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REFRIGERATION

AN ELEMENTARY TEXT-BOOK

BY

J. WEMYSS ANDERSON

M.ENG., M.INST.C.E., M.I.MECH.E.

LONGMANS, GREEN, AND CO.
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INTRODUCTION

In dealing with a subject which has become so important, not only in the development and working of many industries but in connection with the distribution and preservation of our food, it has been thought advisable in an elementary text-book to consider general principles only, such questions as history and design being eliminated as belonging to a more advanced volume.

The object of *Refrigeration* is to produce low temperatures, *i.e.* to make certain masses of matter colder than their surroundings by *extracting heat* from them. Heat will naturally pass or *flow* from a substance warmer than its surroundings, but if it is to be made *colder*, heat must be removed or *pumped* from it. This is the function of a refrigerating apparatus, which may, therefore, be regarded as a *heat pump*.

We have a complete analogy to this manner of regarding heat in the case of water, which will readily flow from a high to a low level, but if it be desired to transfer water from a low to a high level it must be lifted or *pumped*, and for this pumping, *work* must be performed, *i.e.* energy must be expended; the amount so expended will depend on the quantity of water and the height through which it has to be raised.

It is the same with heat pumps (refrigerating apparatus) —they require the expenditure of energy in order to drive them, the amount of energy depending on the quantity of heat removed and the *height* through which it is raised.

The foregoing indicates that the science of "Heat" should claim the first consideration of the student in

Refrigeration, particularly in its effects upon matter, its measurement, the transference of heat from substance to substance direct and also through intervening media, and the elementary ideas of the more important laws which have been established.

"Heat" in this volume is so treated and used as an introduction to "Refrigeration," examples being selected as far as possible from practice.

The Metric system has been used in the introductory chapters, in addition to the general use of the British standard; the student should make himself thoroughly familiar with both systems.

The characteristics of air and water are so important in Refrigeration, as to merit special attention to their general physical properties, and a short chapter is therefore devoted to them.

A few exercises and problems have been included, and among the questions will be found some set by the Board of Trade in their examinations for Engineers, indicated by the letters B.T.

The Author's thanks are due to most of the leading manufacturers of refrigerating machines, who have willingly supplied drawings, photographs, and blocks of their specialities. A list of these firms is appended to the Index.

The Author further acknowledges the help received from his (former) pupil, Mr. A. Guest, B.Eng., Stud.Inst.C.E., in the preparation of some of the diagrams. With but few exceptions, the blocks have been specially prepared by the Publishers for this work.

J. WEMYSS ANDERSON.

February, 1908.

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CHAPTER I

HEAT AND ITS EFFECTS—THERMOMETERS

"MATTER" is anything that can be perceived by the senses and at the same time possesses inertia. Matter can exist in three different forms—as a solid, a liquid, or a gas, the two latter being included under the term **Fluid.**

A *solid* body is one which has a definite shape and endeavours to retain it.

A *liquid* has no definite shape in itself, and requires to be kept in a vessel (not necessarily closed) to which it adapts itself with respect to shape.

A *gas* requires to be kept in a vessel completely closed, as it possesses the property of expanding indefinitely.

The three classes of matter have each their own characteristics, generally termed "properties," the more important—common to all—being that "Matter must have mass (weight), and is thereby capable of possessing inertia, heat, and motion, and transferring the same."

A mass of matter may successively exist as a solid, a liquid, and a gas. Thus a piece of ice (solid) if heated, will melt and form water (liquid), and if still heated, will evaporate into steam (gas). If heat be removed from the steam, water will again be formed, and a further removal of heat will bring the matter into the form of ice. In each state the weight will be constant. The addition or extraction of heat not affecting the weight of a body, at once establishes the fact that heat does not possess mass.

Heat, as we have thus seen, plays an important part in the *condition* of matter, and as the change from one condition to another is of the utmost importance in dealing with our subject, we must consider "Heat and its Effects."

Heat.—A quantity of matter may be regarded as being made up of very small particles called "molecules," which, even in the coldest body, are in a state of agitation. If by any means this agitation is increased, the body becomes warmer, and may eventually reach the condition termed **hot.** For example, if we take a piece of wood and rub a small piece of metal upon its surface, the surfaces will become heated, because *energy* has been expended, a portion of which has been utilized in *increasing* the *agitation* of the *molecules*, and the metal (and wood) possesses *energy in the form of heat*, or, as it may be called, **heat-energy**, or **molecular-energy**.

The effects of increased or decreased agitation of the molecules are generally considered under—

Effects of Heat.—The effects of heat on matter may be classified as follows:—

1. change of size,
2. change of state,
3. change of temperature.

A change of size may occur without a change of state, but the latter is invariably accompanied by the former.

A change of size follows as the result of an increased or decreased agitation of the molecules referred to in the definition of heat, *i.e.* the dimensions change with the *intensity of the heat*, generally termed **Temperature**, that is, if the body does not change its state. Thus, if a body changes its size but not its state, in consequence of heat being applied or removed, its temperature must also have changed. This important fact is utilized, as we shall afterwards see, in comparing the relative intensities of heat in two or more bodies, *i.e.* the *size* of a quantity of matter is taken to determine the *temperature*.

Change of Size.—All bodies expand when heated and contract when cooled. This is clearly indicated by the apparatus shown in Fig. 1.

A is a metal tube with water-tight connections at either end. Let cold water circulate through the tube, and bring the pointer to zero on the scale by means of the screw B. If warm water be now sent through, the pointer will take up a new position as indicated by the dotted lines. If cold water be again circulated, the pointer will rapidly fall back to zero. Should warm water be again substituted, but the pointer fail to reach its former position, we know the water is not so warm as previously. On the other hand, if the pointer should reach a higher index, we can safely conclude that our second quantity of water was warmer than the first, so we have a simple method of testing the relative *temperatures*.

Under the action of the cold water the tube attained a definite length. With warm water circulating through it, the metal of the tube would acquire a higher temperature and *expand*—the higher the temperature the more the expansion. The increased length acting through the simple lever would make the end of the pointer move through an arc whose length would be *proportional* to the *increase* of *temperature*.

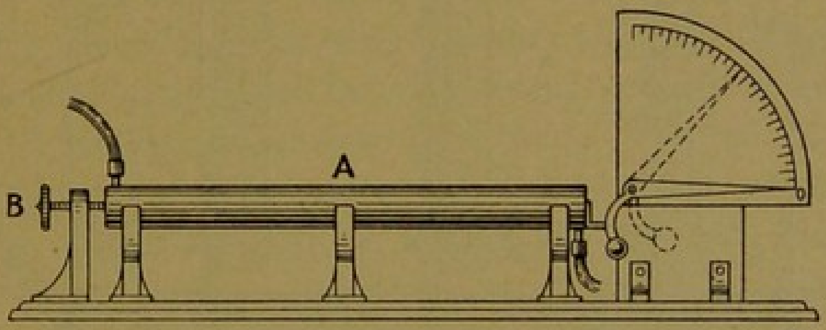


FIG. 1.

Another very instructive experiment is to take three bulbs having stems as indicated in Fig. 2. Fill these respectively with alcohol, turpentine, and water, and regulate the quantities, that when placed in cold water the liquids shall all be of the same height. If all three be now placed in tepid water, it will be seen that the liquids rise in the stems, ultimately coming to rest at different heights in the following order, viz. alcohol, turpentine, water—alcohol being the highest. On replacing the bulbs in the cold water, the three liquids will return to their original levels.

Two important facts have been established by this experiment—

(1) that liquids expand when heated and contract when cooled;

(2) that liquids, bulk for bulk, do not expand and contract equally.

Change of State.—We have already seen, in dealing with matter, that a piece of ice if heated will form water, thereby changing its state. At the same time it changes its size, the water occupying less space than the ice. The converse, of course, holds good, for ice occupies a greater space than the water from which it has been formed.

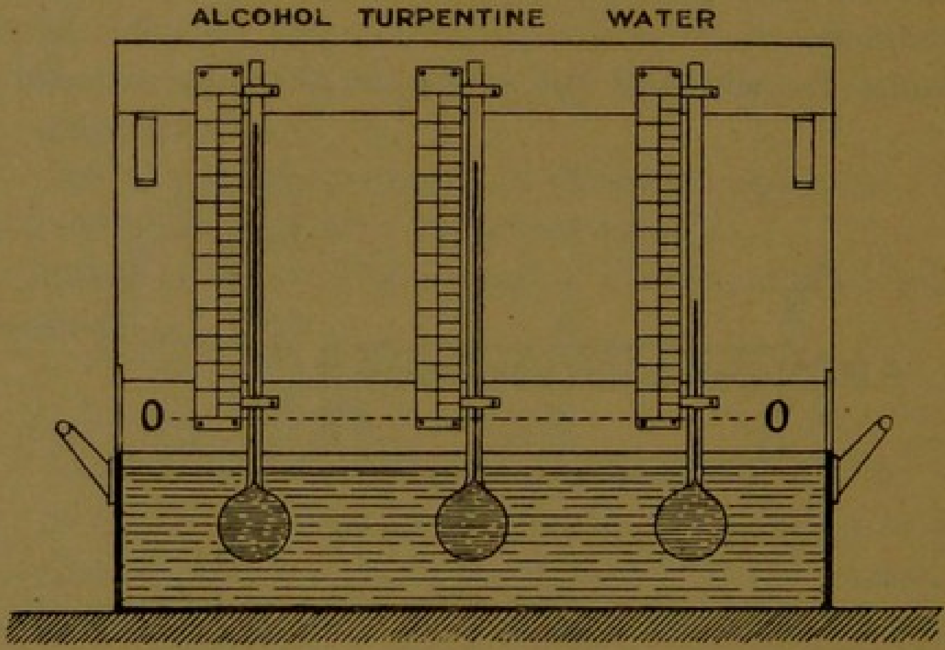


Fig. 2.

If ice is just at *melting point, it may be converted into water at exactly the same temperature,* i.e. the heat expended has been all employed in *changing the state.* Water at freezing point may be converted into ice at the *same* temperature by *extracting heat* from it, the result of such extraction being to change the state. The effects of heat may therefore be summarized as follows: The addition or extraction of heat to or from a mass of matter will *always* result in a *change of size.* The changes of temperature and of state may or may not occur, but a change of temperature or of state *must* accompany the change of size.

Change of Temperature.—Temperature is the term employed—as already explained—in registering the *intensities of heat* in quantities of matter; it in no way, taken alone, indicates the *quantity of heat* a body contains, in exactly the same way as the pressure of steam in a boiler gives in itself no idea whatever of the *quantity* of steam the boiler contains.

Thermometers.—A thermometer is an instrument designed to indicate temperature. Its construction is based upon a knowledge of the properties of matter, and any property which has been found to vary with the temperature can be employed, such as the linear expansion of solids (Fig. 1), cubical expansion of liquids (Fig. 2) or gases. Thus the primary element employed in their construction may be either a solid, a liquid, or a gas. Electrical properties are also employed to indicate temperature, one great advantage being that the indication can be carried any reasonable distance by means of wires; the temperature of a cold storage may in this way be indicated in the engine room.

Construction of Thermometers.—The usual thermometers are those in which the cubical expansion of mercury or alcohol (the latter coloured red) is arranged to give the desired indications on a plan similar to the experiment illustrated in Fig. 2, the top of the stem being closed to prevent loss of liquid, and to ensure that no foreign matter enters the tube.

Mercury Thermometer.—A small bore tube with a bulb at one end is filled with mercury, and the whole heated to a temperature above that which the thermometer is eventually to indicate. A flame is then directed to a point near the plain end, and when the glass fuses the tube may be hermetically sealed. As the tube cools, the mercury will gradually fall, and at any moment the height is an indication of a certain intensity of heat. In its future use, care should be taken that the highest temperature originally selected is not exceeded or there will be a danger of the tube bursting.

Determination of the Fixed Points.—The positions taken up by the mercury at various temperatures are *compared* with those of two known temperatures, viz. the melting point of ice and the boiling point of water, under ordinary fixed conditions.

The former or lower fixed point is obtained by surrounding the thermometer with very small pieces of ice as shown in Fig. 3.

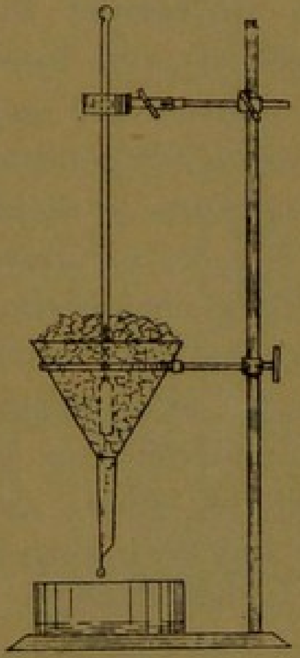


Fig. 3.

When the mercury becomes steady, the glass should be marked with a file or etched at the exact height.

The second or higher fixed point may now be determined by placing it in a special apparatus, illustrated in Fig. 4.

It will be noted that the steam generated from the boiling water comes in contact with practically the whole of the tube, care being taken that the generation of steam is not excessive nor above atmospheric pressure, and that the whole is jacketed to prevent undue influence of the comparatively low temperature of the atmosphere. The height attained by the mercury under these conditions is also marked on the stem. The thermometer would now appear as indicated in Fig. 5—the mercury taking up an intermediate position depending on the temperature of the air.

Graduations of the Thermometer.—The stem of the thermometer shown in the above figure should be divided between the two fixed points—for accurate comparison—into a number of equal spaces called *degrees*, the finished tube being termed the *scale*.

There are three Thermometric Scales.

1. The *Fahrenheit*, in which the distance between the two fixed points is divided into 180 degrees, the lower one being designated 32 (usually indicated as 32° F.), the higher point being 32 + 180 = 212° F.

2. The *Centigrade*, where the distance is divided into 100 degrees, the lower point being 0° C., the higher will consequently be 100° C.

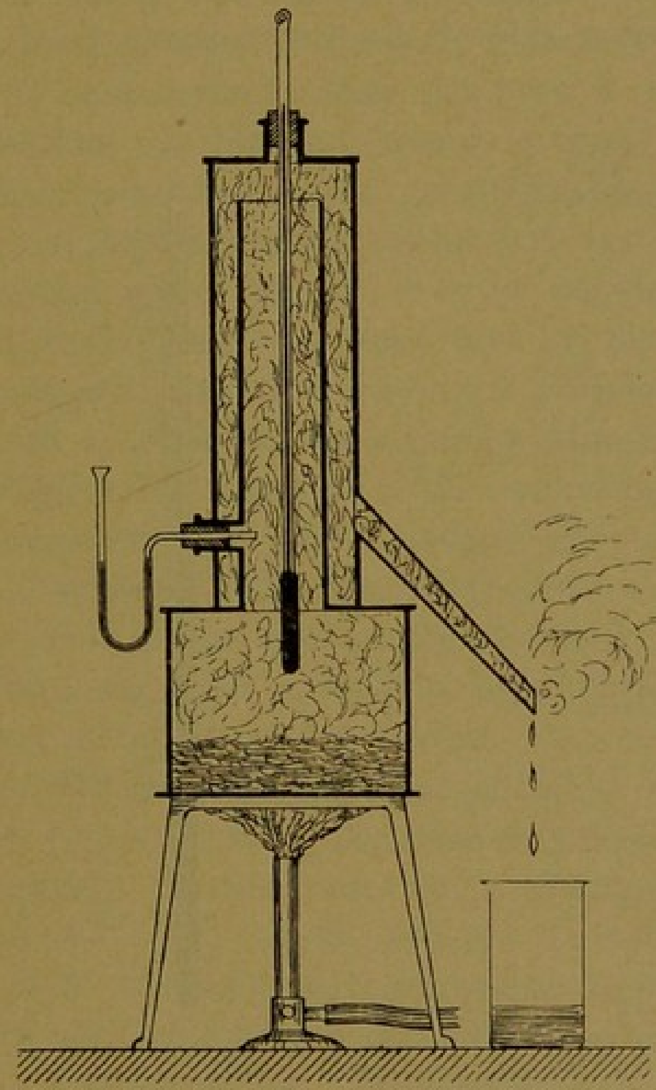


Fig. 4.

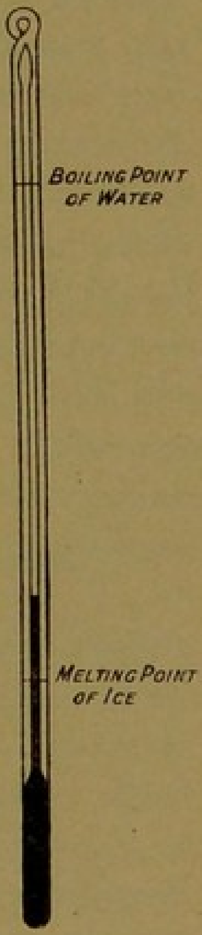


Fig. 5.

3. The *Réaumur*, in which the lower point is 0° R. and the higher 80° R.

The Fahrenheit scale is commonly used by English-speaking people. The Centigrade scale is universally employed for scientific work, and its decimal system of division has much to recommend it. The Réaumur is used in some parts of Europe, but it will not be further referred to.

The stem of the thermometer, as shown in Fig. 5, may be divided in three different ways according to the type of thermometer required, or it may be divided — and frequently is—into the two general scales, Fahrenheit and Centigrade, one or either side of the centre line. Such a thermometer is useful for purposes of comparison, and is represented in Fig. 6.

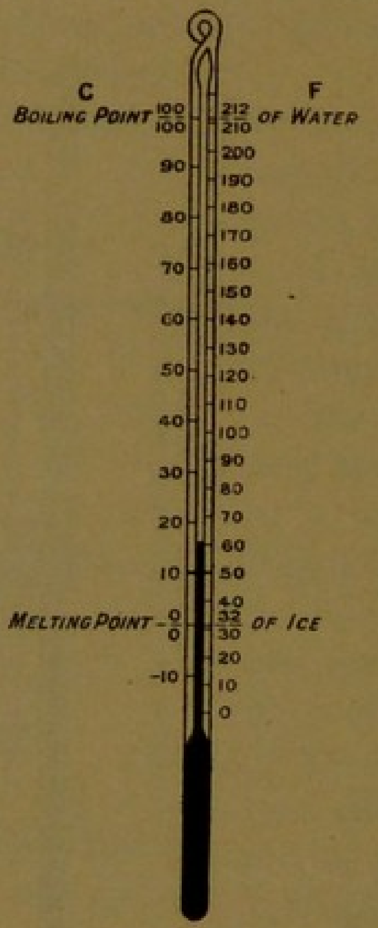


Fig. 6.

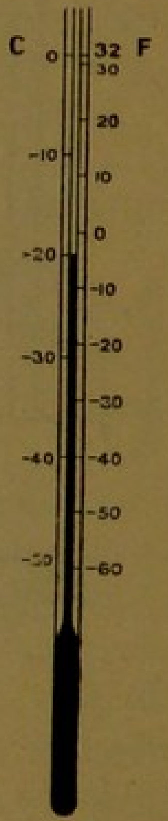


Fig. 7.

In the Centigrade scale, the lower fixed point is conveniently called 0°. Now, clearly the melting point of ice (freezing point of water) is not the lowest temperature that can be obtained. Similarly, 32 degrees below 32° F. or 0° F. is not the *absolute zero of temperature* (an expression which will be discussed later). Temperatures lower than

0° C. and 0° F. have the "minus" sign prefixed—such as −40° C., −40° F. Fig. 7 shows the graduation below the lower fixed point.

Standard Thermometers.—The construction of the mercury thermometer, as indicated in this chapter, requires a great deal of skill and experience in carrying out, and certain corrections and allowances have to be made. For example, in the division of the length between the fixed points, it has been assumed that the bore of the tube at all cross-sections was the same, which is by no means a safe assumption for accurate work. Further, cheap thermometers may be in error by having their divisions marked on the wood casing, which should only be employed as a protection. It is therefore important that all thermometers should be compared with what are termed *Standard Thermometers,* each with a certificate for accuracy, obtained from the National Physical Laboratory. The errors of each thermometer, compared with the standard, should be noted and due allowance made when temperatures are read. For use in cold stores a thermometer with an open scale about the lower fixed point is to be preferred. For engine-room use, metal cases are essential.

Alcohol Thermometers.—Alcohol thermometers cannot be constructed in the manner previously described where mercury is used, as alcohol changes its state (boils) at about 78° C. or 22 degrees C. below the higher fixed point. A standard thermometer is therefore employed in its construction, by which means the stem can be graduated.

Self-registering Thermometers.—It is a matter of great importance in most cold stores that an even temperature should be maintained, and, for the purpose of regulating and checking, a self-registering thermometer may be employed. The *principle* of the construction of this type is shown in Fig. 8. A is a lever having its fulcrum at B, and a pencil or pen at O. A piece of metal—or any definite mass of matter—C, is so arranged that when changing its size, owing to increased or decreased temperature, it moves the point O an amount proportional to the total length of the lever and the distance CB. By comparison with a standard thermometer, the apparatus can be calibrated and marked as indicated. The maximum and minimum temperatures reached will be shown by an arc of a circle.

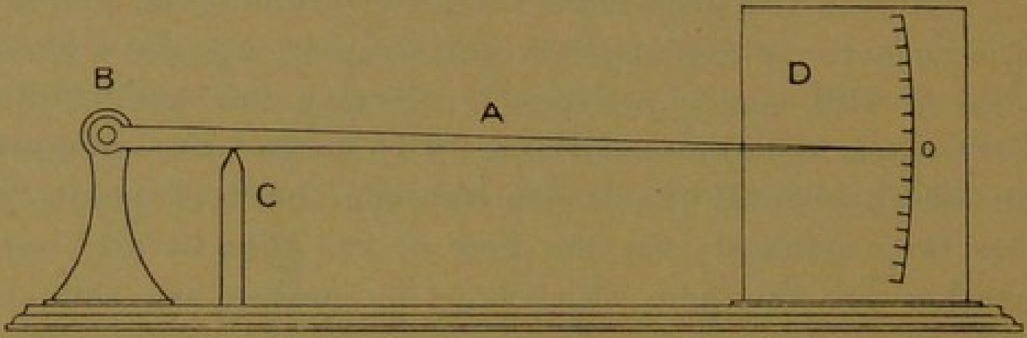


Fig. 8.

If the pencil be made to work on a paper fastened to a drum, D, arranged by means of clockwork to make one revolution in a given time, say one week, the temperature at any time during that period can be determined at a glance.

