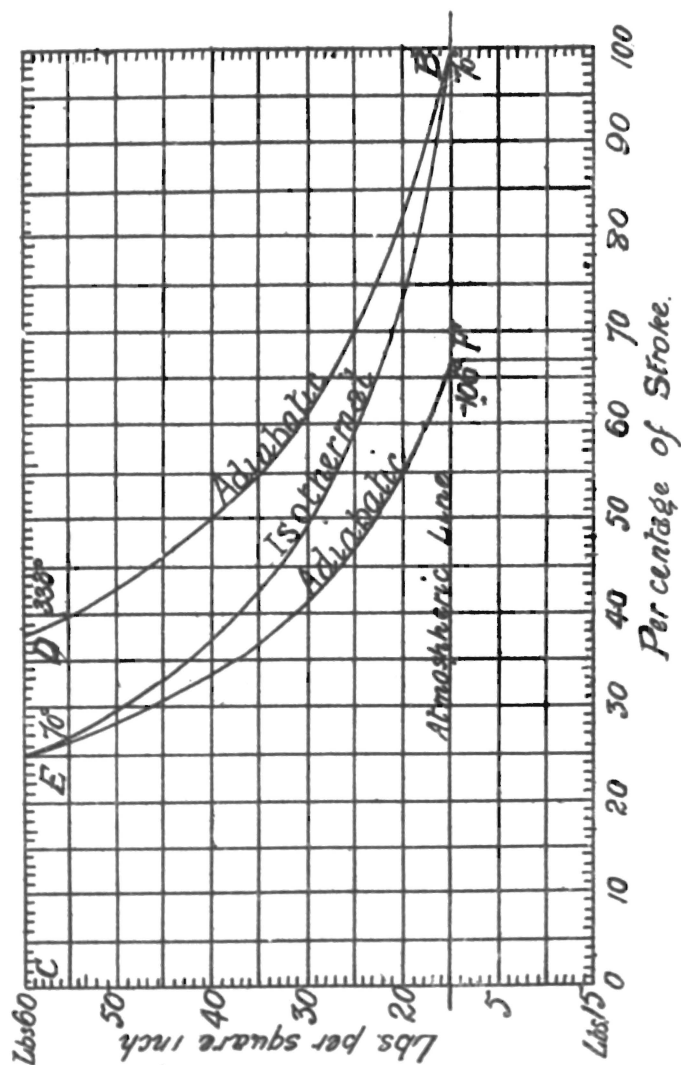
B. Machinery and apparatus employing a volatile liquid the evaporation of which is utilized for the abstraction of heat.

The author has as a matter of convenience taken class " A " first in description, although machines of this system are not the oldest, but for the reason that this system has been developed to serve a special purpose and to meet special conditions, particularly the one being used on ship board, where it was considered impracticable to employ chemical refrigerants.

About the year 1878 the great advantages to be gained by the transportation of the abundant meat supplies in the colonies and America to the large European markets, led to the rapid developments of this system, and not only was it extensively adopted on board ship, but, owing no doubt to its novelty, also frequently used on land ; lately, however, the great advantages of chemical apparatus have been tending to supersede it both for land and ship work.

As air is practically the only gas which is employed in machines of this class, reference to it only is made here. The principle on which a machine of this class works is that its capacity for performing work depends entirely upon the temperature, increase of pressure merely placing the air in such a condition relative to some other pressure as to enable advantage to be take of its intrinsic energy by expansion. If the air is compressed under a frictionless piston, without gain or loss of heat from external sources, it is raised in temperature to an extent measured by the thermal equivalent of the mechanical work expended in compressing it, and if the compressed and heated air is then expanded down to its original pressure again, without gain or loss of heat from external sources, behind a frictionless piston as before, it will resume its original temperature and will

DIAGRAM 1.