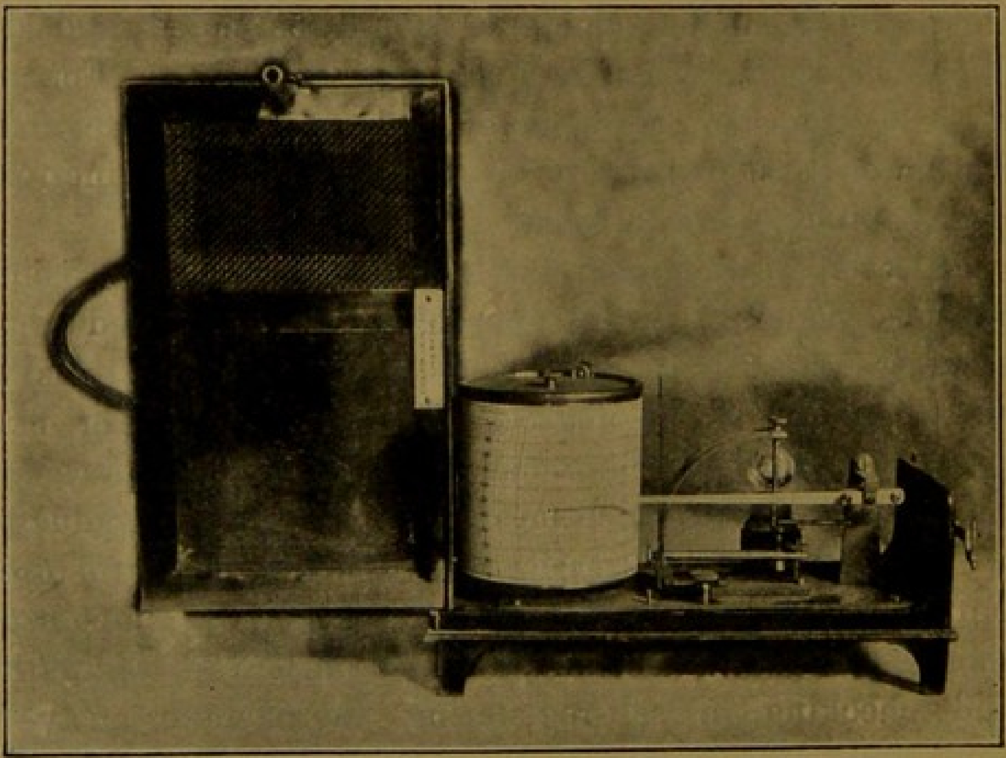


Fig. 8A.

Fig. 8A is a photo of a self-registering thermometer by Messrs. Chadburn. The piece of metal C in Fig. 8 is here replaced by an oval tube filled with a liquid having a low freezing point. A change of temperature causes a change of size, and consequently of pressure, in this fluid, and the oval tube tends to coil or uncoil as the pressure and temperature decreases or increases respectively. The pointer is moved by a simple arrangement of levers, and the whole instrument calibrated to give correct readings from day to day by clockwork, as described for Fig. 8.

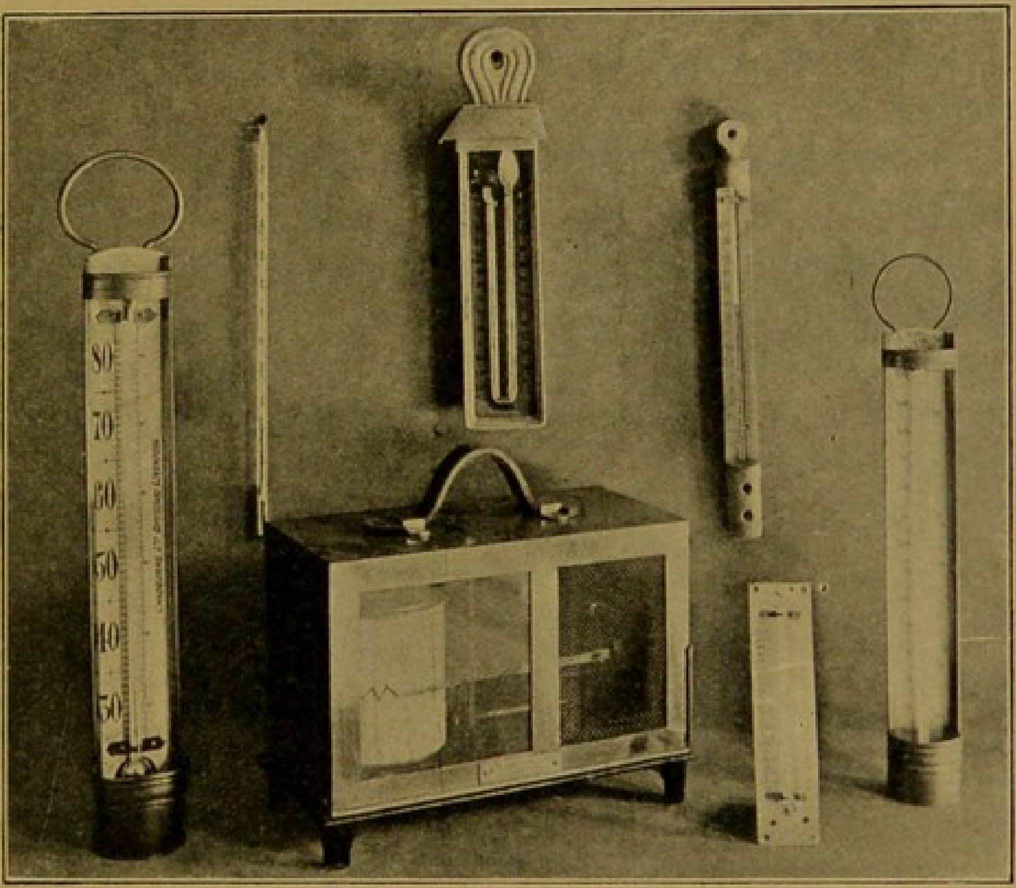


FIG. 8B.

A few of the many types of thermometers are illustrated in Fig. 8B.

On the right is a metal-cased thermometer marked to read both C. and F., and is suitable for taking the temperatures of fluids—such as brine in a refrigerating machine; the next is similar, but not intended for fluids; the third is a type recommended for cold chambers—the bulb being protected from radiant rays; the one hanging in the centre is for registering maximum and minimum temperatures; the second from the left is a standard thermometer; the one on the left is for general use in breweries; while in the centre an outside view is given of Fig. 8A.

Absolute Zero of Temperature.—The zero of the Centigrade scale is the melting point of ice, while the Fahrenheit zero was fixed as the resulting temperature obtained by mixing salt and ice; but although the 0° F. is lower than 0° C., the 0° F., as previously mentioned, is not by any means the lowest temperature obtainable.

It has been found that a volume of gas expands or contracts about $\frac{1}{493}$ part of its volume for every increase of one degree F., and $\frac{1}{273}$ of its volume for each degree C. Thus on the Fahrenheit scale, 493 cubic inches of air at 32° F., if heated one degree, will become 494 cubic inches at 33° F. If cooled to 31° F., the resulting volume will be 492 cubic inches.

Thus—

494 at 33° F.
493 at 32° F.
492 at 31° F.
....
461 at 0° F.
....
0 at -461° F.

It is not necessary to conceive that the air is reduced to zero volume at -461° F., because it becomes a liquid long before reaching that temperature, but its behaviour while it remains a gas is (in common with other gases) so consistent, that the above deductions can be drawn.

On the Centigrade scale, from the same reasoning, 273 cubic centimetres of air (or other gas) at 0° C. will become zero volume at -273° C. Thus the lower fixed point on the ordinary thermometer is 493° F. ($461 + 32$) and 273° C. ($273 + 0$) *on the absolute scale*, more nearly correct figures being 492·6° F. and 273·7° C.

In all calculations *absolute* temperatures must be employed.

Comparison of Centigrade and Fahrenheit Scales.

The distance between the fixed points of the thermometer being divided into 180 parts F. and 100 parts C., it follows that—

$$1 \text{ degree C.} = \tfrac{180}{100} \text{ degrees F.}$$
$$= \tfrac{9}{5}$$

and

$$1 \text{ degree F.} = \tfrac{100}{180} \text{ degree C.}$$
$$= \tfrac{5}{9}$$

That is, when the mercury rises a distance of one degree C, it has risen $\frac{9}{5}$ or 1·8 degrees F., and rising one degree F.

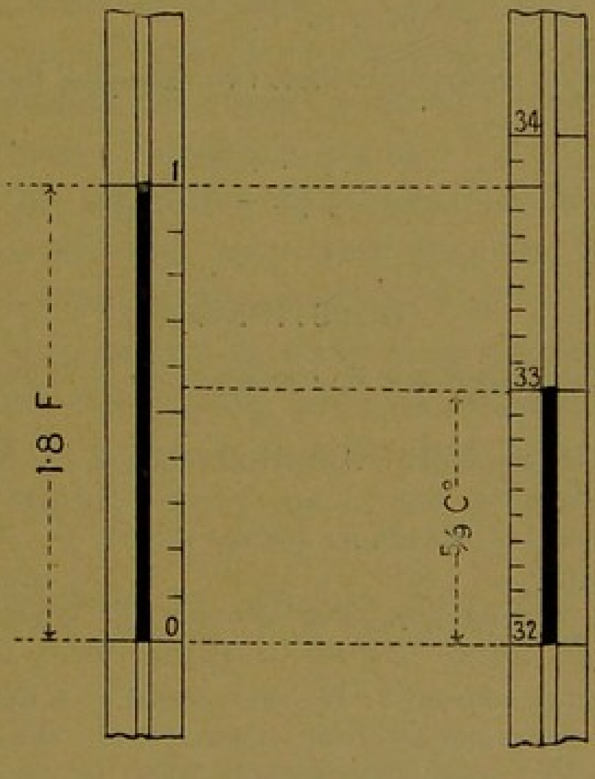


Fig. 9.

means $\frac{5}{9}$ of a degree C. This is illustrated in Fig. 9, a careful study of which will explain the rules for conversion from one scale to another.

EXAMPLES.

(1) What is the temperature F. corresponding to 10° C.?

$$\begin{aligned} &10 \text{ degrees C.} = 10 \times \tfrac{9}{5} \text{ degrees F} \\ \therefore\ &10 \text{ degrees C.} = 18 \text{ degrees F.} \quad \ldots\ldots \quad (a) \\ \text{but}\ &0^\circ \text{ C.} = 32^\circ \text{ F.} \quad \ldots\ldots \quad (b) \end{aligned}$$

Adding equations (*a*) and (*b*),

$$\begin{aligned} 0^\circ \text{ C.} + 10^\circ \text{ C.} &= 32^\circ \text{ F.} + 18 \text{ degrees F.} \\ 10^\circ \text{ C.} &= 50^\circ \text{ F.} \end{aligned}$$

(2) What will be the temperature C. when the mercury is 50° F.?

Here the mercury has risen from the lower fixed point—

$$50 - 32 = 18 \text{ degrees F.},$$

and as

$$\begin{aligned} 1 \text{ degree F.} &= \tfrac{5}{9} \text{ degree C.} \\ 18 \text{ degrees F.} &= 18 \times \tfrac{5}{9} \text{ degrees C.}, \\ &= 10 \text{ degrees C.} \end{aligned}$$

Hence

$$50^\circ \text{ F.} = 10^\circ \text{ C.}$$

As a result of the reasoning in these two examples, the following rules may be adopted :—

$$\begin{aligned} \text{F.} &= \tfrac{9}{5} \text{ C.} + 32 \\ \text{C.} &= \tfrac{5}{9} (\text{F.} - 32). \end{aligned}$$

QUESTIONS.

(1) What is the temperature F. corresponding to −40° C.

Ans. −40° F.

(2) What is the temperature C. corresponding to 98° F. (blood heat)?

Ans. 36·6° C.

(3) Water reaches its maximum density at 39·1° F. What is this on the Centigrade scale? *Ans.* 3·9° C. (4° C.).

(4) The brine in a refrigerator is at −15° C. What is this on the Fahrenheit scale? *Ans.* + 5° F.

(5) What is a thermometer? Its construction? What is the property of matter that is the principle of its construction? What temperatures are regularly noted by careful engineers? What is the temperature of (1) melting ice; (2) boiling water? (B.T.)

CHAPTER II

SOURCES OF HEAT—ENERGY—UNITS—SPECIFIC HEAT—LATENT HEAT

THE most important source of our high temperature heat supply is undoubtedly a chemical one, where fuel, principally *coal* and *oil*, is made to change its state with the consequent production of heat. A portion of this heat or "molecular energy" may be converted by means of heat engines into *mechanical* energy or *work*. Conversely, work may be transformed into heat.

Energy is the capability of, or capacity for, doing work. Any source of energy, *e.g.* water currents, wind, etc., is a source of *work* and consequently of *heat*.

In everything around us there is an abundant supply of low temperature heat: even, for instance, in a tank of water at 60° F. This, however, is truly low temperature heat, and under ordinary conditions is not *available* as a source of energy.

We require *units* to measure heat and work, and to establish the relationship between them. There are two classes of units—

1. primary units,
2. derived units.

PRIMARY UNITS—**Length.**—The British standard (or unit) of length is the *yard*, which is sub-divided into three equal parts, each part being called a *foot*. The foot (ft.) is the engineer's standard of length. The scientific unit is the centimetre (cm.), which is the one-hundredth part of the metric standard of length, viz. the *metre.*

$$1 \text{ ft.} = 30{\cdot}48 \text{ cm.}$$
$$1 \text{ cm.} = 0{\cdot}0328 \text{ ft.}$$

Mass.—The British unit of mass is the *pound* (lb.), and is not in any way derived from the unit of length. The scientific unit of mass is the gram, which has a connection with the unit of length, inasmuch as it may be defined as the mass in one cubic centimetre (c.c.) of pure water at the temperature of its maximum density 4° C. We may take without serious error—

$$1 \text{ c.c. water} = 1 \text{ gram.}$$

Time.—The scientific unit of time is the *second.*

DERIVED UNITS — Velocity. — The distance moved through by a body having a uniform motion in one second is called its *velocity.* If the motion, however, is not uniform, the velocity at any instant is the distance that would have been covered in one second had the velocity at that instant been maintained. It will thus be seen that velocity is compounded of motion and time; it may, therefore, vary (1) in direction, (2) in magnitude, or (3) in both magnitude and direction.

Velocity is measured either in feet per second or centimetres per second, according as the British or the metric system of units is employed.

Force.—Force is that which changes or tends to change the velocity of a body. This definition is applicable to bodies at rest which a force tends to move; rest being "zero velocity" (Lodge).

Unit of Force.—A unit of force is that force which acting on unit mass for unit time produces a change of unit velocity.

The metric unit of force is called a *Dyne.* The British unit is called the *Poundal.*

The Dyne.—A dyne acting on one gram for one second changes its velocity one centimetre per second.

The Poundal.—A poundal acting on a mass of one pound for one second changes its velocity one foot per second. Engineers use the force equivalent to 1 lb. as a more convenient unit than the poundal.

A force of 1 lb. = 32·2 poundals

where g is taken as 32·2 ft. per second per second.

Work.—When a force acting on a mass changes its position, work is said to have been performed, and is measured by multiplying the distance moved by the force acting.

Unit of Work.—The unit of work is the unit force acting through unit distance.

Metric Unit of Work is the work performed by 1 dyne acting through a distance of 1 cm., and is called an *Erg*.

A *Gram-centimetre* is the work performed in overcoming a force equal to that exerted by gravity on a mass of 1 gram through a distance of 1 cm. One gram-centimetre = 981 ergs, where g = 981 cm. per second per second.

British Unit of Work is the work performed by 1 poundal acting through a distance of 1 foot, and is called a *Foot-poundal.*

The unit most generally used, and the one we shall employ, is the *foot-pound,* which represents the work performed in overcoming a force equal to that exerted by gravity on a mass of one pound through a distance of one foot. Taking g = 32·2 ft. per second per second

1 ft. lb. = 32·2 ft.-poundals

Power is the rate of doing work, *i.e.* the number of units of work that can be performed in a given time.

In the C.G.S. (centimetre, gram, second) system the unit is very small, being one erg per second, and other units are used, viz.

1 *watt* = 10^7 ergs per second
1 *kilowatt* = 1000 watts.

The *Horse-power* (H.P.) is the unit—introduced by Watt—generally employed by English-speaking people, and is 33,000 ft.-lb. of work performed in one minute.

Unit of Heat.—The unit of heat is the amount of heat required to raise the temperature of a unit weight of water one unit degree.

The *British Thermal Unit* (B.Th.U.) is the amount of heat required to raise the temperature of 1 lb. of water one degree F., usually given as from 39° F. to 40° F., which is the maximum density of water. Recently the temperature for measuring the unit has been taken as from 62° F. to 63° F.

The C.G.S. unit of heat is the amount required to raise the temperature of one gram of water one degree C., and is called a *therm*. A *calorie* (a larger unit frequently employed) is 1000 therms, and is the quantity of heat required to raise a kilogram (1000 grams) of water one degree C.

Since

$$1 \text{ lb.} = 453{\cdot}6 \text{ grams} = 0{\cdot}4536 \text{ kilogram}$$

and

$$1 \text{ degree F.} = \tfrac{5}{9} \text{ degree C.}$$
$$1 \text{ B.Th.U.} = 0{\cdot}4536 \times \tfrac{5}{9} = 0{\cdot}252 \text{ calorie}$$
$$1 \text{ calorie} = 3{\cdot}968 \text{ B.Th.U.}$$

Mechanical Equivalent of Heat.—It has been previously stated that heat may be converted into work and work into heat. Joule established the relationship between the two by careful experiments with falling weights, which, by means of paddles, were made to expend their energy in water, consequently heating it. He found that

$$1 \text{ B.Th.U.} = 772 \text{ ft.-lb.}$$

and this is known as Joule's equivalent, indicated by the letter J. Later experiments have fixed a higher value, and leading scientists now take 774 to 778.

Joule's equivalent means that if heat is converted into work, then each thermal unit is equal to J ft.-lb. It does not mean that each thermal unit CAN be so transformed.

All available energy can be expressed in *units of work* or *units of heat.*

Using foot-pounds and the Centigrade scale, the mechanical equivalent may be taken as 1400 ft.-lb.

$$J = \begin{cases} 778 \text{ ft.-lb. F.} \\ 1400 \text{ ft.-lb. C.} \end{cases}$$

Specific Heat.—It has been found that unit weights of different substances do not require the same quantities of heat to raise them a unit degree in temperature. Thus one pound of water requires 1 B.Th.U. to raise its temperature one degree F. One pound of cast iron, however, only requires 0·13 B.Th.U.; the "specific heat," or relative thermal capacity, of cast iron is therefore spoken of as being 0·13.

One gram of water requires one therm to raise its temperature 1° C., one gram of cast iron only requires 0·13 of a therm, and the specific heat of cast iron is said to be 0·13. The specific heat of a substance is, as we therefore see, a value independent of the various systems of units.

The *specific heat* (K) of a substance is the quantity of heat (thermal units or therms) required to raise a unit weight, through a unit degree, if the state of the body is not changed.

The specific heat of gases require special attention. Under a constant pressure a gas will expand if heated, and the specific heat (K_p) under these conditions is found to be different to when the gas is confined, and so kept at constant volume (K_v), the pressure increasing.

The relationship of K_p to K_v is expressed in the form—

$$\frac{K_p}{K_v} = \gamma$$

this relationship, γ (gamma), for the various gases being very important.

TABLE OF SPECIFIC HEATS.

LIQUIDS.	K.	SOLIDS.	K.
Water	1·000	Ice	0·504
Anhydrous Ammonia .	1·020	Spermaceti	0·320
Sea Water	0·940	Charcoal	0·241
Lead	0·040	Wood (Average) . .	0·510
Mercury	0·033	Lead	0·032
Carbonic Acid . . .	0·980	Mercury	0·032
Alcohol 20° C. . . .	0·600	Wrought Iron . . .	0·114
„ 160° C. . . .	1·110	Cast Iron	0·130

GASES.	Specific Heat Constant Volume K_p	Specific Heat Constant Pressure K_v	$\frac{K_p.}{K_v.} = \gamma.$
Hydrogen . . .	3·409	2·411	1·42
Air	0·238	0·169	1·40
Oxygen	0·217	0·155	1·40
Ammonia. . . .	0·508	0·393	1·29
Carbonic Acid . .	0·217	0·171	1·26

The specific heat of the same substance varies under certain conditions. Thus γ is always higher for those gases which under ordinary conditions are removed from their liquefying point, and a change of state is always accompanied with a change of specific heat. It will be noted that the value for liquid water is 1·00, for solid water it is 0·504, the tables give further examples.

The average specific heat for unfrozen materials brought into a cold storage may be taken as 0·80, and half this value (0·40) when the material is frozen.

Rule for finding the Heat Absorbed or Extracted from a Quantity of Matter provided there is no Change of State.

Let W = weight of substance,
K = specific heat,
t_1 = original temperature,
t_2 = final temperature.

Then

$$\text{Heat absorbed} = \mathrm{WK}(t_2 - t_1)$$
$$\text{Heat extracted} = \mathrm{WK}(t_1 - t_2)$$

If *thermal units* are required, W must be in lb. and temperatures F°.

If in *therms*, W must be in grams and temperatures C°.

If in *calories*, W must be in kilograms and temperatures C°.

EXAMPLES.

(1) How many B.Th.U. must be extracted from 10 tons of charcoal to reduce its temperature from 50° F. to 40° F. ?

$$\begin{aligned}\text{Heat extracted} &= 10 \times 2240 \times 0{\cdot}241\ (50 - 40)\\ &= 22400 \times 2{\cdot}41\\ &= 53984 \text{ B.Th.U.}\end{aligned}$$

(2) How many therms will be required to heat 500 grams of cast iron from 20° C. to 60° C.?

$$\begin{aligned}\text{Heat supplied} &= 500 \times 0{\cdot}130\ (60 - 20)\\ &= 2600 \text{ therms}\end{aligned}$$

(3) How many calories will be required to raise the temperature of 1000 kilograms of lead from 35° C. to 75° C. ?

$$\begin{aligned}\text{Heat required} &= 1000 \times 0{\cdot}032\ (75 - 35)\\ &= 1280 \text{ calories}\end{aligned}$$

Latent Heat.—When a *unit weight* of a solid body is changed to the liquid state, a quantity of heat is required, called the *latent heat of fusion,* and to change the liquid to a vapour or gas, a further quantity of heat is required, called the *latent heat of vaporization.*

Both these quantities vary very much in different bodies, and even in the same bodies under varying conditions.

Thus, the latent heat of fusion of ice may be taken as 144 B.Th.U. or 112,032 foot-pounds. This means that 1 lb. of ice at 32° F., requires 144 B.Th.U. to convert it into water at 32° F. Conversely, 144 units must be extracted from water at 32° F. to convert it into ice at 32° F. Or that 112,032 foot-pounds (144 × 778) of work must be expended in changing the ice to water without change of temperature.

The latent heat of fusion of ice is 80 therms and 80 calories, *i.e.* 80 therms per gram, and 80 calories per kilogram.

As the units of weight are primary units, the derived units, therms, calories, and thermal units, being calculated per unit weight, the difference in the values, viz. 144 and 80 is due simply to the difference F°. and C°.

Thus

$$144 \times \tfrac{5}{9} = 80$$

$$80 \times \tfrac{9}{5} = 144$$

The latent heat of vaporization of water, or latent heat of steam, is the number of B.Th.U. required to convert 1 lb. of water into steam, the temperatures remaining constant. Under ordinary atmospheric pressure of 14·7 lb. per square inch (760 millimetres of mercury) 212° F. is the vaporization point, and 966 B.Th.U. are required to convert one pound of water at 212° F. into steam at 212° F. If the pressure is increased the latent heat becomes less, but the vaporization temperature is increased; if the pressure is decreased the temperature of vaporization is decreased, and the latent heat increased. Further information on this point will be found in the chapter on the "Properties of Liquids."

Under the ordinary atmospheric conditions, and at 100° C., the latent heat of vaporization of water is 536·6 therms per gram, or 536·6 calories per kilogram.

$$966 \times \tfrac{5}{9} = 536{\cdot}6.$$

EXAMPLES.

(1) How many thermal units must be extracted from water at 63° F. to make one ton of ice at 22° F.?

Heat extracted per lb.—

From water at 63° to water at 32° = 31 B.Th.U.
" " at 32° to ice at 32° = 144 "
" ice at 32° " " 22° = 5 "
180 "

Heat extracted per ton—

180 × 2240 = 403,200 B.Th.U.

(2) "One ton refrigerating capacity" is the number of thermal units equivalent to that required to *melt* one ton of ice. What is one ton of refrigerating capacity in thermal units?

144 B.Th.U. (nearly) is required to melt 1 lb. ice.
Melting 2240 lb. of ice would, therefore, require 322,260 B.Th.U.

This is, a one ton refrigerating machine will remove 322,260 B.Th.U. per day of 24 hours.

(3) One ton of miscellaneous goods at 70° F. are put into a cold store. How many thermal units must be extracted to freeze same and lower the temperature to 18° F.? The average specific heats may be taken as 0·40 frozen, latent heat (average) 100 B.Th.U. per lb. Freezing-point (average) 28° F.

Heat extracted per lb.—

From 70° to 28° = 0·8 × 42 = 33·6 B.Th.U.
During freezing 100·0 „
From 28° F. to 18° = 0·4 × 10 = 4·0 „
137·6 „

Heat extracted per ton—

137·6 × 2240 = 308,224 B.Th.U.

Allowing for losses of all kinds, it may be assumed from (2) and (3), that one ton refrigerating capacity is equal to freezing one ton of miscellaneous goods.

QUESTIONS.

(1) Five hundred gallons of water are cooled from 67° F. to 54° F. in one hour. What is the refrigerating capacity of the machine in tons per twenty-four hours? Take 1 gallon = 10 lb. *Ans.* = 4·8 tons.

(2) One thousand kilograms (2204 lb., approximately 1 ton) of beef at 18° C. is reduced to 2° C. How many calories have been removed? Specific heat of beef 0·75. *Ans.* = 1200 calories.

(3) One pound of water at 32° F. is increased in temperature and finally evaporated into steam at 212° F. How many thermal units (called the total heat of steam at 212° F.) have been expended?

Ans. = 1176 B.Th.U.

(4) Sixty-five grams of water at 20° C. are reduced in temperature and frozen to ice at −10° C. How many therms have been removed?

Ans. = 6825 therms.

(5) For superheated steam $K_p = 0·480$ and $K_v = 0·346$. What is the value of γ? *Ans.* = 1·37.

(6) For carbonic oxide $K_v = 0·173$ and $\gamma = 1·403$. What is the value of K_p in thermal units and foot-pounds? *Ans.* = 0·243 and 189·0.

(7) Express the values of K_p and K_v for air in foot-pounds.
Ans. = 185·16 and 131·48.

Useful Data from this Chapter—

1 ft. = 30·48 cm.
1 cm. = 0·0328 ft.
1 c.c. water = 1 gram
1 lb. = 453·6 grams
g = 981 cms. or 32·18 ft. per sec. per sec.
1 ft.-lb. = 32·18 foot-poundals.
= 981 × 30·48 × 453·6 ergs.
= 1·373 × 10^7 ergs.
1 watt = 10^7 ergs per sec.
1 kilowatt = 1000 watts = 1000 × 10^7 ergs per sec.
= 1000 × 10^7 × 60 ergs per min.
1 H.P. = 33,000 ft. lb. per min.
= 33,000 × 1·357 × 10^7 ergs per min.

$$1 \text{ kilowatt} = \frac{10^7 \times 60 \times 1000}{10^7 \times 1·357 \times 33000} = 1·34 \text{ H.P.}$$

Further—

1 watt = 1 ampere × 1 volt
= 0·7373 ft. lb.
1000 watts = 1 kilowatt = 1·34 H.P.
1 H.P. = 746 watts = 746 volt-amperes
= 0·746 kilowatt.

$$\frac{\text{Volts and amperes}}{746} = 1 \text{ electrical H.P.}$$

1 horse-power-hour = 60 × 33000 ft.-lb.
= 2545 B.Th.U.
1 kilowatt-hour = 1000 watt hours
= 1 electrical unit
Joule's equivalent = 778 ft.-lb. F°.
= 1400 ft.-lb. C°.
1 B.Th.U. = 0·252 Calories.
1 calorie = 3·968 B.Th.U.

The kinetic enery (E) of a body in motion, or a body in falling from a known height is given by—

$$E = \frac{Wv^2}{2g}$$
$$= Wh$$

where E = kinetic energy in ft.-lb.
W = weight of a body in lb.
v = velocity in ft. per sec.
g = 32·18 ft. per sec. per sec.
h = height fallen in ft.

CHAPTER III

TRANSFER OF HEAT—RADIATION—CONDUCTION—CONVECTION

HEAT will, as before stated, readily pass from a hot to a colder body, but a body will not become *colder* than its surroundings.

Heat can be transferred in three ways, viz. Radiation, Conduction, and Convection. If the end of a bar of iron is allowed to remain for a short time in a fire it will become hot. On being withdrawn it will lose heat in the three ways mentioned—

(1) by *radiation* of heat rays into space;

(2) by *conduction* along the bar from the hot to the colder portion;

(3) by heating the air in contact with it, which becoming lighter in consequence, will ascend and be replaced by cooler air. This process being rapidly repeated gives rise to currents of air, and the iron is said to lose heat by *convection*.

The temperature of the iron will fall very rapidly at first, but as its temperature is reduced it cools very slowly. This means that the heat given out at first in a given interval of time is large, which is what we would expect, on account of the great difference of temperature; later on, with a less difference of temperature, the heat given out in a given interval will be less.

Newton's Law of Cooling.—Newton discovered and formulated a law which holds good, provided the difference of temperatures is not excessive, and is certainly applicable in Refrigeration. "*The rate of cooling of a body is proportional to the difference between the temperature of its surface and that of its surroundings.*"

Experiment.—A very simple experiment will serve to illustrate this very important law. Take a flask, beaker, or a common thin drinking glass, and fill with water at a temperature between 60° and 70° C. Place on a cardboard stand, and keep the water stirred with a thermometer by which the temperatures are read at given intervals of time. The results should be tabulated as follows, the figures given being the result of such a test—

Number of observation.	Time Minutes.	Temperatures.		Average difference.	Fall per minute.	$\frac{\text{Fall per minute}}{\text{Average difference}}$
		Air.	Water.			
1	0	15° C.	71·4° C.	—	—	—
2	2	15° C.	68·6° C.	55	1·4	0·027
3	4	15° C.	66·1° C.	52·25	1·25	0·024

The plotted results will give a curve similar to Fig. 10.

Newton's law in respect to the experiment would read: "*The amount of heat lost in a given interval of time by a vessel filled with liquid is proportional to the mean difference of temperature between the liquid and its surroundings.*"

Radiation.—In the piece of hot iron previously referred to, if the hand be placed near but above, a greater intensity of heat will be experienced than if the hand be placed at the same distance below. Convection *and* radiation convey heat to the hand in the first case, but radiation *only* in the second. The iron is emitting energy in the form of heat rays, which are propagated through space in straight lines similar to light. Light and the radiant heat of the sun reach the earth by the same law.

A well-known experiment is to take an optical lens, and focus the light and heat rays into one spot, when intense heat will be felt, sufficient even to ignite a dry substance.

Radiant heat rays will all, practically, pass through good, clear glass. A piece of smooth silver, polished brightly, will reflect the heat rays, while a rough surface, covered with a dead lampblack, will absorb the rays. Radiant heat will readily pass through air, but is slightly absorbed by carbonic acid gas, and still more so by ammonia gas (Tyndall).

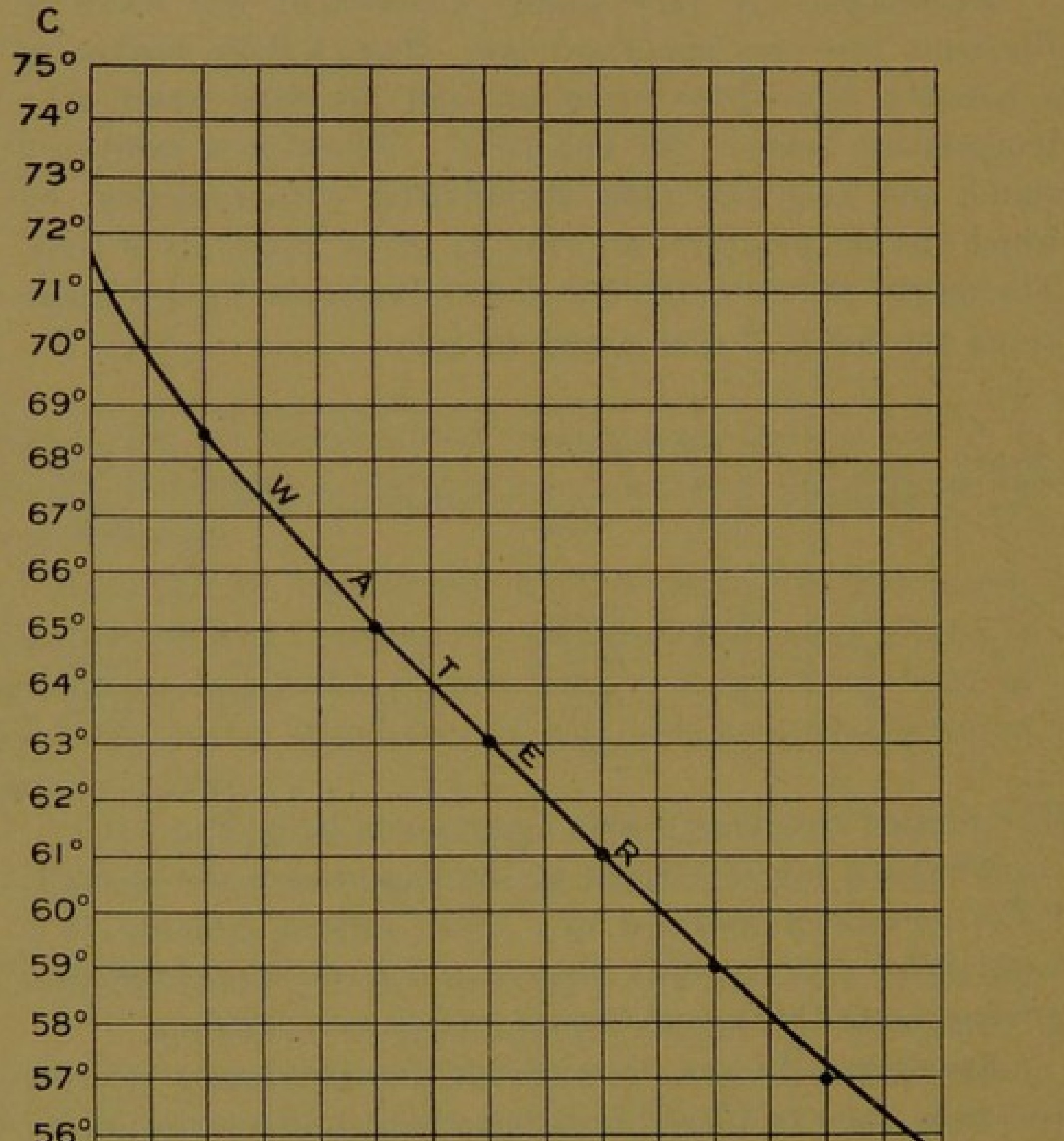


Fig. 10.

Prevost's Theory of Exchanges.—A warm body exposed in the air will lose a certain amount of its heat by radiation. If the body be placed in a small chamber, the walls of which are maintained at the same temperature as itself, it will not lose heat. Are we then to suppose that it stops radiating heat as soon as it is lowered into the chamber? Prevost's theory states that the body *continues* to emit radiant heat to the walls, and the walls to the body, but *in an equal amount.* This theory of exchanges is, of course, applicable to bodies of different temperatures, *i.e.* where there is a difference in the *amount exchanged.* If the hand be placed near a block of ice, a distinct cold sensation will be produced on the side of the hand next to the ice. That side has been cut off by the ice from receiving radiant heat from ordinary surrounding bodies; the hand still emits radiant heat, and, therefore, not receiving *as much* as it received before, a cool sensation is felt. The ice receives from the hand *more* radiant heat than *it emits* to the hand.

In the same way, a thermometer in a cold chamber seldom reads the correct temperature of the air. To do so, the bulb should be screened, but in such a way as to allow free access of the air (see Thermometers, p. 11). It should be hung away from columns, sides of the chamber, and packages. This may not always be practicable—it seldom is—hence the error.

We have stated that a dead black surface will absorb radiant heat. Supposing two exactly similar bodies, covered with lampblack, are lowered into a chamber, all being at the same temperature; they *will remain* at the same temperature. But lampblack readily absorbs radiant heat, therefore, one body is absorbing heat readily while the other must as freely be emitting it, and *vice versâ.* Good *absorbers* are, therefore, good *radiators.* By the same reasoning, bright polished surfaces, such as silver, while they will reflect radiant heat, emit or radiate correspondingly small quantities. A well-polished copper steam pipe will not lose so much heat by radiation as a pipe with a dull rough surface; therefore a steam or hot water "radiator," or heater, should not be polished brightly, while the roof and sides of a cold storage building exposed to the sun should be whitewashed, or have white enamelled bricks, in order to reflect the heat.

Convection.—Convection is the method by which heat is the most readily diffused through fluids (liquids and gases). If one portion of a fluid is heated, its density is altered, and it will be displaced by colder portions, which in turn will be displaced, thus the tendency is to make the whole equalize in temperature, and the fluid is said to be heated by convection.

The following simple experiment is very instructive. Take a test-tube nearly full of water and hold it over a flame, as shown in Fig. 11. The top of the water will soon boil, leaving the bottom cold. Allow the flame to play on the *bottom* of the tube, and the water soon becomes heated by convection currents.

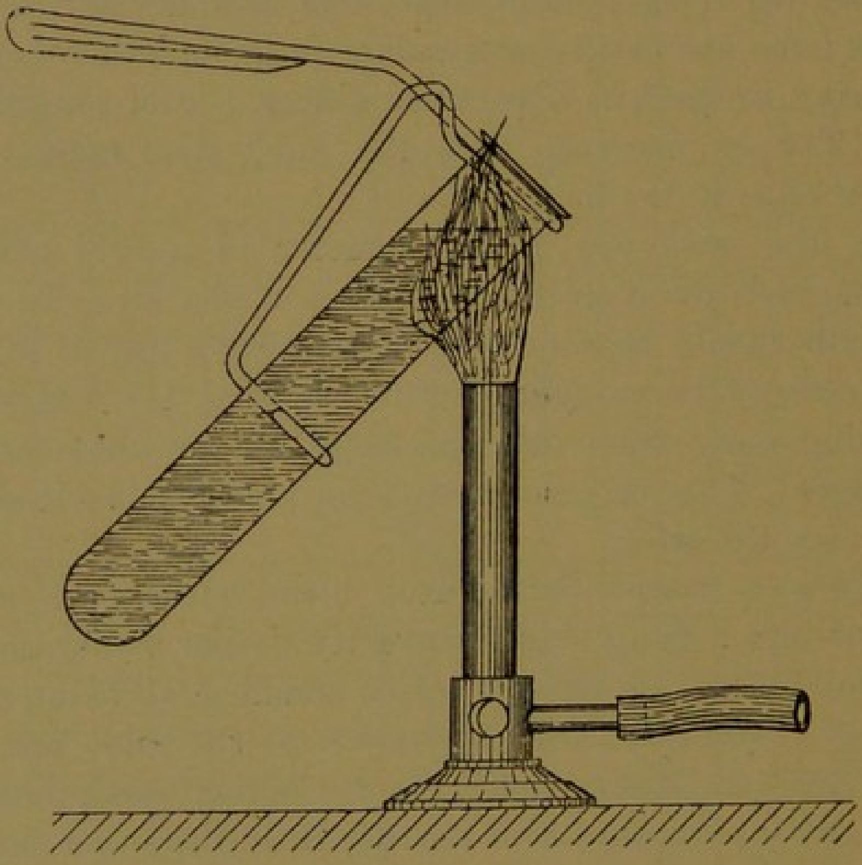
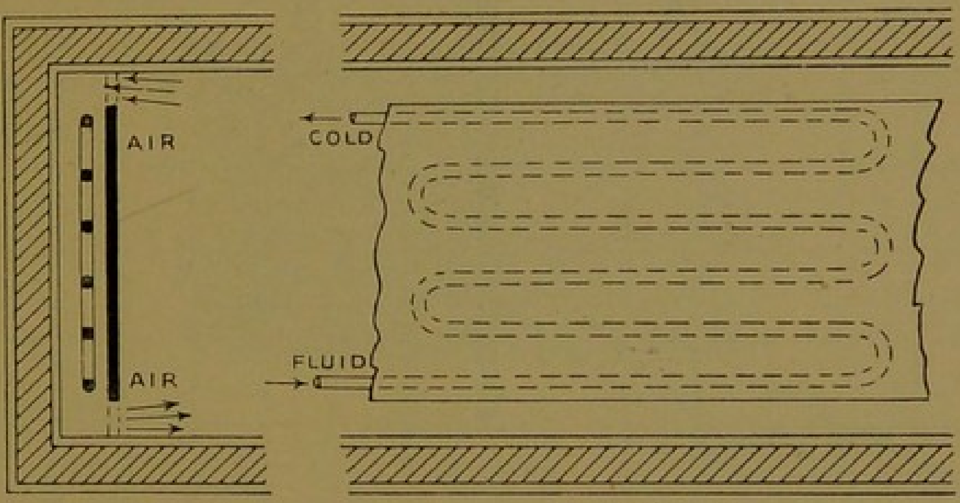


FIG. 11.

If a coil of piping is placed on the side of a chamber, with a partition in front, and a very cold fluid allowed to circulate through the coil in the direction indicated by the arrows (Fig. 12) it will be found that the air will come from under the partition with a certain definite velocity, and a corresponding influx will be noted at the top. This action is due to convection, and the air in the chamber will gradually become colder. If the natural currents be augmented by blowing the air into the top of the partition by means of a fan, it is found that the chamber will cool much quicker.

A heated body in a closed vessel, in which there is a perfect vacuum, will not lose heat by convection, there being no matter to set up the necessary currents.

Conduction.—Conduction is the means by which heat is propagated through a substance (or, to another substance in contact) from molecule to molecule. In a bar of metal, one end of which is hot, the molecules at that end will be in a state of violent agitation, and each will possess a definite quantity of kinetic energy. The molecules more remote will not be so intensely agitated, but will have communicated to them, by contact, a portion of the energy of the more violently agitated molecules, and thus have their own heat energy increased—the heat thereby travelling through the bar by "conduction."



Side Elevation. Front Elevation.

FIG. 12.

Relatively, metals possess, in a marked degree, the property of transferring heat by conduction. That fluids are not good conductors can be deduced by the experiment illustrated by Fig. 11. A piece of wood, one end of which is burning, can be grasped (excepting perhaps for radiation) within a very short distance of the burning part—showing that wood is a bad conductor of heat—a point to be particularly noted in refrigeration.

If two fluids A and B (Fig. 13) are separated by a thin wall of substance C, the heat passing in a given time will be found to be (1) proportional to the mean difference of temperature between A and B; (2) dependent on the nature and thickness of the wall C,—the thicker the wall the less the heat; (3) dependent on the condition of the particles of both A and B—if both are kept agitated so that the surfaces of C are continually scrubbed, a greater amount of heat will pass than if both had been kept as still as the natural convection currents would allow.

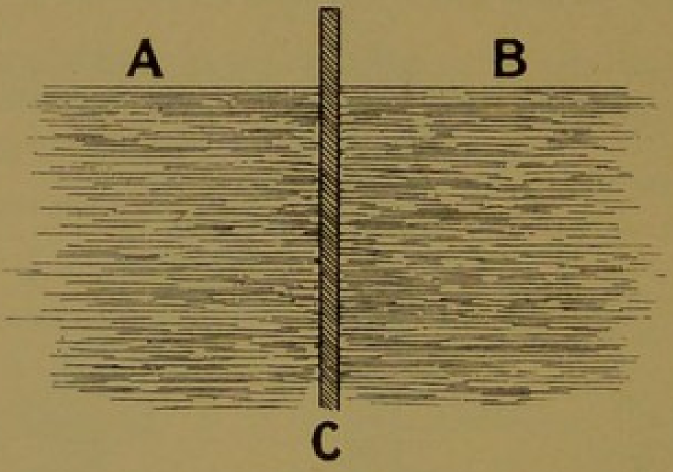


Fig. 13.

Further, if A is the warmer fluid and the particles of B *are not kept agitated* a layer of fluid B next to the wall C will become warmer than the rest—and the difference of temperature between the fluids on either side of C will be reduced and the quantity of heat passing in a given time will fall. The importance of this fact cannot be overestimated in refrigeration—where the differences of temperature are very small compared with the differences met with in heat engines and boilers.

An interesting variation of the experiment whose results are set out graphically in Fig. 10 can be made to illustrate the importance of agitation.

If water in two beakers be heated to the same temperature, say, about 72° C., and allowed to cool in the air—the water in the one being kept as still as possible, the other being stirred by the thermometer by which the temperatures are read—it will be found that the water which is kept agitated will fall in temperature the more rapidly. The result of such an experiment is indicated in Fig. 14.

Copper is a better conductor than iron. This can be clearly shown by a piece of apparatus due to Forbes and shown in Fig. 15.

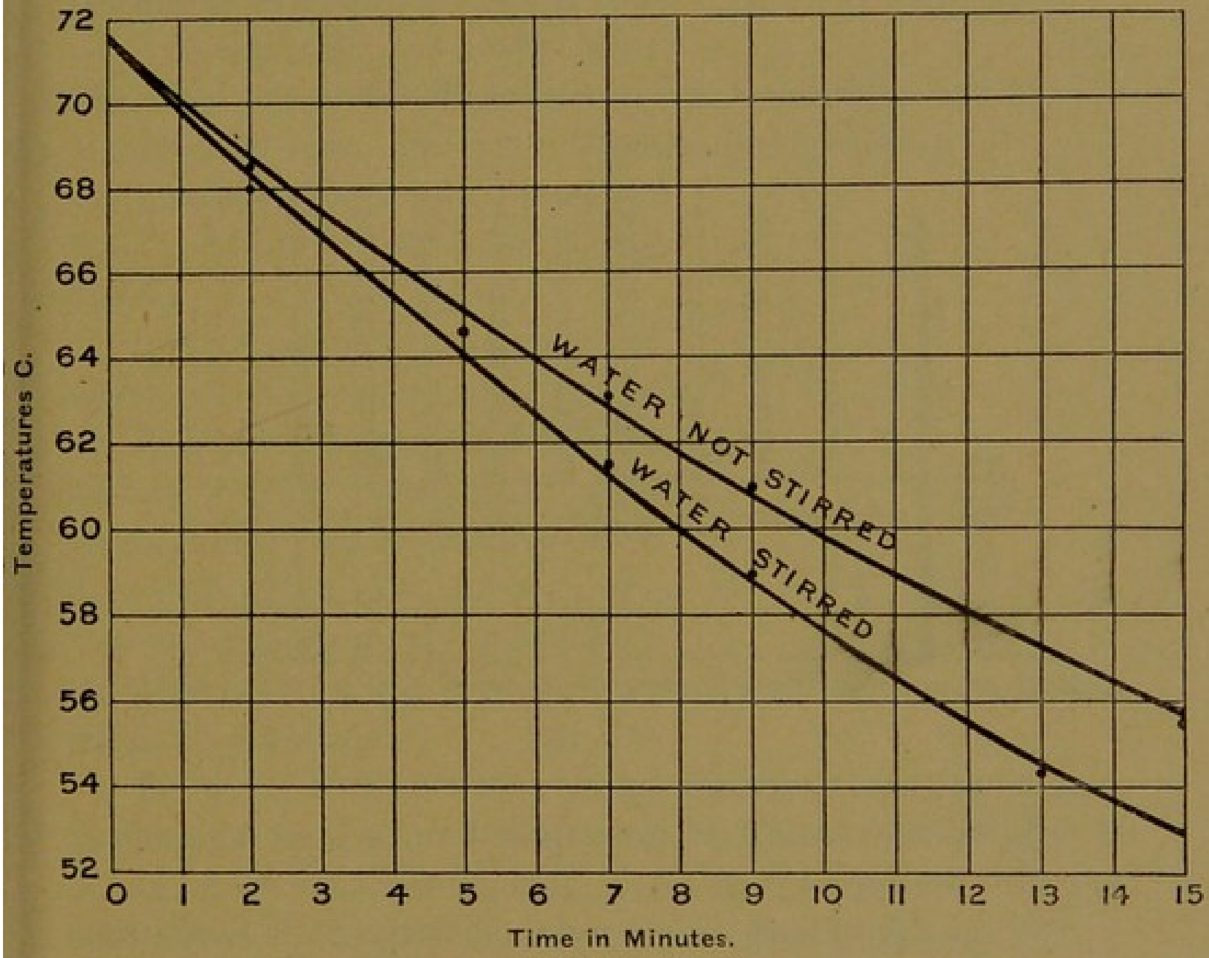


FIG. 14.