Diagram showing curves labeled Adiabatic, Isothermal, Adiabatic, and Atmospheric Line. Y-axis: Lbs per square inch (with markings 5, 20, 30, 40, 50, 60 Lbs; Lbs15). X-axis: Percentage of Stroke (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100). Points labeled C, E, D, B, with values -100 lbs, 70, 15.

have given back, while expanding, exactly the mechanical equivalent of heat acquired during the time it was being com- pressed. But if the air when in a state of compression is cooled down by some external source, by the extraction of some of its sensible temperature, its intrinsic energy will be reduced and the work performed in afterwards expanding will also be reduced, and after expansion the air will occupy a less volume than it did before compression, and its temperature will fall below the initial temperature in the direct proportion of the reduction in volume; and by this method very low temperatures can be obtained. This is shown graphically in the diagram (Diagram 1), using the relations of volume, pressure and temperature, as

$$\frac{P^1}{P} = \left(\frac{V}{V^1}\right) 1{\cdot}408$$

$$\frac{T^1}{T} = \left(\frac{V}{V_1}\right) {\cdot}408$$

$$\frac{T}{T_1} = \left(\frac{P^1}{P}\right) {\cdot}29$$

where A.B. represents a volume of gas at atmospheric pressure and a temperature 70° F. This gas is compressed under a piston to the volume C.D. 60lb. absolute pressure according to the adiabatic curve B.D. rising to a temperature of 333° F., and if then expanded back to its original pressure, adiabatically, performing work on the piston it would resume its original temperature, but, if the hot compressed gas is cooled from external scources by the extraction of some of its sensible tem- perature, under a constant pressure to a temperature of 70° F. and a volume C.E.. and then expanded along the adiabatic curve to the original pressure and a volume A.F., the final absolute temperature of the expanded air will then be lower than the absolute temperature of the original volume, in the same proportion as the temperature of the compressed air was reduced thus :

$$461 + 333 : 461 + 70 : : 461 + 70 = \frac{531 \times 531}{794} = 355 = 461 - 355 = -106°$$

the theoretical temperature of the expanded air, and the work

restored during expansion is considerably less than that used in compression. the difference representing mechanical work which would have to be employed to complete the cycle. Thus it will be seen that for a given temperature of compression, the heat abstracted from the compressed air is the sole measure of reduction in the temperature after expansion. The same result can also be obtained with an expenditure of less power if the compression is done on the isothermal curve, but in this case the cooling of the air must act during compression, and the expansion would be adiabatical as before. This is shown on the diagram as the curve B.E. for compression curve and E.F. for expansion, the energy expended in the compression here is considerably less, because the temperature of the gas is not allowed to rise during the compression. The difference between the two curves representing so much less power required to drive the piston in the case of the isothermal compression than in the adiabatic. Although the calculations show a temperature of 106° as above, such a low temperature is never obtained in practice, the usual being about 50° F., as the air in expanding absorbs a certain amount of heat from the walls of the cylinder and friction.

This explanation would be all that is necessary to arrive at the effect to be produced by mechanical refrigeration, using air as an agent, if the air consisted wholly of oxygen and hydrogen, but such a condition is never met with in practice ; as the air always contains a considerable amount of aqueous vapour, which sometimes exists in sufficient quantity to fully saturate it at its ordinary temperature and pressures, and exercises an important influence on these effects, because at any given temperature a volume of saturated air can only contain a definite amount of vapour, and if from any cause, additional moisture be present, it cannot exist as vapour, but appears as water in the form of fog or mist. The capacity of the air for holding moisture is also affected by pressure, an increased pressure reducing this capacity in direct proportion. The influence of this on machines using

air is apparent in that this moisture in the air increases the pressure during compression, and during expansion as the temperature of the air is reduced below the point at which the air will hold the moisture in solution, it is deposited in the form of water, and forms snow or ice in the cylinder or passages.

This is one of the great obstacles to be overcome in these machines, necessitating some appliance for condensing this moisture before the air is expanded.

A machine of this class, therefore, consists of a compression cylinder (in combination with a condenser or some arrangement for carrying off the heat during compression, or after it, or both), and an expansion cylinder, the two cylinders being so arranged as to take advantage of the air while expanding to give back some of its mechanical work to assist compression, and that given back in expansion, plus the friction of the machine, must be supplied from some external source of power, such as the steam engine, gas engine, &c.

The first machine manufactured on this system, about the year 1845, utilised compressed air at a pressure of 4lbs. per square inch, allowing it to flow into the atmosphere through a small nozzle, the reduction in temperature being stated at about 29 degrees F. This never went beyond mere experiment. Dr. Gorrie's machine, brought out in 1845, was the first to use a compresser, cooler, and expansion cylinder, but no great advances were made until the late Dr. Kirk produced his machine, about the year 1862, which utilised the air in a complete cycle, compressing it at one end of the cylinder and expanding it at the other, the heat of compression being carried off from the water jacketted cylinder cover, and also in a regenerator. From this date considerable improvements have been made, those of Windhausen, Bell-Coleman, Goodfellow, Haslam, Hall, and Lightfoot being the most important and successful. All of these machines work practically on the same basis, with modifications for getting rid of the contained moisture in the air, in order to obviate, as much as possible,

the practical evils resulting from its condensation and freezing.