If equal bars of each of the metals have holes drilled partly through at regular intervals, and are in turn arranged as shown and one end heated (the screen preventing radiation), each thermometer will give a higher reading for the copper than for the iron—the heat of course being conveyed by conduction *through* the metal.

With an arrangement shown in Fig. 13, a copper wall will allow more heat to pass than an iron one of the same thickness. In practice, it has been found that copper walls lose relatively a greater amount of their efficiency by impurities and dirt on their surfaces than iron, and, as copper is more expensive, we find iron and steel are now largely used by engineers for the walls of vessels and pipes, through which heat has to be conducted, where copper was used formerly.

Generally the heat lost by a solid (or fluid) will depend on—

(1) the difference of temperature between the body and its surroundings,

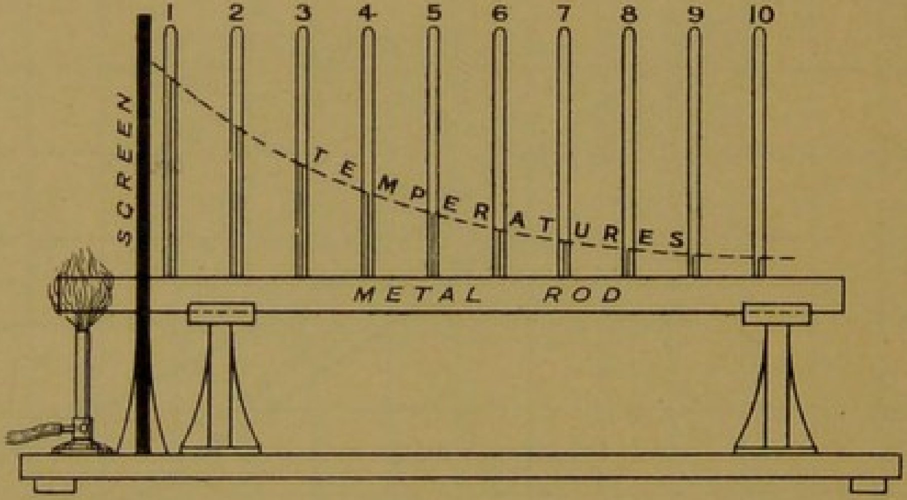


FIG. 15.

(2) on the nature of its exposed surface or containing walls,

(3) on the extent of the exposed surface or containing walls,

(4) on the "scrubbing" action on the surface.

Insulation.—All substances will convey more or less heat, but many are very bad conductors, and are termed "heat insulators."

A most striking example of insulation is to be found in the glass bulbs constructed by Professor Dewar to hold liquefied air, oxygen, etc., the principle of construction being shown in Fig. 16.

There are two (or more) glass vessels, A and B—the space between being pumped free of air (vacuum). The surface of A is silvered. If liquid air, say, is in A, it requires heat for its evaporation. Little or no radiant heat can reach it because of the silvered surface, which reflects same. Heat cannot be conveyed by convection, because there is no matter between A and B to allow of the formation of convection currents. If the whole is suspended by a silk cord, practically the only heat that can reach the liquid is by conduction down the glass from the mouth and through the mouth itself, which should be very small.

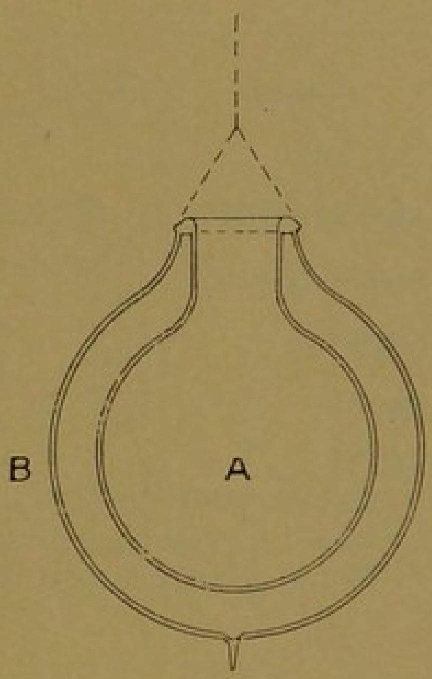


FIG. 16.

Cold chambers require to be insulated in order to prevent an influx of heat from external bodies. This "insulation" will be described when dealing with the construction of a cold chamber, but an important point must be enunciated here, viz. *that the object of insulation is to prevent the passage of heat.*

Referring to Fig. 13, we found that the quantity of heat passing through a wall depended on (1) the difference of temperature; (2) nature and extent of the surface; (3) the movement of the particles over the surface (fluids).

In practical refrigeration, the three conditions are so varied—particularly the latter—that no standard conditions have been laid down, but generally, the heat passing through a substance may be measured by its *Coefficient of Conductivity*, which is *the quantity of heat passing through a unit area of a wall, one unit thick, in unit time, with a unit degree of difference of temperature.*

The only reliable results of the coefficients of various bodies are those found in the C.G.S. system of units: this is the quantity of heat in therms passing through 1 sq. cm.

1 cm. thick in 1 second, per degree C. difference of temperature. *The values differ with the intensity of the heat,* i.e. *the value between* 0° *and* 1° *C. is different to that between* 100° *and* 101° C.

Edser[1] gives, amongst others, the following figures :—

Substance.	Mean Temperature.	Coeff. of Conductivity.	Substance.	Coeff. of Conductivity.
ALUMINIUM .	0°	0·3430	CLAY SLATE . . .	0·00272
	100°	0·3620		
BRASS (yellow)	0°	0·2041	GRANITE From .	0·00510
	100°	0·2540	GRANITE To . .	0·00550
COPPER . .	0°	0·7189	MARBLE From .	0·00470
	100°	9·7226	MARBLE To . .	0·00560
IRON	0°	0·1660	SAND (white dry) .	0·00093
	100°	0·1630		
LEAD	0°	0·0836	SNOW (in compact layers)	0·00051
	100°	0·0764		
TIN	0°	0·1528	PLASTER OF PARIS	0·00130
	100°	0·1423		
ZINC	0°	0·3030	PASTEBOARD . .	0·00045
			WOOD—FIR:	
			Along the grain . .	0·00030
			Across the grain .	0·00009

In experiments carried out to determine the value of various substances for *low temperatures and small ranges of temperature,* Lamb and Wilson have given the following results[2] :—

Substance.	Coeff. of Conductivity.	Substance.	Coeff. of Conductivity.
HAIR FELT (two sheets, each ½″) . .	0·000106	PINE SHAVINGS	0·000162
KAPOK (loose) . . .	0·000122	BROWN PAPER (crumpled up) . .	0·000167
KAPOK	0·000144	AIR (no baffles) . .	0·000200
HAIR FELT (broken)	0·000145	PINE SAWDUST .	0·000242
CHARCOAL	0·000150	DRY ASBESTOS .	0·000297
RICE HUSKS . . .	0·000150	SAND	0·000740
SILICATE COTTON .	0·000151		

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[1] "Heat for Advanced Students." Macmillan.

[2] *Transactions Royal Society,* 1899, pp. 283–288.

Let C = co-efficient of conductivity,

t_s = time in seconds,

H = quantity of heat passing in therms.

Then for 1 sq. cm. 1 cm. thick, and 1° C. difference of temperature

$$H = Ct_s$$

If A = total area in sq. cm.

t_1 = higher temperature

t_2 = lower temperature

then $H = Ct_sA(t_1 - t_2)$ for unit thickness;

if $t_{cm.}$ = thickness of substance in cm.

$$H = \frac{Ct_sA(t_1 - t_2)}{t_{cm.}}$$

EXAMPLE.

Taking 0·000156 as an average value of C for cold storage insulation, find the B.Th.U. transmitted per sq. ft. per day through an insulation 12 in. thick. Average inside temperature 14° F., and external 68° F.

Taking 12 in. = 30·5 cm.

14° F. = −10° C.

68° F. = +20° C.

$$H\ (\text{therms.}) = \frac{0{\cdot}000156 \times 24 \times 60 \times 60 \times 30{\cdot}5 \times 30{\cdot}5 \times 30}{30{\cdot}5}$$

= 12,333 therms

= 48·9 B.Th.U.

Hence 50 B.Th.U. may be taken as an average value under the conditions named.

QUESTIONS.

(1) State Newton's law of cooling. Explain by its means the reason why a glass of hot water will keep hot only a short time, while it will keep warm a considerable time.

(2) The air in a cold chamber is maintained at 30° F. A can of milk inserted at 60° F. was found to be 52° F. after one hour, 42° F. after four hours, but to reach 32° F. it required twenty hours. Explain the reason of this.

(3) It is not found convenient to lag or insulate all parts of a cast-iron steam engine cylinder. Would it be better to leave those parts rough or polished? *Ans.* Polished, to reduce radiation.

(4) On a frosty day a piece of iron feels colder than a piece of wood. Why is this?

Ans. The iron being a better conductor will extract more heat in a given time from the hand than the wood, hence the difference felt.

(5) What is meant by "conduction," "convection," and "radiation" of heat? Give examples of it in the boiler and in the engine (B.T.).

(6) Which is convection, which is radiation, and which is conduction in the following cases? (*a*) Heat from the glowing fuel to the furnace crown; (*b*) heat passing from one side of the furnace crown plate to the other; (*c*) heat passing from the steam pipes in the engine room; (*d*) the heat of evaporation (*i.e.* the heat that causes evaporation) (B.T.).

(7) State Prevost's theory of exchanges, and show how it follows from the theory that the radiating and absorbing powers of a surface at a given temperature are the same. (S. & A., 1894.)

(8) A ship's cold chamber is insulated 1 ft. thick with boards, paper, felt, and air space, for which an average coefficient of conductivity may be taken as 0·00015. How many B.Th.U. will pass per sq. ft. per day of 24 hours? Difference of temperatures 36° F. *Ans.* 33·5 B.Th.U.

(9) Cold air chambers on board ship are insulated. How and why insulated? (B.T.)

CHAPTER IV

THE PROPERTIES OF FLUIDS—GASES

Fluids.—In refrigerating machines or heat pumps certain fluids, such as air, ammonia, carbon dioxide, sulphur dioxide, and water, are used as the media for conveying the heat from the low to the high level. Of these, only water at ordinary atmospheric temperature and pressure is a liquid, while air is the only one which is used as a gas, the others being made to constantly change from a vapour into a liquid.

Gases.—Air is so far removed from its liquid state at ordinary temperatures that it is considered a gas. A *perfect* gas is only an ideal form of matter which obeys certain well-defined laws. Air, hydrogen, oxygen, and nitrogen may be taken to follow these laws, there being practically no error between the limits we have to consider.

Laws of Perfect Gases.—Law I. (Boyle). *At constant temperature, the volume of a mass of gas varies inversely as the pressure:* (or) *at constant temperature the product of the volume and pressure of a given quantity of gas remains a constant.*

This is expressed by the equation—

$$PV = \text{constant}$$

where P is the pressure and V the volume.

The volume of 1 lb. of air at 32° F. or 0° C. is 12·387 cub. ft., and taking the atmospheric pressure at 14·7 lb. per sq. in., which is 2116·2 lb. sq. ft. (in order to keep the same units—cubic *feet*, square *feet*), we have—

$$\begin{aligned} PV &= \text{constant} = C \\ &= 2116{\cdot}2 \times 12{\cdot}387 \\ &= 26{,}214 \text{ foot-pounds} \end{aligned}$$

Now, in whatever way that 1 lb. of air alters as to P or as to V, provided the temperature is kept constant, we find—

$$PV = 26{,}214$$

Hence $$P = \frac{26{,}214}{V}$$

and $$V = \frac{26{,}214}{P}$$

It is convenient (for engineers) to deal with 1 lb. of a gas, and

$$PV = C$$

refers to 1 lb. unless the contrary is expressed.

EXAMPLE.

One pound of air at 32° F. is found to occupy 4 cub. ft. What is the pressure per sq. in.?

Here

$$\begin{aligned} P &= \frac{26{,}214}{4} \text{ lb. sq. ft.} \\ &= \frac{26{,}214}{4 \times 144} \text{ lb. sq. in.} \\ &= 45{\cdot}5 \text{ lb. sq. in.} \end{aligned}$$

The formula

$$PV = C$$

may be used for any system of units, such as lb. per sq. in., and often the volume is taken in terms of the original volume at any temperature, provided that temperature is supposed to be constant. In this case

$$pv = c$$

are the symbols generally employed.

EXAMPLES.

(*a*) A quantity of air at 50° F. and 14·7 lb. per sq. in. is compressed to half its original volume. What is its pressure if the temperature is kept constant?

$$pv = c$$
$$p_1v_1 = c = p_2v_2$$
$$p_2v_2 = p_1v_1$$
$$p_2 = \frac{p_1v_1}{v_2}$$
$$= \frac{14{\cdot}7 \times 1}{\frac{1}{2}}$$
$$= 29{\cdot}4 \text{ lb. sq. in.}$$

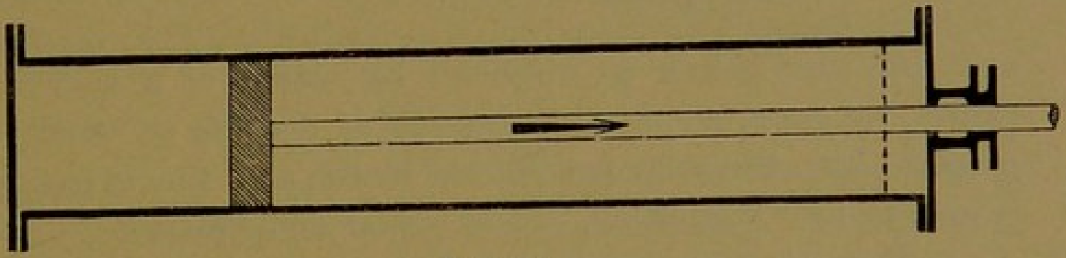

Fig. 17.

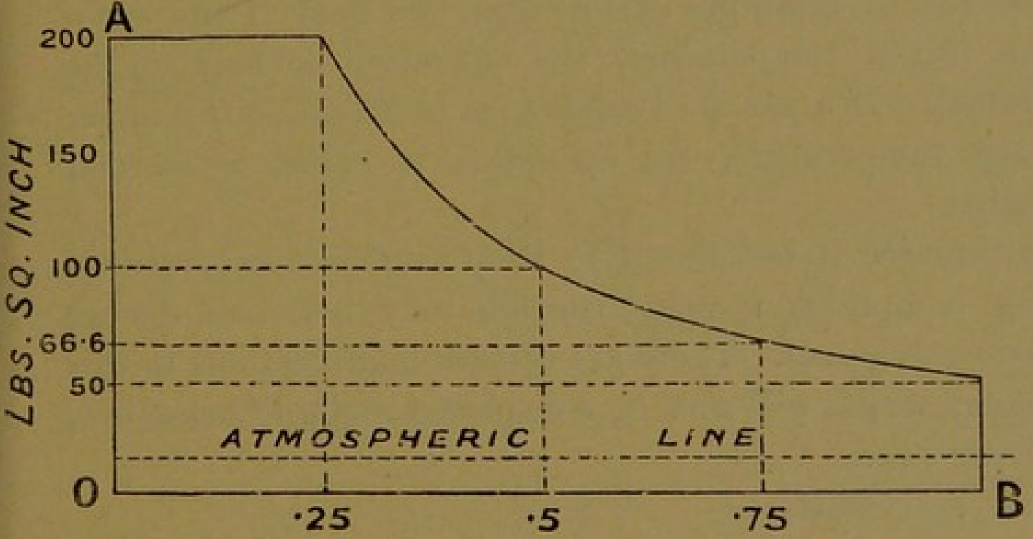

Fig. 18.

(*b*) Fig. 17 represents a cylinder and piston. The latter has been driven through $\frac{1}{4}$ of its stroke with air at a pressure of 200 lb. sq. in. absolute. What will be the pressure of the air when the piston reaches the end of its stroke?

Take $p_1v_1 = \text{constant}$

Here $p_1v_1 = c = p_2v_2$

$$v_1 = 1$$
$$v_2 = 4$$
$$p_2 = \frac{p_1v_1}{v_2} = \frac{200 \times 1}{4}$$
$$= 50 \text{ lb. sq. inch absolute.}$$

By the same method, the pressure at half stroke would be 100 lb. and three-quarter stroke 66·6 lb.

If we take two lines (Fig. 18) OA, OB at right angles, and set up on OA the *absolute* pressures to scale, and let OB equal the volume, which will be at all points proportional to the stroke passed through by the piston (Fig. 17) and mark off at—

$\frac{1}{4}$ stroke . . .	200	lb. pressure
$\frac{1}{2}$ stroke . . .	100	,, ,,
$\frac{3}{4}$ stroke . . .	66·6	,, ,,
Full stroke . .	50	,, ,,

and join the points so obtained by means of a curve, as shown, *we get a graphical indication of the way in which the pressure has altered throughout the stroke,* and the expansion is said to be "*isothermal,*" *i.e.* of equal temperature.

Isothermal Compression and Expansion.—If a gas is compressed (as in Example (*a*)) so that the final is the same as the initial temperature, the operation is said to be isothermal. If a gas is expanded (as in Example (*b*)) under constant temperature, the operation is called isothermal expansion.

In practice it is difficult to keep uniform temperatures. During compression gases become very hot, and *during expansion, very cold.* There are certain qualifications to this statement, which will now be considered under Charles' law, and Joule's law.

Law II. (Charles)—

(1) under constant pressure, perfect gases increase in volume equally for every degree increase of absolute temperature; or

(2) under constant volume, perfect gases increase in pressure equally for every degree increase of absolute temperature. (Refer back to absolute temperature.)

This may be written—

$$(1) \quad v_p \propto \mathrm{T}$$
$$(2) \quad p_v \propto \mathrm{T}$$

Where the suffix indicates the quantity which is constant.

T is the absolute temperature.

$\propto$ is a sign to indicate "varies as."

The two expressions (1) and (2) may be combined and written—

$$pv \propto T$$

So that if a volume v_1 of a gas at a pressure p_1. and absolute temperature T_1 should have its temperature increased to T_2, involving a change *both* of volume (v_2) and pressure (p_2), the following would hold by Charles' Law :—

$$\frac{p_2v_2}{T_2} = \frac{p_1v_1}{T_1}$$

and for any further change, say to T_3, v_3, p_3

$$\frac{p_3v_3}{T_3} = \frac{p_1v_1}{T_1}$$

so that if

$$\frac{p_1v_1}{T_1} = R$$

then

$$\frac{p_2v_2}{T_2} = R$$

$$\frac{p_3v_3}{T_3} = R, \text{ and so on.}$$

Hence the general equation—

$$\frac{pv}{T} = R$$

$$pv = RT$$

where R = some constant depending on the gas.

EXERCISE.

Find the value of R for 1 lb. of air at atmospheric pressure (14·7 lb. per sq. in.) and the temperature of melting ice.

p_1 = 2116·2 lb. per sq. ft.
v_1 = 12·387 cub. ft.
T_1 = 492·66 F.
273·7 C.

Fahrenheit scale—

$$\frac{pv}{\mathrm{T}} = \frac{2116{\cdot}2 \times 12{\cdot}287}{492{\cdot}66} = \frac{26{,}214}{492{\cdot}66}$$
$$= 53{\cdot}2$$
$$\text{and } pv = 53{\cdot}2\mathrm{T}$$

Centigrade scale—

$$\frac{pv}{\mathrm{T}} = \frac{2116{\cdot}2 \times 12{\cdot}387}{273{\cdot}7} = \frac{26{,}214}{273{\cdot}7}$$
$$= 95{\cdot}7$$
$$\text{and } pv = 95{\cdot}7\mathrm{T}.$$

EXAMPLE.

One pound of air at 32° F. is heated to 33° F., the pressure remaining constant. What is its volume?

Taking the general equation—

$$\frac{p_2 v_2}{\mathrm{T}_2} = \frac{p_1 v_1}{\mathrm{T}_1}$$

the pressure remaining constant, we have—

$$\frac{v_2}{\mathrm{T}_2} = \frac{v_1}{\mathrm{T}_1}$$
$$v_2 = v_1 \frac{\mathrm{T}_2}{\mathrm{T}_1}$$

From previous data, and taking 32° F. = 493° F. absolute,

$$v_2 = 12{\cdot}38 \times \tfrac{494}{493}$$
$$= 12{\cdot}412 \text{ cub. ft.}$$

The last example may be illustrated as shown in Fig. 19.

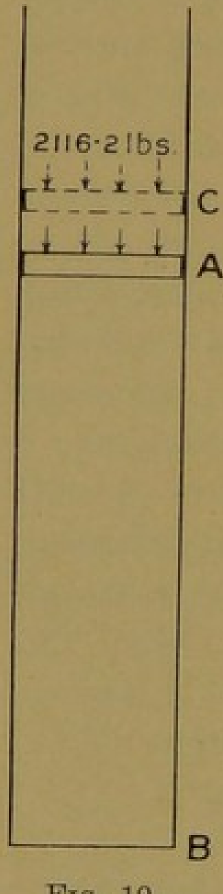

Fig. 19.

If there is a cylinder of 1 sq. ft. cross-section, fitted with a frictionless piston, containing 1 lb. of air at 32° F., the distance AB would be 12·387 ft. If the temperature is raised to 33° F., the piston will move and take up a new position at C, such that CB = 12·412 ft.

$$\text{Distance moved} = 12{\cdot}412 - 12{\cdot}387 = 0{\cdot}025 \text{ ft.}$$
$$\text{Work done} = 0{\cdot}025 \times 2116{\cdot}2 = 52{\cdot}9 \text{ ft.-lb.}$$
$$= 0{\cdot}068 \text{ B.Th.U.}$$

Supposing the piston to be wedged at A, then on heating the air one degree, the amount of heat it would take would of course be 0·169 B.Th.U., *i.e.* the specific heat of air at constant volume (the weight being 1 lb.), but as there is no movement, *no work would be done.* In the former example, not only was 1 *lb. of air heated one degree* (0·169 B.Th.U.), but, as we have seen, *work was done* equivalent to 0·068 B.Th.U.

Now, clearly

$$0{\cdot}169 + 0{\cdot}068 = \text{specific heat at constant pressure}$$
$$= 0{\cdot}237$$

i.e. $$K_v + 0{\cdot}068 = K_p \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (a)$$

With a finer degree of working, we should get a result closer to 0·238, the value previously given in the table of specific heats.

The example further shows that—

Pressure × increase of volume = work done

or $p(v_2 - v_1)$ = work done

But since $pv = \text{R}T$

then $p(v_2 - v_1) = \text{R}(T_2 - T_1)$

therefore work done $= \text{R}(T_2 - T_1)$

in our example when $T_2 - T_1 = 1$(Fig. 19)

work done = R

= 52·9 ft.-lb.

= 0·068 B.Th.U.

and from equation (*a*) since R = 0·068

we get $K_p = K_v + \text{R}$

and $K_v = K_p - \text{R}$

$\text{R} = K_p - K_v$

We further remember that

$$\frac{K_p}{K_v} = \gamma$$

Work done by a Gas.—If a certain volume of gas is under pressure, by allowing it to expand, moving (say) a loaded piston, we can make it *do work*, and under the new conditions of P and V the temperature will be reduced, because a definite quantity of *heat* from the gas has been converted into *work*.

Adiabatic Expansion.—When a gas expands doing work without taking in or giving out heat (as heat), the gas is said to expand adiabatically.

Adiabatic Compression.—When a gas is compressed (work thereby being expended) without taking in or giving out heat (as heat), the gas is said to be compressed adiabatically.

When fluids expand or are compressed, it has been found that in general the equation—

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

holds good.

For gases expanding—

(*a*) isothermally $n = 1$
(*b*) adiabatically $n = \gamma$

so that the relation of P to V for gases expanded or compressed adiabatically is given by the equation—

$$PV^\gamma = \text{constant} = C \; . \; . \; . \; . \; . \; . \; (1)$$

and

$$P_2V_2^\gamma = P_1V_1^\gamma \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; (2)$$

These equations can be readily solved by the aid of logarithms, thus—

$$\log P + \gamma \log V = \log C \; . \; . \; . \; . \; . \; . \; . \; . \; (1)$$

$$\log P_2 + \gamma \log V_2 = \log P_1 + \gamma \log V_1 \; . \; . \; . \; (2)$$

EXAMPLE A.

A quantity of air at 50° F. and 14·7 lb. sq. in. is compressed to half its original volume. What is its pressure and temperature?

PRESSURE.

$$v_1 = 2$$

$$v_2 = 1$$

$$p_1 = 14{\cdot}7$$

$$\gamma = 1{\cdot}4$$

$$p_2 v_2^\gamma = p_1 v_1^\gamma$$

$$\log p_2 + 1{\cdot}4 \log v_2 = \log p_1 + 1{\cdot}4 \log v_1$$

$$\log p_2 + 0 = 1{\cdot}1673 + 1{\cdot}4 \times 0{\cdot}301$$

$$= 1{\cdot}1673 + 0{\cdot}4214$$

$$\log p_2 = 1{\cdot}5887$$

$$p_2 = 38{\cdot}79 \text{ lb. sq. in.}$$

NOTE.—*Isothermally* (Example *a*) the terminal pressure was 29·4 lb. per sq. in. (p. 41).

TEMPERATURE.

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

$$\text{here } p_2 = 38{\cdot}79 \text{ (from above)}$$

$$T_1 = 511$$

$$\frac{14{\cdot}7 \times 2}{511} = \frac{38{\cdot}79 \times 1}{T_2}$$

$$29{\cdot}4 T_2 = 511 \times 38{\cdot}79$$

$$T_2 = \frac{19821{\cdot}69}{29{\cdot}4}$$

$$= 674{\cdot}2$$

$$t = 213{\cdot}2^\circ \text{ F.}$$

EXAMPLE B.

A piston is driven by compressed air at 200 lb. per sq. in. through a quarter of its stroke and then the supply of air is cut off. (i.) With adiabatic expansion, what will be the final pressure? (ii.) If the initial temperature was 69° F., what will be the final temperature?

(i.)

$$p_2 v_2^{1{\cdot}4} = p_1 v_1^{1{\cdot}4}$$

$$\log p_2 + 1{\cdot}4 \log 4 = \log 200 + 1{\cdot}4 \log 1$$

$$\log p_2 + 0{\cdot}84294 = 2{\cdot}3010 + 0$$

$$\log p_2 = 2{\cdot}3010 - 0{\cdot}84294$$

$$= 1{\cdot}45806$$

$$p_2 = 28{\cdot}72 \text{ lb. sq. in.}$$

(ii.)

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

$$\frac{200 \times 1}{530} = \frac{28{\cdot}72 \times 4}{T_2}$$

$$T_2 = \frac{28{\cdot}72 \times 4 \times 530}{200}$$

$$= 304{\cdot}43$$

$$t = -156{\cdot}57^\circ \text{ F.}$$

With *isothermal* expansion (Example *b*) it will be noted that the final pressure under similar conditions was 50 lb. sq. in. (p. 41).

EXAMPLE C.

In a cold air machine, air at 65 lb. per sq. in. (absolute) and 70° F. is expanded, doing work, to 14·7 lb. per sq. in. What is the final temperature?

First, find v_2 supposing v_1 = unity.

$$p_2 v_2^{1\cdot4} = p_1 v_1^{1\cdot4}$$

$$1\cdot4 \log v_2 = \log 65 + 1\cdot4 \log 1 - \log 14\cdot7$$

$$= 1\cdot8129 + 0 - 1\cdot1673$$

$$\log v_2 = \frac{0\cdot6456}{1\cdot4}$$

$$= 0\cdot4611$$

$$v_2 = 2\cdot891$$

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2}$$

$$\frac{65 \times 1}{531} = \frac{14\cdot7 \times 2\cdot891}{T_2}$$

$$65T_2 = 14\cdot7 \times 2\cdot891 \times 531$$

$$T_2 = 347\cdot1$$

$$t = -113\cdot9^\circ \text{ F.}$$

Mr. Giffard[1] in a test of a cold air machine, from which the data for this example is taken, found the final temperature of the air to be −82° F., which is about the lowest generally registered in these machines. The difference between this and −113·9° F. obtained in example (C) is due to the heat from the expansion cylinder walls, and also to the fact that the moisture in the air is, during expansion, frozen to snow and ice, and will give up 144 B.Th.U. per lb. of ice formed, the heat given up, being taken by the air, is thus increased in temperature. The snow and ice are very objectionable in the machine, blocking the ports and leading to many troubles in the expansion cylinder, such as fracture of the covers, etc.

Law III. (Joule)—"If a perfect gas expands without doing work, or without receiving heat, its temperature does not change."

Joule established this law by taking two copper vessels; in one was compressed air, and in the other a vacuum. He connected the two by a short pipe, in which a valve was inserted, the whole being placed in water. When the valve was opened, and the gas allowed to expand, it was found that the temperature of the water did not alter. Later experiments by Joule and Kelvin prove that there is a slight drop of temperature with most gases on free expansion,

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[1] *Proceedings Institution of Mechanical Engineers*, 1881.

and quite a measurable and *important quantity* with carbonic acid gas (carbon dioxide), and other gases easily liquefied. With a *perfect* gas Law III. may be taken as quite correct.

QUESTIONS.

(1) Complete the following table, taking J = 778. In calculating R, take J = 778 and J = 1400 (F. ° and C. °).

GAS.	K_p.		K_v.		γ	R.	
	Th.U.	Ft.-lb.	Th.U.	Ft.-lb.		J = 778.	J = 1400
AIR	0·238	185·16	0·169	131·482	1·407	53·68	96·6
OXYGEN . . .	0·217	—	0·155	—	—	—	—
AMMONIA . . .	0·508	—	0·393	—	—	—	—
CARBONIC ACID	0·217	—	0·171	—	—	—	—

(2) Taking K_p for air as 0·238, and R = 53·2, J = 774.[1] Find K_v.
Ans. 0·169.

(3) For air, taking R = 53·18, J = 774,[1] and K_p = 0·2375, find K_v in Th.U., and ft.-lb., and the value of γ.
Ans. 0·1688 Th.U.; 130·65 ft.-lb.; $\gamma = 1·407$.

(4) A fluid expands from a point on the diagram where p is represented by 1·5 ins., and v by 1 in., to a place where v is 3·5 ins. According to each of the laws of expansion pv constant, $pv^{1·0646}$ constant, and $pv^{1·13}$ constant, find the value of p at the end of the expansion in each case. (S. and A., Adv. Steam.)
Ans. (1) $p_2 = 0·428''$; (2) $p_2 = 0·395''$; (3) $p_2 = 0·3642''$.

(5) Assuming for saturated steam

$$pv^{1·0646} = 479$$

where p = pressure in lb. sq. in., v = volume of 1 lb. in cub. ft., find the volume in cub. ft. of 1 lb. of saturated steam at atmospheric pressure (14·7 lb. sq. in.).
Ans. 26·37 cub. ft.

(6) Four cubic feet of ammonia gas at 30 lb. pressure per sq. in. and 0° F., is compressed to 150 lb. sq. in. What is the new volume and temperature? Take $\gamma = 1·3$.
Ans. 1·16 cub. ft.; 207·45° F.

(7) What is the duty of the expansion cylinder of a cold air machine? (B.T.)

(8) What objection is there to the presence of moisture in the air passed through the cold air machine? (B.T.)

---

[1] This value for J (774) is often used.

(9) What is the maximum pressure found in the compressors of cold air machines? What is the minimum temperature of the air? (B.T.)

Ans. (1) About 65 lb. sq. in., absolute; (2) −85° F.

(10) Explain (1) Isothermal, (2) Adiabatic expansion of a gas.

(11) A small air-pump, used for inflating pneumatic tyres, if worked quickly, is found to become very hot, but if worked slowly, simply warm. Why is this?

Ans. The quicker the pump is worked the more closely will the compression of the air tend to become adiabatic, the metal of the pump not being able to transfer the heat generated in the interval between each stroke. If the pump is worked slowly, the compression tends to be isothermal in consequence of the heat having a greater interval of time to pass off from the barrel.

(12) Air compressors for pneumatic machines are generally water-jacketed. Why is this?

Ans. To keep down the temperature and work expended to reach a given pressure, as the temperature would, in any case, fall on the way to the machines, with a consequent drop in pressure.

(13) State the laws of Boyle and Charles upon the subject of perfect gases.

(14) When a gas changes its volume and pressure, does it necessarily follow that the temperature changes also? Give reasons for your answer.

Ans. No. External work must be done if the gas is to lose energy (heat), or work done *on* it, if it is to gain energy.

CHAPTER V

THE PROPERTIES OF FLUIDS (*continued*)—*LIQUIDS—VAPOURS*

Change of State.—Certain fluids, such as ammonia (NH_3), carbon dioxide (CO_2), and sulphur dioxide (SO_2), are capable of changing from a liquid to a vapour, and from a vapour to a liquid under conditions which are favourable to the production of low temperatures.

If 1 lb. of each of the three fluids be taken at a temperature of 5° F., and placed in a cylinder 1 sq. ft. in cross-sectional area, fitted with a frictionless but tight piston, the conditions shown in Fig. 20 would obtain. One pound of ammonia would occupy 0·02475 cub. ft.; the carbon dioxide 0·017 cub. ft.; and the sulphur dioxide 0·0108 cub. ft. To keep each from vaporizing, loads or weights of 4920 lb., 49,248 lb., and 1690 lb., respectively, would be required, representing the total pressure per square foot.

If each weight is very slightly decreased, and the surrounding temperature be *kept* by some definite means at 5° F., the liquids will slowly vaporize, all the ammonia eventually becoming vapour and occupying 8·07 cub. ft., and absorbing 552 B.Th.U. during the operation. The carbon dioxide would occupy 0·26 cub. ft., and absorb 121 B.Th.U. The sulphur dioxide 6·5 cub. ft., and absorbing 170 B.Th.U.

This vaporization and absorption of heat is the action which is continually going on in the refrigerator or evaporator of a vapour machine at a *low temperature.*

If the reverse operation be performed, taking ammonia only as an example—then if a pressure slightly greater than 4920 lb. be applied, the vapour will condense and *give up* 552 Th.U. to the surrounding media, which will constantly need changing if it is to be kept at 5° F., or it would otherwise rise above this stipulated temperature.

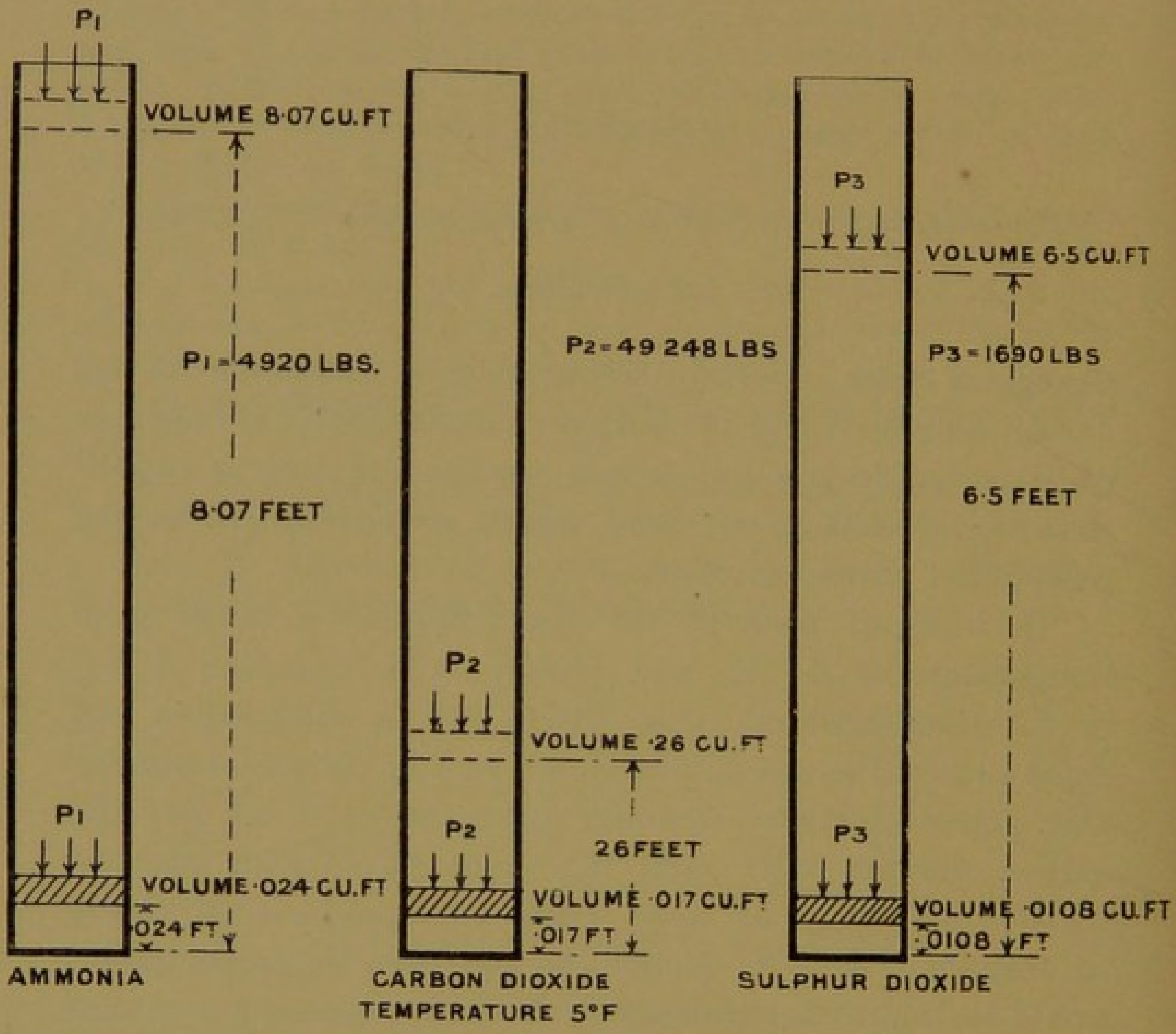

Fig. 20.

The 552 Th.U. is an amount called the "latent heat of vaporization or evaporation" at 5° F., and at a pressure of 4920 lb. per sq. ft. The importance in refrigeration of ammonia, carbon dioxide, and sulphur dioxide lies in the fact that large quantities of heat, as just indicated, *can* be absorbed at low temperatures.

If the temperature of 5° F. be increased to, say 86° F. we find the "properties" have undergone a change. For ammonia, $P_1 = 24{,}600$ lb., and the latent heat = 524 Th.U.; carbon dioxide, $P_2 = 155{,}520$ lb., and the latent heat = 19·28 Th.U.; sulphur dioxide, $P_3 = 9555$ lb., and the latent heat = 144·8 Th.U.

Certain terms are used in connection with these "properties" which will now be explained.

Let 1 lb. of a liquid (volume = V_1) be placed in a cylinder having an area of 1 sq. ft., and covered with a frictionless piston, weighted with a certain load, which, together with any pressure (such as that of the atmosphere) will give a total pressure per sq. ft. P, and $\frac{P}{144}$ = pressure in pounds per sq. in. = p.

(*a*) If heat be applied to the bottom of the cylinder, a temperature t, at which the liquid will boil, will eventually be reached. This t depends on P. The heat necessary for this operation is called *sensible heat* (h_s).

(*b*) Vapour—known as saturated vapour—is formed until the 1 lb. is evaporated, the piston being forced up a certain height, depending on the liquid. The heat necessary for this operation is called *latent heat* (L), the greater part of this heat being employed in changing the state of the fluid, and is referred to as *internal latent heat* (L_I), the remaining part being absorbed in doing work by forcing the piston with its total load P through the certain height, and the work done (called *external work*) in foot-pounds would be PV, and the heat equivalent—

$$\frac{PV}{J} = L_E$$

L_E being "*external latent heat*,"

$$L = L_I + L_E$$

The volume V_2, occupied by 1 lb. of the saturated vapour is called "*specific volume*." The number of pounds in a cubic foot will be $\frac{1}{V_2}$ = weight of 1 cub. ft., and is called the "*specific density.*"

The specific volume and density must always be referred to the particular t and P under consideration.

The total heat (H) required for the operation would be—

$$\begin{aligned} H &= h_s + L_1 + L_E \\ &= h_s + L \end{aligned}$$

measured from the starting temperature.

(c) If heat is applied after all the liquid has vaporized, the vapour will become "superheated," and the greater the degree of superheat the more nearly will the vapour approximate to a perfect gas.

Dry saturated vapour is one which, at a certain temperature, has a definite pressure, a definite specific volume, and a definite specific density.

Wet or supersaturated vapour is one which has a quantity of very fine particles of liquid floating in the dry vapour. The proportion of this dry vapour to the whole is called the "*dryness fraction,*" thus—

$$\text{Dryness fraction} = \frac{\text{weight of dry vapour}}{\text{total weight of vapour}}$$

Summary.—Taking the three examples mentioned in Fig. 20, at 5° F., we have the following:—

(1) *Ammonia*—

Volume occupied by dry saturated vapour . . $V_2 = 8{\cdot}07$

" " " liquid . . . . $V_1 = 0{\cdot}024$

Increase of volume during evaporation $V_2 - V_1 = V = \overline{8{\cdot}046}$

$$\begin{aligned} \text{Work done during evaporation} &= PV \\ &= 4920 \times 8{\cdot}046 \\ &= 39{,}586 \text{ ft.-lb.} \\ \frac{PV}{J} &= \frac{39{,}586}{778} \\ &= 50{\cdot}8 \text{ Th.U.} \end{aligned}$$

If we take the total latent heat at the given t, 5° F. 552·4 Th.U., then—

$$\begin{aligned} L &= 552{\cdot}4 \text{ total latent heat} \\ \frac{PV}{J} &= \ \ 50{\cdot}8 \text{ external} \quad ,, \quad ,, \\ L - \frac{PV}{J} &= 501{\cdot}6 \text{ internal} \quad ,, \quad ,, \end{aligned}$$

(2) *Carbon dioxide*—

Volume occupied by dry saturated vapour	0·260
,, ,, ,, liquid	0·017
Increase of volume during evaporation . . . V =	0·243

$$\begin{aligned} \text{Work done} &= PV \text{ ft.-lb.} \\ &= 49{,}248 \times 0{\cdot}243 = 11{,}967{\cdot}2 \\ &= 15{\cdot}4 \text{ Th.U.} \\ L &= 121{\cdot}5 \text{ total latent heat} \\ \frac{PV}{J} &= \ \ 15{\cdot}4 \text{ external} \quad ,, \quad ,, \\ L - \frac{PV}{J} &= 106{\cdot}1 \text{ internal} \quad ,, \quad ,, \end{aligned}$$

(3) *Sulphur dioxide*—

Volume occupied by dry saturated vapour . . .	6·50
,, ,, ,, liquid	0·0108
Increase of volume during evaporation . . V =	6·4892

$$\begin{aligned} \text{Work done} &= PV \text{ ft.-lb.} \\ &= 1690 \times 6{\cdot}4892 = 1096{\cdot}67 \text{ ft.-lb.} \\ &= 14{\cdot}09 \text{ Th.U.} \\ L &= 169{\cdot}94 \text{ total latent heat} \\ \frac{PV}{J} &= \ \ 14{\cdot}09 \text{ external latent heat} \\ L - \frac{PV}{J} &= 155{\cdot}85 \text{ internal latent heat} \end{aligned}$$

The following tables and curves (Figs. 21, 21A, and 22) give the properties of the three fluids now generally used in refrigeration.

SATURATED AMMONIA (De Volson Wood).

Temperature.		Lb. Pressure Absolute.		Heat of Vaporization.	External Heat.	Internal Heat.	Volume per Lb. in Cub. Ft.		Weight of a Cub. Ft. of Vapour $\frac{1}{V_2}$ lb.
Degrees F. t	Absolute T	Per Sq. Ft. P	Per Sq. In. p	L Th.U.	$\frac{PV}{J}$	$L-\frac{PV}{J}$	Vapour V_2	Liquid V_1	
− 40	420·66	1540·0	10·69	579·67	48·25	531·42	24·38	0·0234	0·0411
− 30	430·66	2035·8	14·13	573·69	48·85	524·84	18·67	0·0237	0·0535
− 20	440·66	2656·4	18·45	567·67	49·44	518·23	14·48	0·0240	0·0690
− 10	450·66	3428·0	23·77	561·61	50·05	511·56	11·36	0·0243	0·0880
± 0	460·66	4373·5	30·37	555·50	51·38	504·12	9·14	0·0246	0·1094
+ 5	465·66	4920·5	34·17	552·43	50·84	501·59	8·04	0·0247	0·1243
10	470·66	5522·2	38·55	549·35	51·13	498·22	7·20	0·0249	0·1381
20	480·66	6905·3	47·95	543·15	51·65	491·50	5·82	0·0252	0·1721
30	490·66	8556·4	59·41	536·92	52·02	484·90	4·73	0·0254	0·2111
40	500·66	10512	73·00	530·63	52·42	478·21	3·88	0·0257	0·2577
50	510·66	12811	88·96	524·30	52·82	471·44	3·21	0·02601	0·3115
60	520·66	15494	107·60	517·93	53·21	464·76	2·67	0·0265	0·3745
70	530·66	18606	129·21	511·52	53·67	457·95	2·24	0·0268	0·4664
80	540·66	22192	154·11	504·66	53·96	450·75	1·89	0·0272	0·5291
90	550·66	26295	182·80	498·11	54·28	443·70	1·61	0·0274	0·6211
100	560·66	30980	215·14	491·50	54·54	437·35	1·36	0·0279	0·7353

In connection with this table it is found approximately—

$$pu^{1\cdot03} = 293$$

where p = lb. per sq. in.
u = volume in cub. ft. per lb.