It is not within the scope of this paper to enter into a comparison of the merits of the different machines, but the author merely wishes to remark that these machines having been produced, as before mentioned, to meet a special purpose, are now being rapidly supplanted by machines using chemical refrigerating agents, the chief reasons for which is the enormous power required to produce a given refrigerating effect, due to the low specific heat of air, which is only ·283, necessitating an enormous quantity being compressed in a given time. This means a boiler power and consumption of fuel which is now admitted to be from four to seven times that required by the best machines working on chemical systems. The great trouble arising from the presence of aqueous vapour in the air necessitating cumbersome and expensive condensers, also that the air being delivered at, on an average, a temperature of 55° F. below zero, therefore causes, from reasons already explained, the continuous presence of fog or mist in the air passages and rooms which are being cooled, entailing continuous attention in keeping these clear; it also causes a deposit of frost or snow on the articles being frozen, and tends to produce a dampness and clamminess on their being introduced to a warmer temperature. Another objection they labour under is, that the air which is delivered from the machine into the rooms to be cooled has been in actual contact with the inside of the compression and expansion cylinders, and there, meeting with the lubricants employed for the reduction of friction, gets contaminated and acquires a flavour which produces a mustiness and closeness in the rooms.

System A.—The principle on which machines of this system do their work, is that when a liquid changes its physical condition from a liquid to a gas, heat is absorbed without producing a change in the sensible temperature, or, in other words, this change can only be brought about by the acquirement of heat, and this heat is termed the latent heat of vaporisation.

For the purposes of refrigeration it is apparent that, other

things being equal, that liquid is the best, which has the highest heat of vaporisation, because it allows of the least quantity being dealt with to produce the effect required. But the amount of this latent heat varies considerably in different liquids, and even for the same liquid to a certain extent, according to the temperature and pressure at which vaporisation occurs, and also in the conditions under which the change can be effected, thus causing other considerations than the latent heat to be taken into account in the selection of a refrigerating agent to be used under this system.

Those which chiefly influence this selection are :—

1. The latent heat of the agent when changing from a liquid to a gas.

2. Temperature and pressure at which such change can be effected.

3. The specific heat of the liquid.

It is essential that not only must the latent heat of the liquid be high, but also that its specific heat should be low in proportion to its latent heat.

That refrigerating agent which gives the best combination, taking all things into consideration, of these conditions, will be the one to select as the liquid for employment to gain highest economy for given results.

In order to avoid the renewal of the liquid it is necessary to deprive it of the heat acquired during vaporisation, and as this rejection of heat can only take place while under pressure, if the temperature of the gas is above that of the cooling body which carries off this heat (which is always water), it is important that the liquifying pressure of the gas, at the temperature of the cooling water available, should be as low as can possibly be obtained without sacrificing other requirements.

Again, as the liquification of the gas is effected by cooling water, which may be as high as 90 F., and the temperature of the liquified agent will be say 100° F. above this, it is obvious that a portion of the cold produced in evaporation must be expended

in reducing the temperature of the liquid itself from this tem-
perature, down to the temperature corresponding to the pressure
at which it is evaporated, which may be below zero F., that is,
the liquid will draw on itself to supply heat to the amount
depending on the extent of the difference between the two
temperatures. It is, therefore, of absolute importance that the
agent should give off relatively little heat in being cooled, or, in
other words, that its specific heat should be low in proportion to
its latent heat.

To make this perfectly clear, suppose we take a liquid with a

Specific heat ...   . $S = 1$
Latent heat of vaporisation .. $H = 150$
Temperature of liquid   ... $t = 100°$ F.
$H—(t—t_1)$ ...   . $S = E$
Temperature of evaporation $t_1 = 0°$ F.
Available theoretical efficiency $E =$
$\therefore E = 150—(100—0)\ 1 = 50 = 33\%$

or 66 per cent. has been uselessly expended in cooling the liquid
itself. This serves to show that a liquid with the highest latent
heat is not necessarily the best refrigerating agent, nor that one
with a low latent heat is necessarily bad.