SATURATED SULPHUR DIOXIDE (De Volson Wood).

Temperature.		Lb. Pressure Absolute.		Heat of Vaporization.	External Heat.	Internal Heat.	Volumes per Lb. Cub. Ft.		Weight of a Cub. Ft. of Vapour
Degrees F. t	Absolute T	Per Sq. Ft. P	Per Sq. In. p	L Th.U	$\frac{PV}{J}$	$L - \frac{PV}{J}$	Vapour V_2	Liquid V_1	$\frac{1}{V_2}$ lb.
− 20	440·66	845·526	5·878	175·829	13·487	162·342	12·40572	0·01056	0·08068
− 10	450·66	1133·102	7·868	173·683	13·754	159·829	9·45485	0·01066	0·10590
± 0	460·66	1483·226	10·300	171·260	13·991	157·269	7·34900	0·01078	0·13627
+ 5	465·66	1690·709	11·741	169·945	14·095	155·850	6·49701	0·01084	0·15418
+ 10	470·66	1921·648	13·344	168·562	14·199	154·363	5·75960	0·01092	0·17395
20	480·66	2457·702	17·067	165·587	14·360	151·227	4·55676	0·01101	0·21999
30	490·66	3105·809	21·568	162·337	14·490	147·847	3·64071	0·01113	0·27551
40	500·66	3881·261	26·953	158·811	14·580	144·231	2·93377	0·01125	0·34217
50	510·66	4800·128	33·334	155·009	14·627	140·382	2·38216	0·01138	0·42180
60	520·66	5879·188	40·828	150·931	14·630	136·301	1·94756	0·01151	0·51652
70	530·66	7135·782	49·554	146·577	14·587	131·990	1·60197	0·01164	0·62880
80	540·66	8584·079	59·612	142·447	14·544	127·903	1·32998	0·01177	0·75861
90	550·66	10253·125	71·202	137·042	14·339	122·703	1·10022	0·01191	0·91886
100	560·66	12150·406	84·380	131·860	14·154	117·706	0·91822	0·01205	1·10342

SATURATED CARBON DIOXIDE (Ledoux).

Temperature in Degrees F.	Absolute Pressure Lb. Sq. In.	Heat of Vaporization.	External Heat.	Internal Heat.	Increase of Volume.	Weight of Cub. Ft. Vapour.
t	p	L Th.U.	$\frac{PV}{J}$	$L - \frac{PV}{J}$	V	Lb.
− 22	210	136·15	16·20	119·95	0·4138	2·321
− 13	249	131·65	16·04	115·61	0·3459	2·759
− 4	292	126·79	15·80	110·99	0·2901	3·265
5	342	121·50	15·50	106·00	0·2435	3·853
14	396	115·70	15·08	100·62	0·2042	4·535
23	457	109·37	14·58	94·79	0·1711	5·331
32	525	102·35	13·93	88·42	0·1426	6·265
41	599	94·52	13·14	81·38	0·1177	7·374
50	680	85·64	12·15	73·49	0·0960	8·708
59	768	75·37	10·91	64·46	0·0763	10·356
68	864	62·98	9·29	53·69	0·0577	12·480
77	968	46·89	7·06	39·83	0·0391	15·475
86	1080	19·28	2·95	16·33	0·0147	21·519

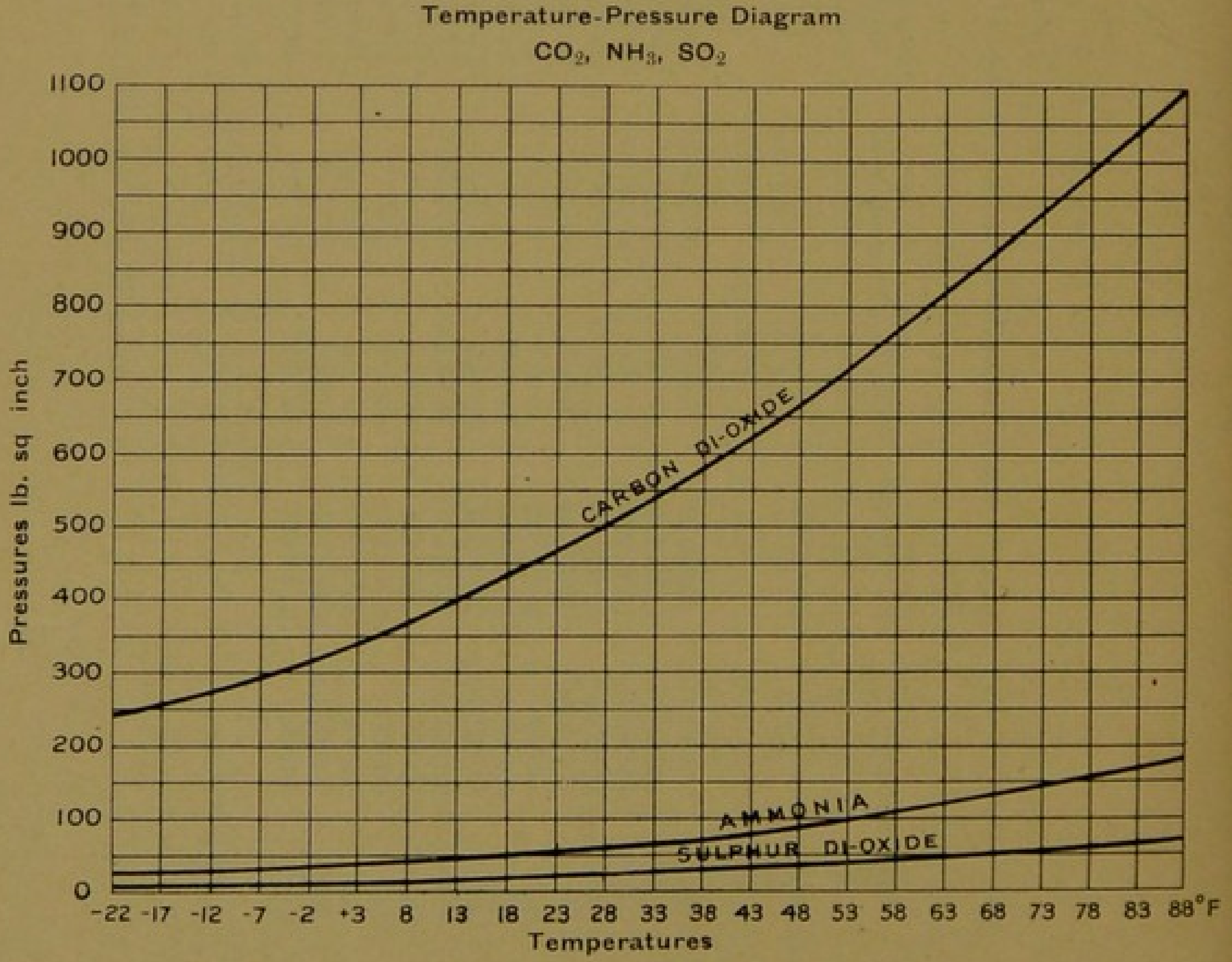

Fig. 21.

CRITICAL DATA.

Critical Temperature.—There is a certain temperature for each vapour, *above* which it is impossible to liquefy it, however great the pressure may be.

Critical Pressure.—The pressure that will cause liquefaction *at* the critical temperature is called the "critical pressure." For ammonia and sulphur dioxide, the critical temperature is far above and for air far below the ordinary working temperatures. For carbon dioxide, Andrews found the critical temperature to be 30·9° C. (87·6° F.), and the critical pressure 74 atmospheres.

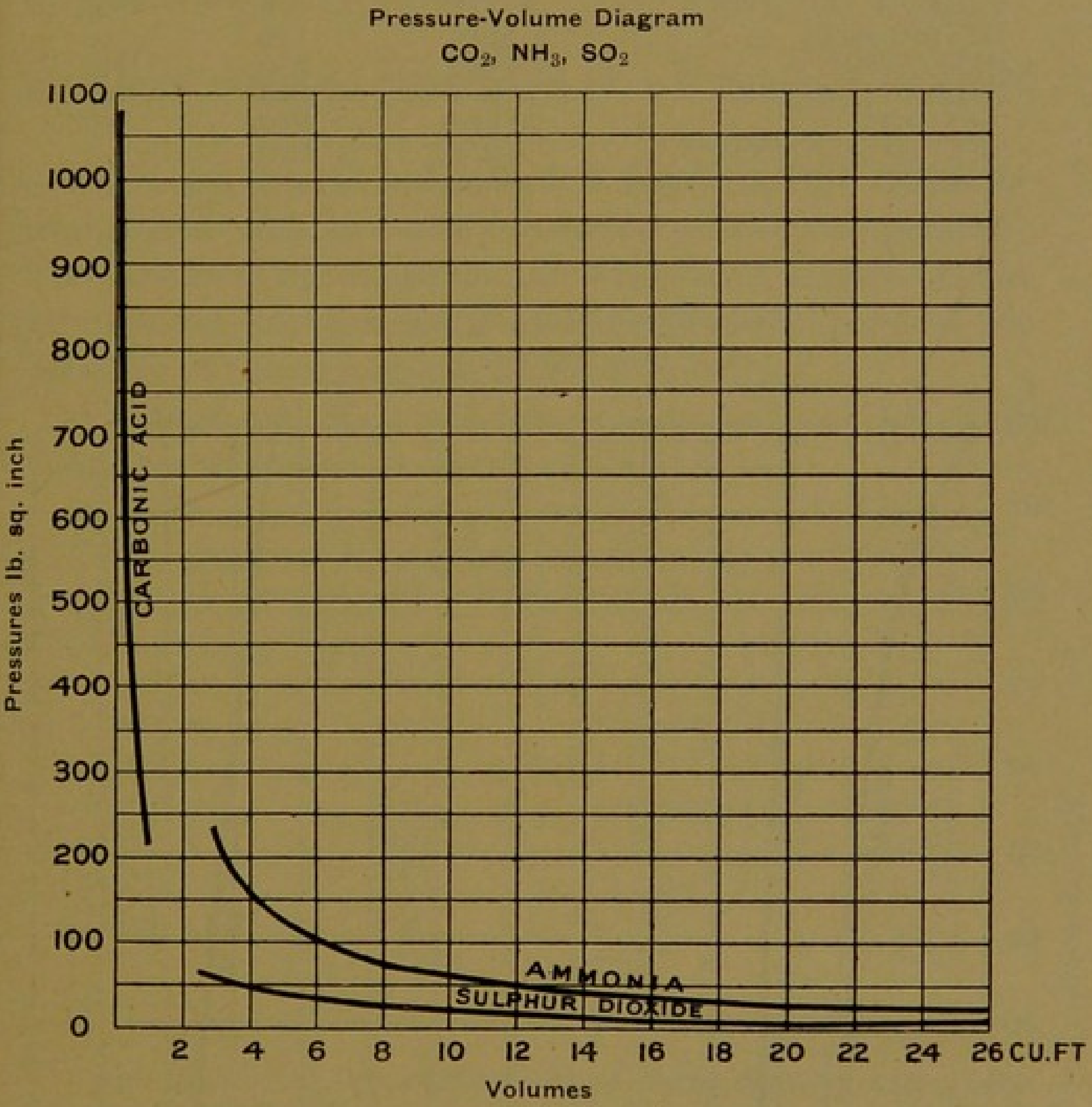

FIG. 21A.

TABLE OF CRITICAL DATA.

SUBSTANCE.	CRITICAL TEMPERATURE CENTIGRADE.	CRITICAL PRESSURE ATMOSPHERES.	DENSITY.
AIR	– 146·6	45·0	0·59
AMMONIA	131·0	115·0	—
CARBON DIOXIDE . .	30·9	74·0	0·46
HYDROGEN	– 240·0	13·3	—
NITROGEN	– 146·0	35·0	0·44
NITROUS OXIDE . . .	35·4	75·0	0·41
OXYGEN	– 118·0	50·0	0·60
SULPHUR DIOXIDE .	155·4	79·0	—
WATER	358·0	195·0	—

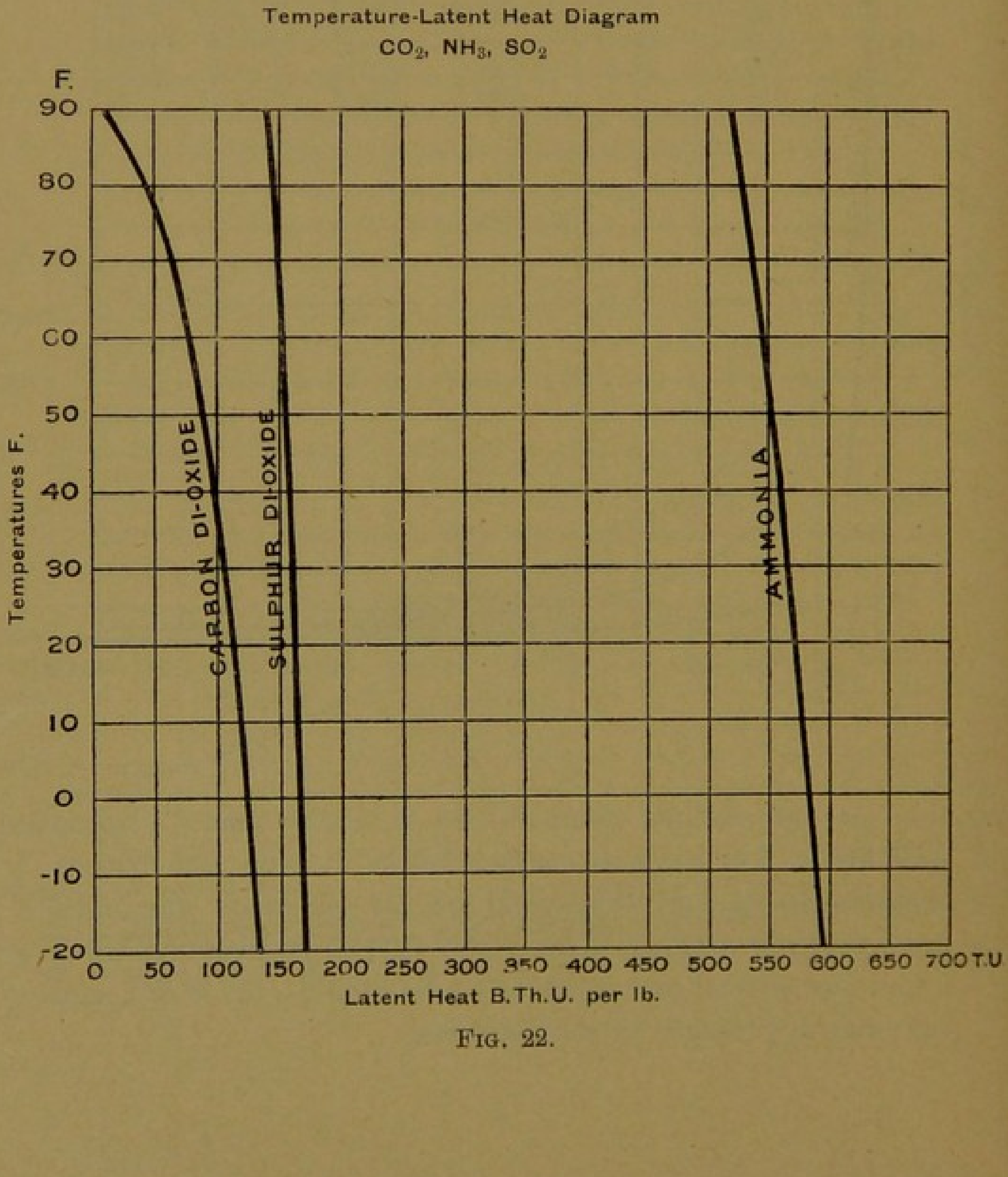
Temperature-Latent Heat Diagram
CO_2, NH_3, SO_2

FIG. 22.

Density of Liquefied Gases and their Saturated Vapours.—In the saturated tables, the density or weight of 1 cub. ft. of the saturated vapour is given for the various temperatures and pressures. For example, the weight of 1 cub. ft. of CO_2 at 23° F., or $-5°$ C., is given as 5·331 lb. Comparing this with water whose average density may be taken as 1·00, and 62·3 lb. per cub. ft.,

$$\text{density of saturated vapour } CO_2 \text{ at } -5° \text{ C.} = \frac{5{\cdot}331}{62{\cdot}3} = 0{\cdot}085$$

other values can be calculated if required, but it can be readily seen that the density increases with the temperature, The density of the liquid, on the other hand, *decreases* as the temperature increases, until at the critical temperature the densities of the vapour and liquid are identical.

Cailletet and Mathias[1] have determined the following values for the densities of carbon dioxide :—

DENSITY OF CARBONIC ANHYDRIDE (CO_2).

SATURATED VAPOUR.		LIQUID.	
Temperature C.	Density.	Temperature C.	Density.
− 23 degrees	0·057	− 34 degrees	1·057
− 5 ,,	0·085	− 25 ,,	1·016
+ 0·5 ,,	0·0983	− 11·5 ,,	0·966
+ 10·1 ,,	0·141	− 1·6 ,,	0·910
+ 19·7 ,,	0·201	+ 11·0 ,,	0·840
+ 30·2 ,,	0·350	+ 22·2 ,,	0·726

The graphical representation of these figures are given in Fig. 23, the dotted extensions of the liquid and vapour curves being carried only to the critical temperature of 30·90° C., with a corresponding density of 0·46.

Specific Heat of Vapours and their Liquids.—The specific heat of vapours, both at constant pressure and constant volume, vary with the temperature, more so when nearing their saturation point. The temperature also affects the

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[1] *Journal Chemical Society*, vol. l. p. 758.

specific heat of the liquid, but the given values may be taken as average figures.

SPECIFIC HEATS.

SUBSTANCE.	VAPOUR.		LIQUID.
	CONSTANT VOLUME.	CONSTANT PRESSURE.	
Ammonia	0·393	0·508	1·02
Carbon dioxide	0·177	0·217	0·98
Sulphur dioxide . . .	0·123	0·154	0·40

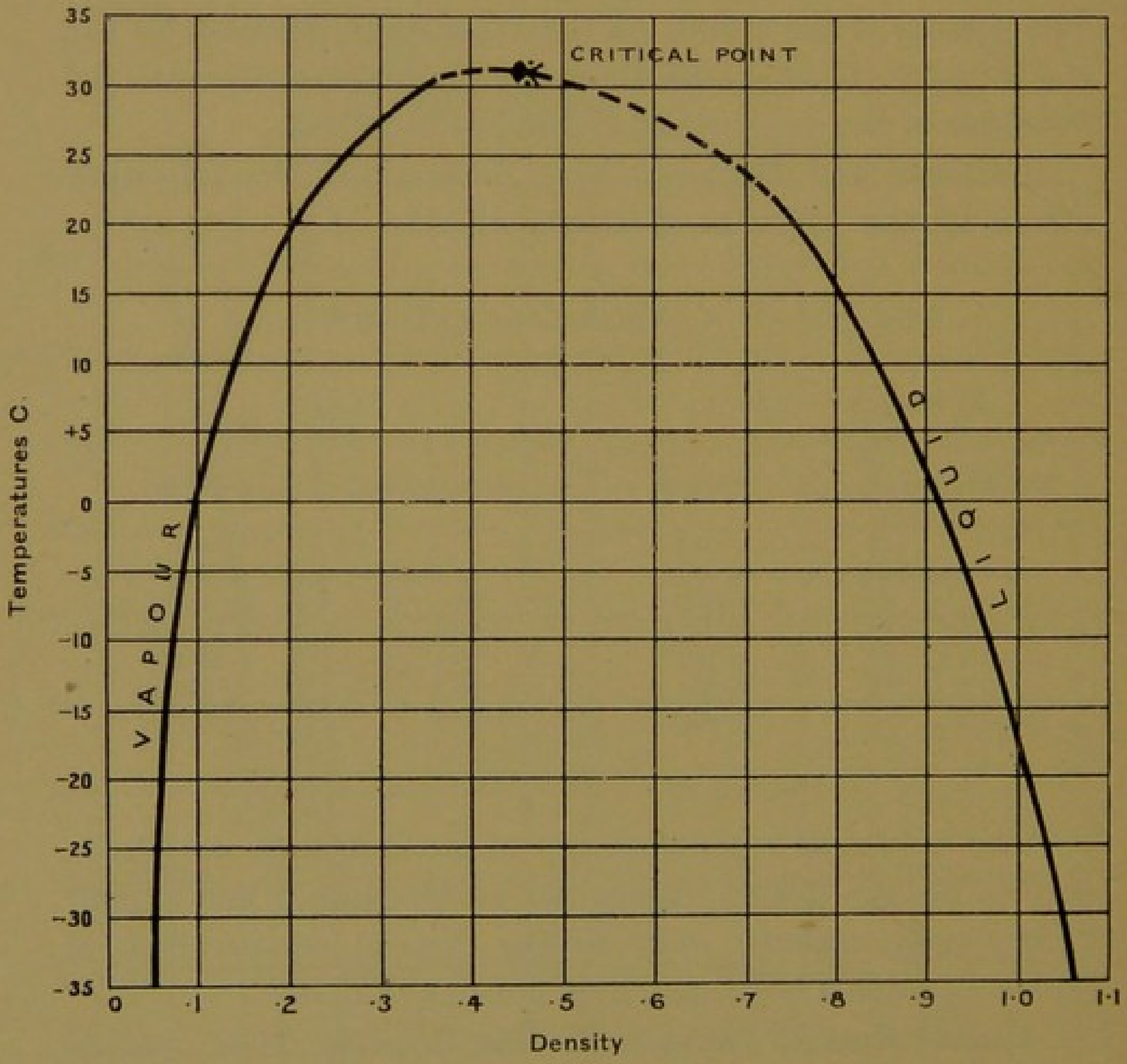

FIG. 23.

The following table may be taken as typical of the manner in which specific heats of liquids vary with the temperature—a further example (water) will be given in a subsequent chapter:—

SPECIFIC HEAT OF LIQUID AMMONIA.[1]

Temperature C.	Specific Heat.	Temperature C.	Specific Heat.
– 40	0·837	+ 10	1·020
– 30	0·873	20	1·057
– 20	0·910	30	1·093
– 10	0·947	40	1·130
± 0	0·983	50	1·166

Sulphuric ether, Methylic ether, and Pictet fluid are also used to a limited extent in refrigerating machines, and the following table gives the pressures and corresponding temperatures according to Ledoux:—

Temperature F. °	Pressure of Vapour in Lb. per Sq. In.		
	Sulphuric Ether.	Methylic Ether.	Pictet Fluid.
– 4	1·30	17·06	13·5
+ 14	2·19	25·27	19·3
32	3·55	36·34	26·9
50	5·54	50·84	36·2
68	8·38	69·35	48·1
86	12·31	92·41	64·1

Pictet fluid is a mixture of sulphur dioxide and carbonic acid, only 3 or 4 per cent. of the latter, however, being employed.

QUESTIONS.

(1) Using the approximate formula, $pv^{1·03} = 293$, find the volume occupied by saturated ammonia vapour, when (*a*) $p = 10·7$ lb. sq. in.; (*b*) 30·37 lb.; (*c*) 154 lb.; and also the pressure when (*d*) the volume $v = 18·6$ cub. ft.; (*e*) 8·04 cub. ft.; (*f*) 2·24 cub. ft.—For Answers, consult the Ammonia Table.

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[1] "Ice and Refrigeration," June, 1898.

(2) Explain what is meant by the terms "critical pressure" and "critical temperature."

(3) Draw the curve for specific heats of ammonia, taking temperatures as ordinates and specific heats as abscissæ.

(4) De Volson Wood gives for saturated ammonia at 50° F.—$P = 12811$; $V_1 = 0{\cdot}02601$; $V_2 = 3{\cdot}21$ cub. ft., and the external heat 52·82 Th.U. Prove this, taking $J = 778$.

(5) What do you understand by the expression "properties of fluids"?

(6) What is the maximum pressure found in the compressors of ammonia machines? (B.T.)

Ans. The maximum pressure will depend on the temperature of the circulating or condensing water. To this temperature add ten degrees and consult the tables, thus:

(*a*) Circulating water 60° F.: 60 + 10 = 70° F.; at 70° F. the pressure is 129 lb. per sq. in.

(*b*) Condensing water 76° F.: 76 + 10 = 86° F.; at 86° F. the pressure is 171 lb. per sq. in.

The reason for adding 10 degrees is, that the ammonia will always be warmer than the water.

(7) What is the maximum pressure found in the compressors of carbonic acid machines? (B.T.)

Ans. As in question 6:

(*a*) Circulating water at 58° F.: 58 + 10 = 68° F.; at 68° F. the pressure is 864 lb. per sq. in.

(*b*) Circulating water at 76° F.: 76 + 10 = 86° F.; at 86° F. the pressure is 1080 lb. per sq. in.

CHAPTER VI

THE LAWS OF THERMODYNAMICS—CARNOT'S CYCLE—EFFICIENCY—COEFFICIENT OF PERFORMANCE

Laws of Thermodynamics.—*First Law.*—When heat is transformed into mechanical energy or mechanical energy transformed into heat, a certain definite relationship exists, which is expressed as the mechanical equivalent of heat, or Joule's equivalent. *Second Law.*—The second law has been expressed in various ways. Maxwell gives one of the best definitions :—

"Admitting heat to be a form of energy, the second law asserts that it is impossible, by the unaided action of natural processes, to transform any part of the heat of a body into mechanical work except by allowing heat to pass from that body into another at a lower temperature."

As an analogy—water in an elevated reservoir cannot do work unless it is allowed *to pass* to a lower level. In the reservoir it represents so much potential energy.

A heated body contains an amount of energy (potential), but unless the heat is allowed to fall to a lower level aided by a suitable machine, no work will be done.

Again, a body may contain a large quantity of heat, but if it is at the same temperature as its surroundings the heat cannot be made to do work, because it cannot change its level, *i.e. it is not available.*

It is not *every* thermal unit that *can* be transformed into work, and we must bear in mind that "energy is only useful when transferred—it is during transference of energy that work is done, hence any condition that prevents or lessens the transferability of energy prevents or lessens the performance of work by means of it, *i.e.* makes it more or less useless" (Lodge).

Clausius gives the second law in a manner that appears peculiarly applicable to refrigeration:—

"It is impossible for a self-acting machine, unaided by any external energy, to convey heat from one body to another at a higher temperature."

This, in common with the other definitions of the second law, places a *limit* to the fall of temperature in a body doing work by pointing out that it actually requires *work* to be expended (external aid) to convey heat from one body to another at a higher temperature, in other words, to make a body colder than its surroundings.

It is important to at once inquire in what way heat can be conveyed from a colder to a warmer body.

The water analogy can again be used.

Work can be done by allowing water to flow from the tank A (Fig. 24) to the tank B, through the water engine C. With a definite amount of water, the greater the height AC, the greater the amount of work done.

If water is to pass from B to A—the engine C must be replaced by a pump—which will require an expenditure of work to drive it. For a given quantity of water, the greater the height BA the greater the amount of energy expended.

Heat will naturally flow (it can be made to do work) from a temperature T_1 (Fig. 24) to T_2, but, as Clausius points out, heat can only be transferred from T_2 to T_1 by the aid of an external agency—or by the expenditure of work in driving a *heat pump*.

An apparent difference between heat and water as used in the analogy must be noticed, viz. in the case of water the same quantity that leaves the tank A will reach the tank B, and *vice versâ;* but of the heat flowing from A at a temperature of T_1 only a portion will reach B at T_2, the remainder being converted into work.

The heat leaving B at T_2 during the reverse action will be supplemented before reaching A at T_1 by an amount equal to the work *expended* in the heat pump C.

The explanation of the difference is simple.

The water is the agent or medium by which the force of gravity performs work; small lead shot would do almost as well for the purpose.

Heat also requires an agent or substance in order to perform work (heat engine), or on which work may be performed (heat pump), and this agent *does not suffer any change in weight.*

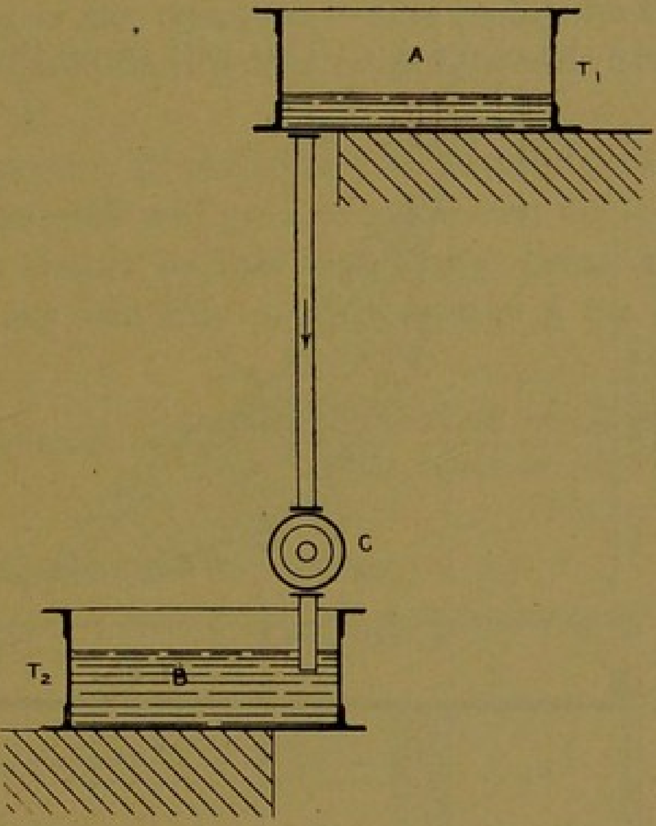

FIG. 24.

Working Substance in Heat Engines and Pumps.—Heat being only a state or condition, and not possessing mass, a substance is necessary in heat engines and heat pumps for the transference of heat.

This working substance may be a solid or a fluid, and in a complete *cycle* of operations it suffers a change of volume and often of state, but not of weight. On the score of economy it is often brought back to its original state for re-use.

Heat Engine: Carnot's Cycle.—Suppose a volume of a gas, V_1 (Fig. 25), and absolute temperature T_1 and pressure P_1, is behind a frictionless piston in an insulated cylinder on which three covers can be placed at will.

The cover A_1 is able to supply or withdraw any required quantity of heat at a temperature of T_1, C_1 being similar at T_2, while B_1 is a perfect heat insulator—no heat being able to enter or leave the cylinder, as heat, when it is applied.

(1) Apply the cover A_1. This will cause the volume V_1 to expand isothermally along the curve AB to a volume V_2. The heat taken in is, say, H_1 thermal units at a temperature T_1.

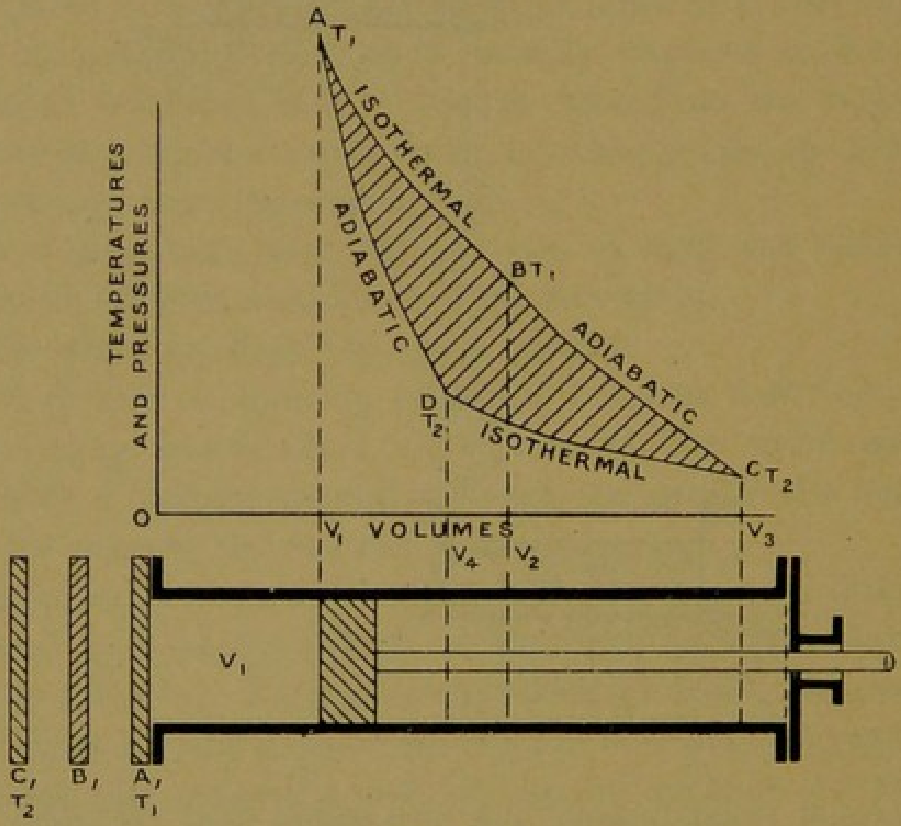

FIG. 25.

(2) Remove A_1, apply B_1 and allow the gas to expand adiabatically along the curve BC to V_3 and T_2. No heat is taken in or rejected *as heat*, but the gas has fallen in temperature, having been called upon to do work at the expense of its internal or intrinsic energy.

(3) Remove the cover B_1 and apply C_1, and compress isothermally at T_2 to volume V_4, rejecting H_2 thermal units at T_2.

(4) At the point D on the curve remove C_1 and apply B_1, and compress adiabatically to A at T_1 and V_1. No heat is taken in or rejected *as heat,* but the temperature has increased by virtue of the work expended.

Efficiency of the Operation.—The useful work performed during the operation is indicated graphically by the shaded area ABCDA.

The proportion of the total heat *received* to that portion *converted* into work will give an expression for the efficiency which must always be less than unity, because we cannot convert all our heat into work by virtue of the second law.

Thus—

$$\text{Efficiency} = \frac{\text{heat equivalent of work done}}{\text{heat received}}$$

and

heat equivalent of work done =

heat received minus the heat rejected

hence,

$$\text{Efficiency} = \frac{H_1 - H_2}{H_1} \quad . \quad . \quad . \quad . \quad . \quad . \ (1)$$

The weight of the perfect gas remaining the same throughout the cycle, H_1 and H_2 will be proportional to T_1 and T_2; hence equation (1) may be written—

$$\text{Efficiency} = \frac{T_1 - T_2}{T_1} \quad . \quad . \quad . \quad . \quad . \quad . \ (2)$$

$$= \frac{t_1 - t_2}{T_1}$$

This gives the efficiency of a perfect heat engine, which depends solely on the *temperature of reception and rejection of heat;* the greater the range of temperature (*i.e.* the greater the value of $T_1 - T_2$) the greater the efficiency.

Lodge gives as one reading of the second law—

"The transferable portion of heat is to the whole heat as the available difference of temperature is to the whole temperature above absolute zero. Hence the efficiency of transfer, which means the ratio of the transferable to the total heat, is equal to the ratio of the available difference of temperature to the maximum absolute temperature."

This embodies equations (1) and (2).

Carnot's Cycle. Heat Pump.—Suppose a volume of a gas V_1 (Fig. 25) and absolute temperature T_1 is—

(1) expanded adiabatically from A at T_1 to D at T_2 and V_4, neither receiving nor rejecting heat as heat;

(2) expanded isothermally from D at T_2 to C at T_2 and V_3, receiving (extracting) H_2 thermal units of heat from C_1 at T_2;

(3) compressed adiabatically from C at T_2 and V_3 to B at T_1 and V_2, not receiving heat as heat;

(4) compressed isothermally from B at T_1 and V_2 to A at T_1 and V_1, rejecting H_1 thermal units of heat to A at T_1.

The cycle of the heat engine is thus reversed, giving the cycle of the heat pump or refrigerating machine.

The ratio of the heat pumped or extracted from the cold body (C_1) is called the *coefficient of performance*, as it is a value greater than unity, and the term "efficiency" cannot, therefore, be employed.

$$\left.\begin{matrix}\text{Coefficient of per-}\\ \text{formance}\end{matrix}\right\} = \frac{\text{heat extracted}}{\text{heat equivalent of work expended}}$$

$$= \frac{H_2}{H_1 - H_2}$$

$$= \frac{T_2}{T_1 - T_2}$$

This value will be a maximum when $T_1 - T_2$ is a minimum.

From this follows directly one of the most important rules in practical refrigeration—

The condenser (higher) temperature should be kept as *low as possible, while the temperature of the refrigerator or evaporator (lower) should be kept as high as circumstances will permit.*

EXAMPLE.

A refrigerating machine has a condenser temperature of 86° F. (547° absolute) and evaporator temperature of 5° F. (466°). What is its ideal coefficient of performance?

$$\text{Coefficient of performance} = \frac{T_2}{T_1 - T_2} = \frac{466}{547 - 466} = 5{\cdot}75$$

or

$$\text{Coefficient of performance} = \frac{T_2}{t_1 - t_2} = \frac{466}{86 - 5} = 5{\cdot}75$$

That is, for every thermal unit given to the machine as work, it will extract, under the given conditions, 5·75 thermal units from the cold body.

Ewing[1] gives the following interesting table:—

COEFFICIENTS OF PERFORMANCE OF A PERFECT REFRIGERATING MACHINE.

LOWER LIMIT OF TEMPERATURE T_2 IN DEGREES F.	UPPER LIMIT OF TEMPERATURE T_1 IN DEGREES F.					
	50°	60°	70°	80°	90°	100°
–10°	7·5	6·4	5·6	5·0	4·5	4·1
0°	9·2	7·7	6.6	5·8	5·1	4·6
10°	11·7	9·4	7·8	6·7	5·9	5·2
20°	16·0	12·0	9·6	8·0	6·8	6·0
30°	24·5	16·3	12·2	9·8	8·2	7·0
40°	50·0	25·0	16·7	12·5	10·0	8·3

"Taking the perpendicular columns, it is seen how the

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[1] "Howard Lectures."

refrigerating effect of a given amount of work depends on the temperature of the thing from which the heat is being absorbed. Taking the numbers horizontally, it is seen how the same quantity depends on the temperature of the condensing water; that is to say, on the temperature to which you are obliged to raise the heat in order to get rid of it."

EXAMPLE.

Refrigerating machines cool (*a*) 1 lb. of water from 70° to 60° F.; (*b*) 10 lb. of water from 70° to 69° F. (I.) How many thermal units are removed? and (II.) what is the maximum coefficient of performance in each case?

(I.) (*a*) 1 lb. from 70° to 60° = 10 Th.U. removed
(*b*) 10 lb. „ 70° to 69° = 10 „ „

The quantity of heat removed is the same in each case.

(II.) (*a*) Coefficient of performance $\frac{T_2}{t_1 - t_2} = \frac{521}{70 - 60}$

$$= 52{\cdot}1$$

(*b*) „ „ $= \frac{530}{70 - 69}$

$$= 530$$

This example (although ideal to the extent of supposing a refrigerating machine capable of working through so small a range of temperature as that of the water it is cooling) indicates very clearly that the *range of temperature*, and *not* the *number of thermal units extracted*, regulates the efficiency of a refrigerating plant.

In other words, it requires more work to cool a certain weight of a substance (whose state does not alter) through n number of degrees than to cool n times the weight through one degree.

Carnot's Cycle using a Liquefiable Vapour.

I. Heat Engine.—Imagine a cylinder provided with three covers as in Fig. 25, and that at the start of the stroke there is 1 lb. of a liquid occupying a volume V_1 (Fig. 26) at T_1 and P_1.

(1) Apply the cover, which is at a temperature of T_1; the liquid will gradually vaporize at T_1. When the whole is just vaporized, the volume occupied (V_4) will be the specific volume for P_1 and T_1; the heat absorbed will be H_1 (say).

The line AB will represent this action on the diagram.

(2) At V_4 withdraw the cover T_1 and place on the non-conducting cover. The vapour will expand adiabatically, doing work, to $T_2P_2V_3$. No heat, as heat, will be received or rejected; the curve BC represents the action.

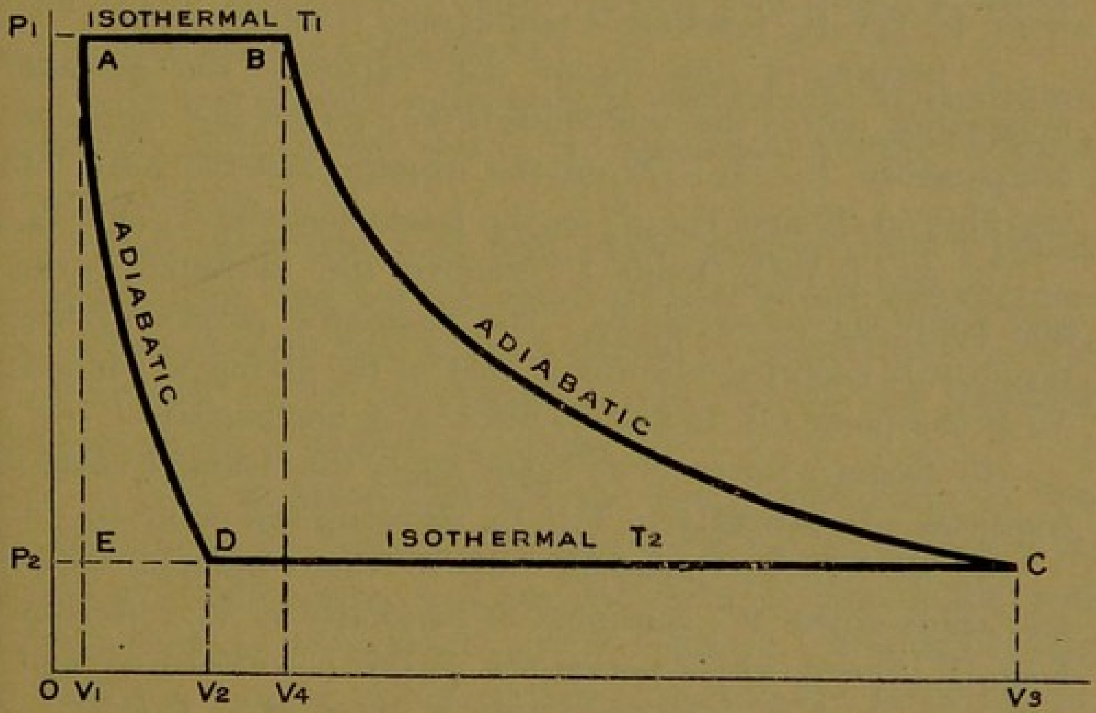

Fig. 26.

(3) Remove the insulated cover and place on the cover which is at a temperature of T_2; compress slowly to V_2, represented by the line CD. Heat rejected = H_2.

(4) At V_2 place on the insulated cover, and compress adiabatically until $P_1T_1V_1$ is again reached, following the curve DA. No heat, as heat, supplied or rejected, and the liquid will now be in its original condition.

The area ABCDA will represent the work performed during the cycle, and

$$\text{Efficiency} = \frac{H_1 - H_2}{H_1} = \frac{T_1 - T_2}{T_1} = \frac{t_1 - t_2}{T_1}$$

II. Refrigerating Machine.—Starting at the point A (Fig. 26), we have a liquid at $P_1T_1V_1$.

(1) Apply the insulated cover, expand adiabatically, doing work, to $T_2V_2P_2$, reaching a point (say) D on the curve.

A portion of the liquid will vaporize, the amount depending on (*a*) the temperature T_1; (*b*) on the range of temperature $T_1 - T_2$; (*c*) on the average specific heats of the fluid at T_1 and T_2; (*d*) on the latent heats at T_1 and T_2.

(2) At $T_2V_2P_2$ (point D) remove the insulated cover and apply the cover at T_2. The remaining portion of the liquid will vaporize, absorbing heat $= H_2$, giving a volume V_3 at the point C; T_2 and P_2 remaining unchanged.

(3) Remove the cover at T_2 and apply the insulated cover; compress adiabatically to $T_1P_1V_4$, reaching the point B.

(4) At $T_1P_1V_4$ (point B) remove the insulated cover and apply cover T_1; compress isothermally to V_1, rejecting heat H_1, during which period the vapour is condensing, and at the point A the original liquid is obtained at $P_1T_1V_1$.

The work expended during the cycle is represented by the area ABCDA.

The heat rejected (H_1) = heat extracted (H_2) + heat equivalent of work expended; hence—

$$\text{heat equivalent of work expended} = H_1 - H_2$$

and

$$\text{Coefficient of performance} = \frac{H_2}{H_1 - H_2} = \frac{T_2}{T_1 - T_2} = \frac{T_2}{t_1 - t_2}$$

The heat engine cycle would be performed by an ideal steam engine; but in actual practice it is not feasible to generate steam, condense same, and then dynamically heat the fluid to T_1 in one vessel.

The use of the feed pump for raising the water from a low to a high pressure, at the same time sending it into the boiler at the lower temperature, makes the ordinary steam engine a **non-reversible** action.

In the vapour refrigerating machine the use of the regulating valve renders the cycle **non-reversible.**

A cycle which is non-reversible cannot attain the efficiency of a Carnot cycle—*reversibility being a thermodynamic test of an ideal cycle.*

All heat should be taken in at one definite temperature, and all heat rejected should be rejected at another definite temperature.

It is clear that cold feed water pumped into a boiler under steam does not receive all its heat at one temperature.

Recognizing that a **steam engine** is non-reversible, it is compared, not to the Carnot cycle, but to the **Rankine cycle**, which is defined as follows:—[1]

"It is assumed that all the component parts of the steam plant are perfect, and that there are no losses due to initial condensation, leakage, radiation, or conduction, and that there is no clearance in the cylinder. The feed water required is taken into the boiler at the exhaust temperature, is gradually raised until that corresponding to saturated steam is reached. Steam is then formed at constant pressure until dry saturated steam is produced, after which, if the steam is to be super-heated, heat is added at constant pressure and at increasing temperature until the required temperature of super-heat is reached.

"The steam is introduced into the cylinder at constant pressure, displacing the piston, and performing external work equal to the absolute pressure multiplied by the volume swept through by the piston up to the point of cut off.

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[1] *Proceedings Institution of Civil Engineers*, vol. cxxxiv. p. 287.

"Beyond that point expansion takes place adiabatically, doing work until the pressure in the cylinder is equal to the back pressure against which the engine is working.