The point to be aimed at to get the highest efficiency and
economy is that the difference between the latent heat and the
temperature at which the agent is liquified, minus the tempera-
ture of evaporation, multiplied by the specific heat of the liquid
itself is large.

Diagram 2 has been prepared to further explain these points
and shows the curves of vapour tensions or corresponding tem-
peratures and pressures of most of the agents employed.

Diagram 3 shows the latent heat of some of these agents at
different temperatures. Thus water has an extremely high
latent heat, 966 B.T.U. at 212° F., but as its vaporising point
at atmospheric pressure is also high, evaporation at such
temperature as would enable it to be used for refrigerating
purposes can only be effected under an almost perfect vacuum,
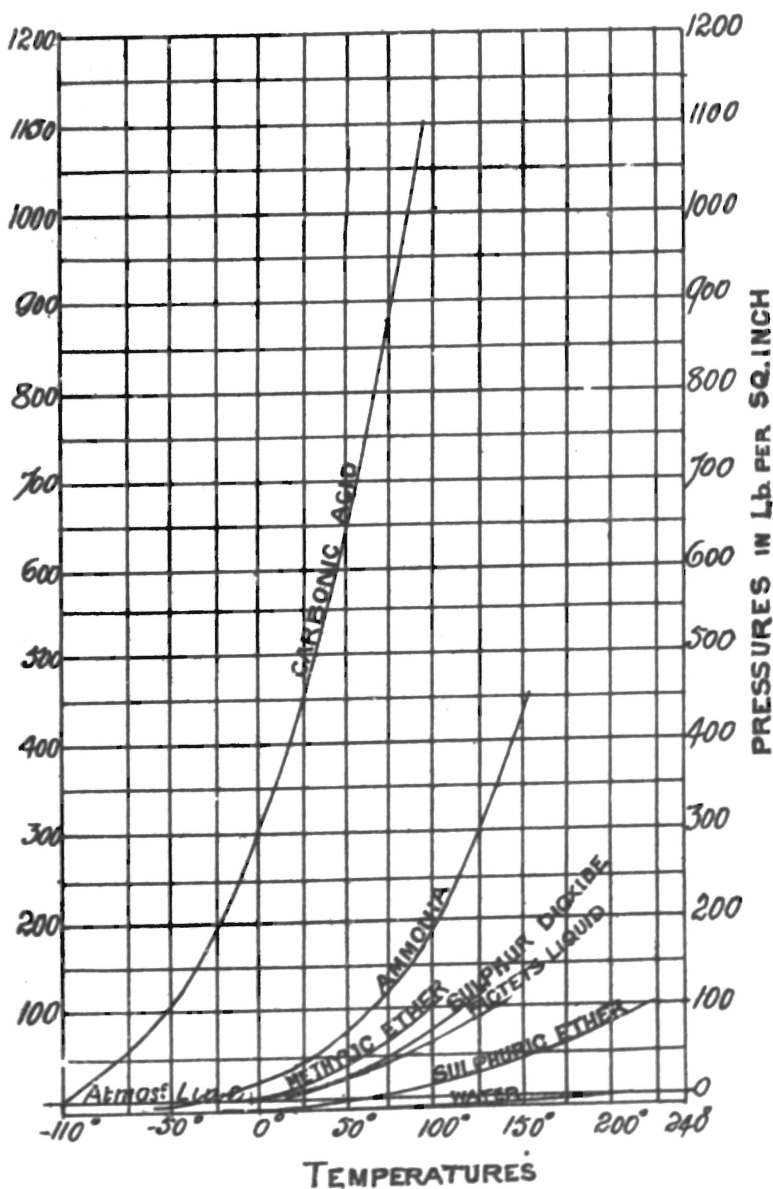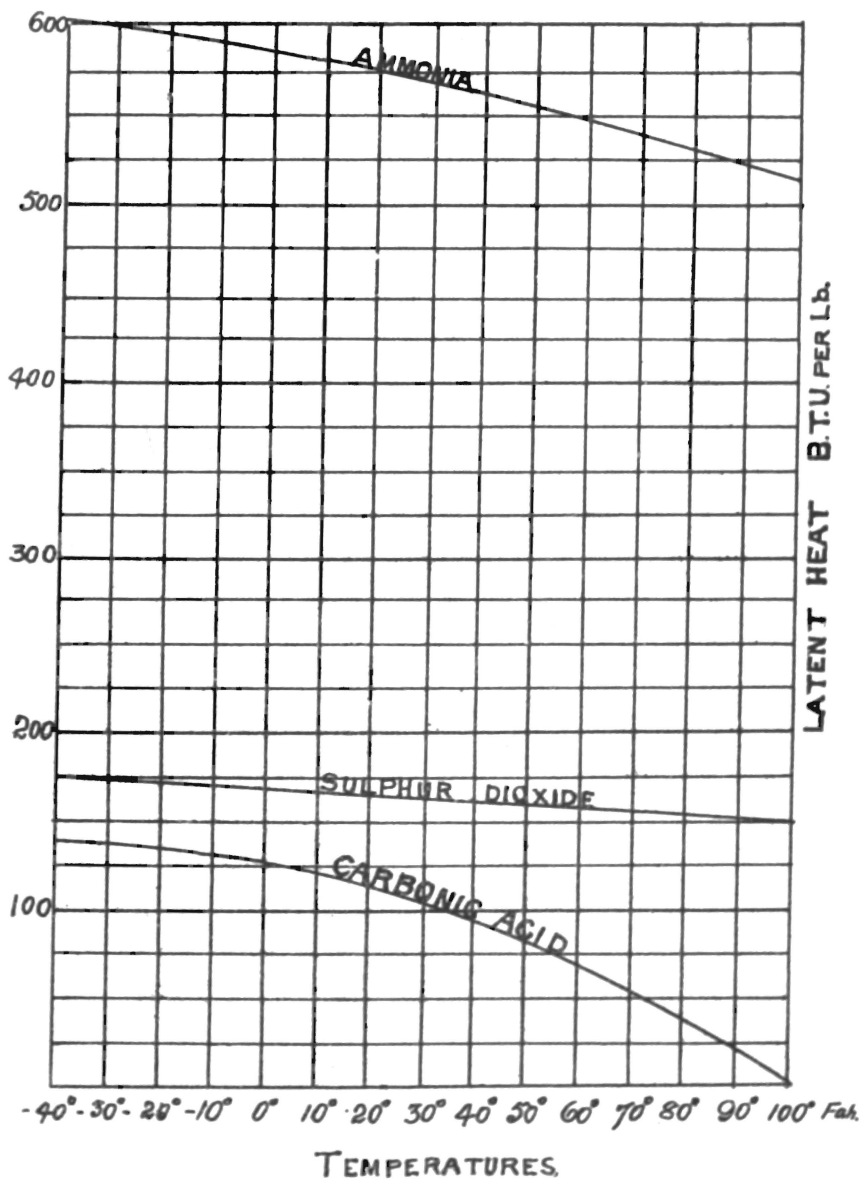
DIAGRAM 2.

DIAGRAM 3.

AMMONIA

SULPHUR DIOXIDE

CARBONIC ACID

LATENT HEAT B.T.U. PER Lb.

600

500

400

300

200

100

-40° -30° -20° -10° 0° 10° 20° 30° 40° 50° 60° 70° 80° 90° 100° Fah.

TEMPERATURES.

see Diagram 2 where the tension is only ·089 per square inch at a temperature of 32° F., this has put its use out of practical consideration, the few machines made to employ it have proved too cumbersome and delicate for general work.

Sulphuric ether, methylic ether, sulphur dioxide have been used to a considerable extent, and their curves of vapour tension are shown on Diagram 2.

Each of these liquids possess very much the same properties as regards efficiency as a refrigerating agent, the principal feature in their favour being that the point of liquification is at 90° F., more or less, between 100lbs. per square inch above atmospheric pressure, but their comparatively low latent heat, and comparatively high temperature at atmospheric pressure, has also prevented their extensive adoption, the most extensively adopted has perhaps been ether, a large number of machines having been at one time constructed employing it.

Pictet's liquid—A mixture of about 3 per cent, carbonic acid and 97 per cent. sulphur dioxide, the vapour tensions of which, as shown on Diagram 2, are very much the same as ether and sulphur dioxide, though somewhat below it for temperature above 78° F. The latent heat of this fluid has not been definitely ascertained, but from actual tests of machines using it, the efficiency has not been found to be much above that of ether, or pure sulphur dioxide.

The advantages of low pressure with these agents are counterbalanced by the necessity for the quantities to be dealt with being proportionately large, which means heavy and cumbersome machinery, it is this which has more than anything else led to the disuse of them for refrigerating purposes.

Carbonic acid—Is a liquifiable gas under pressure, and now easily obtainable as a liquid, and its production is very simple, the cost is small commercially. As a gas it is colourless, and while not being actually poisonous to animal organisation, will destroy life because it does not contain any oxygen, that is, it would be impossible for any living animal to exist in a closed

chamber if there were present any large percentage of it, as a candle flame will be extinguished in air containing only 4 per cent. of carbonic acid.

The curves or vapour tensions or corresponding pressure and temperature is shown on Diagram 2, and on reference to it is seen that the evaporating point at atmospheric pressure is— 108° F. while at a temperature of + 86° F., the pressure rises up as high as 1080lbs. per square inch.

The latent heat of vaporisation of carbonic acid has been found to vary very considerably with its pressure and sensible temperature, the higher the temperature the lower the latent heat, as on Diagram 8, varying from about 186 B.T.U. at a temperature of—22° F. to about 25 B.T.U., at a temperature of 86° F.. this affects its value as a refrigerating agent considerably, and,but taken in conjunction with its specific heat, shows that its efficiency is very low. Working out the theoretical efficiency as before taking the

$$Specific\ heat \qquad\qquad S. = \ \cdot 88$$
$$Temperature\ of\ evaporation \quad t. = \ \ 0\ F.$$
$$Latent\ heat\ of\ evaporation\ as \ \ H. = 125\ B.T.U.$$
$$Temperature\ of\ the\ liquid \quad t_1 = \ \ 90°\ F.$$
$$E. = 125 - (90-0)\ \cdot 88 = 46.$$

that is, only 46 B.T.U. are available for refrigerating work per lb. of liquid evaporated, equal to an efficiency of 36·8 per cent., or 64·2 per cent. has to be uselessly expended in cooling the liquid itself, and as the latent heat decreases as the temperature rises, it is patent that when being used under tropical conditions the capacity for useful work is reduced. There is, however, to be set off against this the fact that the density or weight of one cubic foot of the gas is very high, being as much as 3·5 lb. at 0° F., thus reducing the size of the compresser to very small dimensions, this again being counterbalanced by the excessively high pressure of the gas as before referred to on Diagram 2, being for a condenser pressure of say 90° F. 1,110lb. per square inch, which is 6·75 times greater than that which is reached by

ammonia. This requires the machinery to be unusually strong, and that very special arrangements be made for the packing of glands, &c., it being no small matter to prevent a leakage from a piston rod gland even at the suction pressure of 300lb. per square inch. Taking these points into consideration, there does not appear to be any good grounds for the employment of this agent, though there are machines for its use now being manufactured both in England and America, but its suitability is still a matter for decision.

Ammonia—now obtainable as an article of commerce, in its anhydrous form, is a gas which is easily liquified and remains a stable liquid ; it is not inflammable, and a mixture of air with it is inexplosive. The vapour tensions or corresponding pressures and temperatures are shown in the curve on Diagram 2, from which it is seen to have at atmospheric pressure a boiling point of $27 \cdot 5°$ F. below zero, and at a temperature of $90°$ F. corresponding to that most likely to be met with in work in these colonies—a pressure of about 170 lb. per square inch.

The latent heat of ammonia varies, as shown in Diagram 3, only to a comparatively small amount, from about 600 at a temperature of $40°$ F., decreasing as the temperature and pressure increase to 573 at a temperature of $104°$ F.

Ammonia gas is also very soluble in water, which is able to absorb about 700 times its volume of ammonia, and this fact is of great importance in a refrigerating machine using it, since the presence of any water in connection with the ammonia, or if the ammonia is not " anhydrous," reduces its efficiency as a heat-extractor to a great extent. The specific heat of liquid anhydrous ammonia is given as $\cdot 886$ according to latest researches. The theoretical efficiency of it as a refrigerating agent using our former formula is therefore

$$600 — (90—0) \cdot 88 = 520 \cdot 8 = 86 \cdot 5 \text{ per cent.}$$

giving $520 \cdot 8$ B.T.U. available for refrigerating work per lb. of liquid, or that only $11 \cdot 5$ per cent. is expended in cooling the liquid itself when being evaporated.

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