"The steam is then completely exhausted from the cylinder at constant pressure, corresponding with the lower limit of temperature, work being done on the steam by the engine during exhaust, equal to the absolute back pressure multiplied by the total volume swept through by the piston.

"The steam is thus removed from the cylinder, and the cycle is complete."

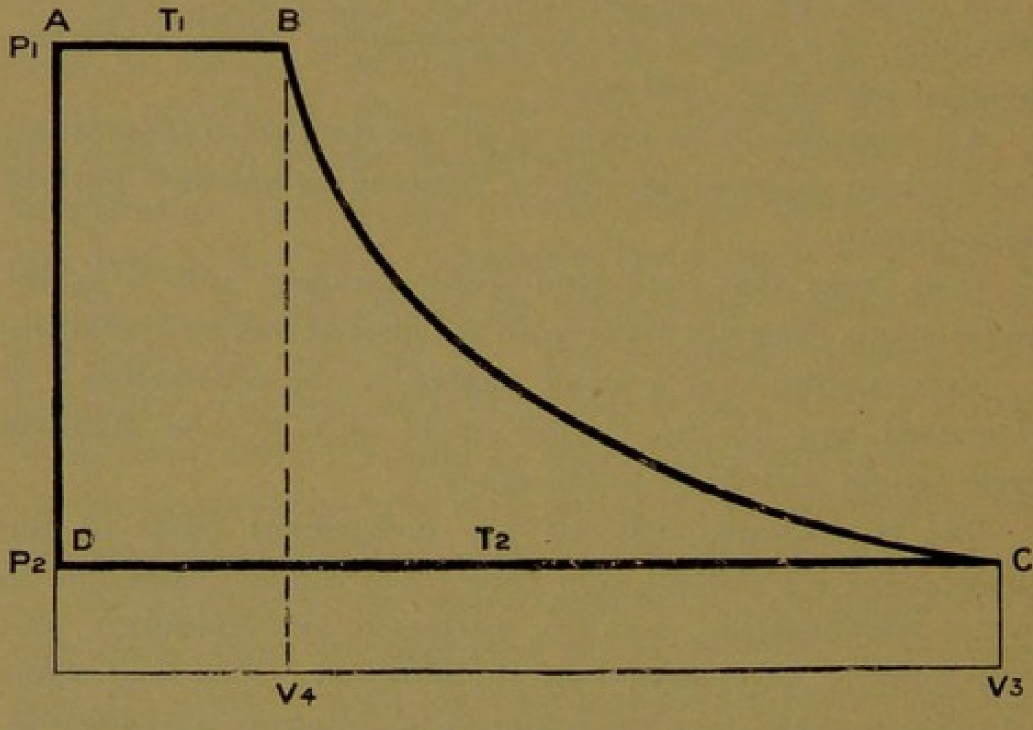

Fig. 27.

The diagram of such an engine using saturated steam is shown in Fig. 27.

During the expansion BC a certain portion of the steam (if not super-heated) would condense, inasmuch as steam, which in its initial state is "dry saturated," if expanded adiabatically (giving out heat as work) will become wet and partially condense.

The means adopted to prevent this is to surround the cylinder with a jacket, and provide sufficient heat to prevent condensation.

Refrigerating Machine.—The practically ideal vapour refrigerating machine would have a similar diagram from its compressor, and the action would be as follows: Liquid at $P_1V_1T_1$ is allowed to expand through a small opening (called a regulating valve) into a vessel (refrigerator or evaporator), whereby a portion of the liquid is vaporized, reducing the whole to $P_2V_2T_2$. In the refrigerator sufficient heat is supplied at T_2 to cause complete evaporation. A cylinder (compressor), with a piston which is mechanically moved, takes the vapour as soon as it is formed at P_2, sweeping through a volume V_3 (Fig. 27).

The communication to the evaporator is then closed, generally by a self-acting valve, and the piston is moved in, compressing the vapour along the saturation curve CB (during which operation heat should be removed by a jacket in the ideal machine) to P_1, V_4, T_1.

Communication is then made to the condenser (by automatic valves), and the piston *sweeps out the whole volume up to the line AD.* During the part of the stroke B to A the condenser has been liquefying the vapour by *extracting* heat, and, at the completion, contains the whole as a liquid at $P_1V_1T_1$. This liquid is then ready for the next cycle of operations.

The practically ideal vapour refrigerating cycle is the exact reverse of the Rankine dry-steam cycle, and it must be particularly noticed,

(1) that the compression curve should be kept saturated.

This can hardly be done in practice, but in many machines the vapour is brought from the evaporator in a super-saturated or wet condition, and consequently superheating to a large extent prevented by the wet particles evaporating during compression, taking up the latent heat and thereby keeping down the temperature. Linde, in his early machines, actually injected liquid during this stroke.

(2) that evaporation by a regulating valve results in a loss.

The Carnot cycle as shown by Fig. 26 is the ideal for a vapour machine, and the area of work expended for a certain refrigerating effect is ABCDA.

In the ordinary machine the work expended is ABCDA (Fig. 27), or ABCEA (Fig. 26), which is greater than the ideal by an amount represented by the area ADEA (Fig. 26), *which is approximately the amount of work the liquid would do if allowed to expand in a cylinder under suitable conditions.*

The loss occasioned by the use of a regulating valve will be discussed in the next chapter.

QUESTIONS.

(1) Give, as briefly as possible, the laws of thermodynamics. Explain how the second law limits the extent to which thermal units by the first law may be converted into foot-pounds.

(2) Deduce an expression, referring to Carnot's cycle for (*a*) the maximum efficiency of a heat engine; (*b*) the coefficient of performance of a refrigerating machine.

(3) Find the coefficient of performance of a perfect refrigerating machine working between (i.) −10° F. and 70° F.; (ii.) 0° F. and 70° F.; (iii.) 10° F. and 70° F.; (iv.) 40° F. and 70° F.

Ans. (i.) 5·6; (ii.) 6·6; (iii.) 7·8; (iv.) 16·7.

(4) Explain why, for a given number of thermal units extracted, it is more economical to cool a large quantity of matter through a few degrees than to cool a small quantity a great number of degrees.

(5) Show that a vapour refrigerating machine traces a reversed card to the Rankine dry-steam cycle.

(6) What is the efficiency of a heat engine where (*a*) t_1 is 370° F. and t_2 110° F.; (*b*) t_1 is 370° F. and t_2 212° F.?

Ans. (*a*) 0·313; (*b*) 0·19.

(7) What was the object in the original Linde system of injecting liquid ammonia into the compressor during compression?

CHAPTER VII

GENERAL OUTLINE OF REFRIGERATING MACHINES —COLD AIR MACHINES—VAPOUR MACHINES— COMPRESSION MACHINES AND ABSORPTION PLANTS

Refrigerating Machines.—Thermodynamically it does not matter what working fluid is employed in a refrigerating cycle, yet certain characteristics, physical properties, and practical considerations limit the choice, which may be cited as follows :—

(1) it must be able to stand the temperatures and pressures employed.

(2) its capacity for heat must be great, in order to carry off the heat extracted from the body to be cooled.

If a liquid is employed, then—

(3) its vaporizing point must be low, and the resulting volume not too great.

(4) its pressures at the temperatures employed must be practicable.

(5) the relation of the latent heat to the specific heat should be high.

Air offers the advantage of being very abundant, and fulfilling the first condition admirably, but, unfortunately, its capacity for heat is very small ; hence, to produce the refrigerating effect required in practice, the machine must be very large.

Also, the air being carried in the expansion cylinder to many degrees below 0° F. leads to a very great range of temperature, which gives, as we have seen, a very low coefficient of performance.

Thus it is that the cold air machine is both cumbersome and extravagant.

They are not, however, without their advantages. In out-of-the-way districts, for instance, where certain classes of fuel may be cheap, the advantage of being able to work without "chemicals" is obvious.

Water.—Water, although an excellent fluid for conveying heat (as in steam engines) cannot be used as a refrigerant, because it freezes at a higher temperature than that usually required in refrigeration.

The fluids which approximate the closest to the conditions named are—

I. anhydrous ammonia (NH_3).
II. carbonic anhydride
  or carbon dioxide (CO_2).
III. sulphurous anhydride
  or sulphur dioxide
  or sulphurous acid (SO_2).

The latter, we find, on consulting the tables, has a pressure of 10·3 lb. per sq. in., or 4·4 lb. below the pressure of the atmosphere at a temperature of 0° F. Thus air is liable to leak into the machine—and is actually found to do so—a condition which seriously interferes with the working.

The field is, therefore, left practically to ammonia and carbonic anhydride.

Of these, the former has the advantage of comparatively low-working pressures, whereas the latter has an advantage, inasmuch as its increase in volume during vaporization is, roughly, only $\frac{1}{33}$ that of the former.

The effect of this is such that, supposing everything theoretically perfect and the fluid working in a Carnot cycle (reversed), carbonic anhydride would give, for the *same compressor piston displacement,* about four times the refrigerating effect of ammonia.

For a given horse-power expended the two would give as near as possible the same results—the difference, if any, being in favour of ammonia.

In order to complete the comparison, it is necessary to refer to the practical cycle of operations.

Cycle of Refrigerant.—Referring to Fig. 28, the refrigerant is drawn from the refrigerator or evaporator at the inferior pressure (P_2), compressed and delivered to the condenser at the superior pressure (P_1), where it is condensed and passes, as a liquid, to the regulating valve, which allows a regulated quantity to pass from the pressure P_1 to the evaporator at P_2, where it evaporates, and the cycle is thereby completed.

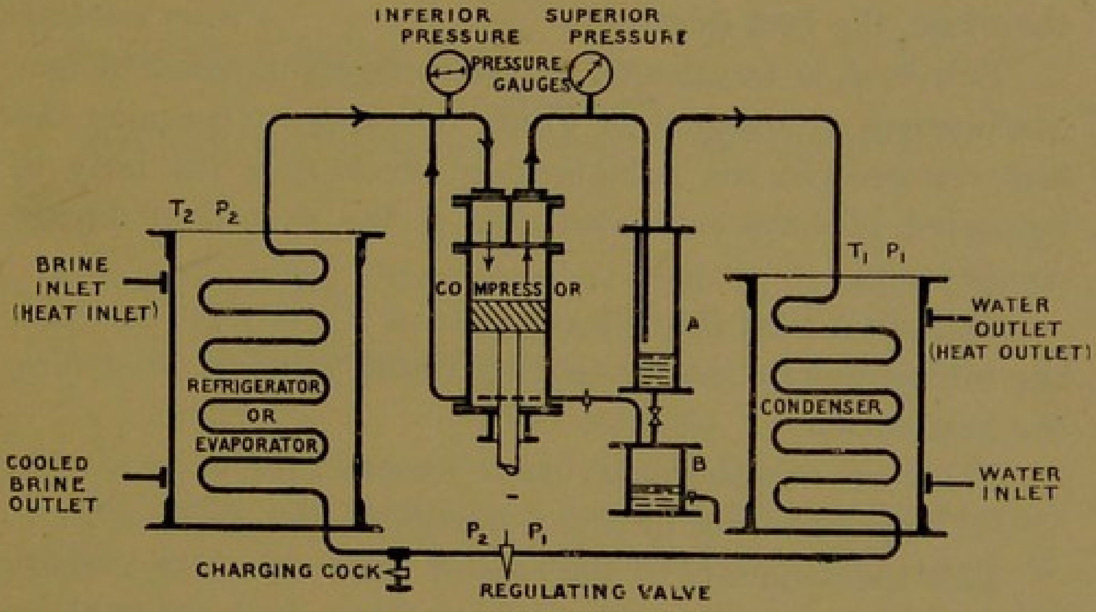

Fig. 28.

(1) The *refrigerator* or *evaporator* is generally composed of coils of pipe through which the refrigerant passes—the outside of the coils being surrounded by "brine" where brine circulation is used, or by air where the direct expansion system is used.

The brine or air, as the case may be, enters the refrigerator at a certain temperature, and leaves it at a lower temperature, *i.e. it gives up heat*, and is thereby cooled.

(2) The *compressor* requires to be driven, *i.e.* work has

to be expended. Steam, gas, and oil engines, or electromotors are the chief prime movers employed for this purpose.

(3) The *condenser* in general construction does not differ greatly from the evaporator. It consists of coils through which the refrigerant passes and is surrounded by the condensing media—water, or air and water, or air only in some cases.

With regard to the thermal operations, and taking a machine outlined in Fig. 28, the heat (low-level heat at T_2) is brought into the machine by the **brine**, having been removed from the body to be cooled. The brine inlet is, therefore, the **heat inlet**.

This heat is transferred to the refrigerant, which is now compressed, at the end of which operation it contains the *heat removed* (*i.e.* the refrigerating effect) from the body to be cooled, *plus* the *heat equivalent* of the work done during compression.

This total heat (high level heat at T_1) is removed from the refrigerant by the circulating **water**, which is, therefore, the **heat outlet**.

There are two thermodynamic losses in the cycle:

(1) super-heating in the compressor.

This loss amounts in the case of ammonia to an average of about 6 per cent., and with carbonic anhydride to about 11 per cent.

(2) in passing the regulating valve.

This loss is due to the refrigerant passing from the condenser at a high temperature to the evaporator or refrigerator at a low temperature—without doing work in an expansion cylinder—which means that *heat* is *carried* into the evaporator.

It would *not* be *more* economical in practice to fit an expansion cylinder to a vapour machine—but still a loss does occur.

What really happens is that the refrigerant partially evaporates, the (latent) heat for this operation being taken from the remaining liquid, which is thereby cooled.

The amount of heat the liquid is capable of giving up depends on its specific heat, which, it will be remembered, alters with the temperature.

Thus the *latent heat* and *specific heat* are important factors, and, together with the *range of temperature* ($T_1 - T_2$), determine the *loss* which takes place—and thus the *value* of the fluid as a *refrigerant.*

EXAMPLE.

In an ammonia machine the liquid in the condenser is at 68° F. and in the evaporator 5° F. (latent heat 580 B.Th.U.). Taking the average specific heat at 1·00, find approximately the percentage loss due to the regulating valve.

Assume 1 lb. to pass the valve.

$$T_1 - T_2 = 63 \text{ degrees}$$

$$\begin{aligned} \text{Heat to be removed per lb.} &= \text{temperature fall} \times \text{specific heat} \\ &= 63 \times 1{\cdot}00 \\ &= 63 \text{ B.Th.U.} \end{aligned}$$

Loss in refrigerating effect, 63 units out of 580.

$$\begin{aligned} \therefore \text{Percentage loss} &= \frac{63 \times 100}{580} \\ &= 10{\cdot}8 \text{ (approx.)} \end{aligned}$$

The **liquid heat** sometimes given in tables of saturated vapours may be used with advantage for this type of calculation.

The liquid heat (*i.e.* per lb.) is simply the range of temperature reckoned from 0° C. or 32° F. multiplied by the specific heat, thus—

$$q_1 - q_2 = (t_1 - t_2) \text{ specific heat.}$$

Taking the example just given, together with another, we have for ammonia—

RANGE t_1 TO t_2	LATENT HEAT AT t_2 r	$q_1 - q_2$	NET REFRIGERATING EFFECT PER LB. $r - (q_1 - q_2)$	PERCENTAGE LOSS $\left(\frac{q_1 - q_2}{r}\right)100$
68° F. to 5° F.	580·56	63·95	516·61	11·1
68° F. to 14° F.	575·40	55·31	520·09	9·6

Ewing gives for temperatures 68° F. and 14° F., 8·5 per cent. loss for ammonia, and 29 per cent. loss for carbonic anhydride.

Ledoux gives for 64·4° F. and 5° F., 7 per cent. and 33 per cent. respectively.

Taking both the losses in the compressor and at the regulating valve, Ewing gives the following table for ammonia and carbon anhydride, with wet compression :—

THEORETICAL COEFFICIENT OF PERFORMANCE

(Upper limit of temperature 20° C. or 68° F.).

LOWER LIMIT t_2		COEFFICIENT OF PERFORMANCE IN CARNOT CYCLE.	THEORETICAL COEFFICIENT OF PERFORMANCE.	
C.	F.		NH_3	CO_2
10	50	28·3	27·8	25·7
5	41	18·5	18·1	—
0	32	13·6	13·2	11·4
- 5	23	10·7	10·2	—
- 10	+ 14	8·8	8·3	6·8
- 20	- 4	6·3	5·9	4·5

Ammonia is, therefore, the more economical refrigerant, and this fact, in combination with the low-working pressures, makes it a favourite refrigerant.

If large quantities should escape, however, it is very dangerous to life, and a man cannot withstand its noxious fumes, and, consequently, we find the Board of Trade will not allow such a plant to be placed in the main engine-room of a steamship.

Carbonic anhydride is not noxious, but should a considerable quantity escape, being heavier than air, it may displace the atmosphere, making respiration impossible.

The Board of Trade allow only small machines to be fitted in the main engine-rooms of ships.

Taking all points into account, the claims of both ammonia and carbonic anhydride would have to be considered with special reference to situation and purpose.

It may be well, at this stage, to again draw a comparison between heat engines and refrigerating machines.

In a heat engine heat is taken in at a high level, *work is performed by it,* and the unconverted heat rejected at a low level.

The efficiency is higher the greater the difference between the temperatures of reception and rejection.

In a refrigerating machine heat is taken in at a low level, *work is performed on it,* and the total heat discharged at a higher level.

The coefficient of performance is greater the smaller the difference between the temperatures of reception and rejection.

The Refrigerating Machine as a Warming Machine.—In 1852 the late Lord Kelvin suggested that a reversed heat engine would make an economical warming machine.

The temperature of the heat required for warming purposes is not very high—yet the very highest temperatures are generally employed in heating appliances.

We have seen that a large body may be heated (or cooled) through a small range of temperature much more economically than a small body through a great range—the same quantity of heat being expended (or extracted) in each case.

The employment of a fire for heating, therefore, is not economical, owing to the great difference of temperature between the fire and the air to be warmed.

In a refrigerating machine with the evaporator at 30° and condenser at 100° F., for every thermal unit expended eight thermal units would be passed over to the condenser and be available for heating.

The hot and vitiated air of a building could be sent through the evaporator as a source of heat on cold days, or, indeed, at any time, provided the building did not require to be cooled.

Lord Kelvin's suggestion has been carried out in buildings in the United States—air for ventilating and warming being sent through the condenser of a refrigerating machine in winter, and through the evaporator for ventilating and cooling in the summer.

COLD AIR MACHINES.—In the cold air or compressed air machine, air is used as the medium for lifting or pumping heat from a low to a high level.

A steam engine is generally employed as the motive power for compressing air in the compression cylinder (Fig. 29), from about atmospheric pressure and 20° F. to about 65 lb. sq. in. (absolute) and 270° F.

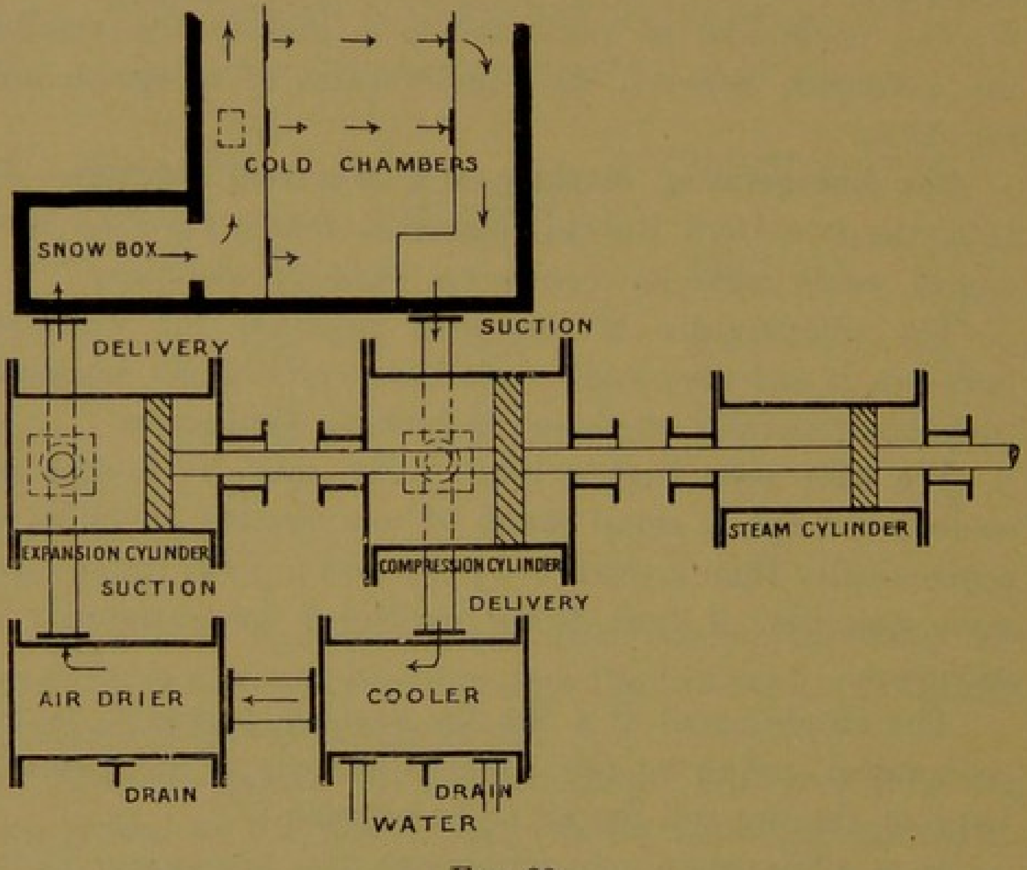

FIG. 29.

The air is then delivered to the cooler, where it passes through a number of brass or other yellow metal tubes around which water is circulated, being thereby reduced to about 70° F., and at the same time depositing a considerable amount of its moisture in the form of water, which is drained away from time to time.

The air may then circulate through the drier; a drier, however, is not always fitted.

The design of the drier varies with different makers, and may be mechanical—depending on centrifugal action (Hall's), the air being whirled round in a circular vessel, the water being thrown to the sides and drained off at the bottom; or the drier may consist (Haslam's) of a nest of tubes through which the compressed air passes, and around which the air from the cold chamber circulates on its return to the compressor—the compressed air is by this means further reduced in temperature, and consequently deposits further water.

After leaving the drier the air passes to the expansion cylinder, which is generally double acting, the air being admitted by means of a long D slide valve, on the back of which works an expansion valve.

The temperature of the exhaust air is about $-80°$ F., and the moisture (representing the difference of humidity at inlet and outlet) is deposited as snow in the snow box, and must be regularly removed.

The air is circulated through the cold chambers by means of air ducts, equal distribution being maintained by small openings or ports in the main ducts at regular intervals.

Return ducts carry the air back to the suction valves of the air compressor. These valves, together with the delivery valves, are usually of the common mushroom type and made of gun-metal.

With respect to the relative sizes of the various parts of a cold air machine, one of the three Haslam cold air machines at the Victoria Dock, London,[1] may be mentioned.

It is capable of circulating 170,000 cub. ft. of air per hour, and is similar in appearance to the machine shown in Fig. 30. The steam engine is horizontal, jacketed, compound surface condensing, with cylinders 20 in. × 31·4 in. diameter × 36 in. stroke, placed side by side, and working on to a crank shaft carrying two flywheels and valve gear.

The tail rod of each engine passes to a compressor, each

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[1] Donaldson on Cold Storage. *Minutes of Proceedings Institution of Civil Engineers*, vol. cxxix.

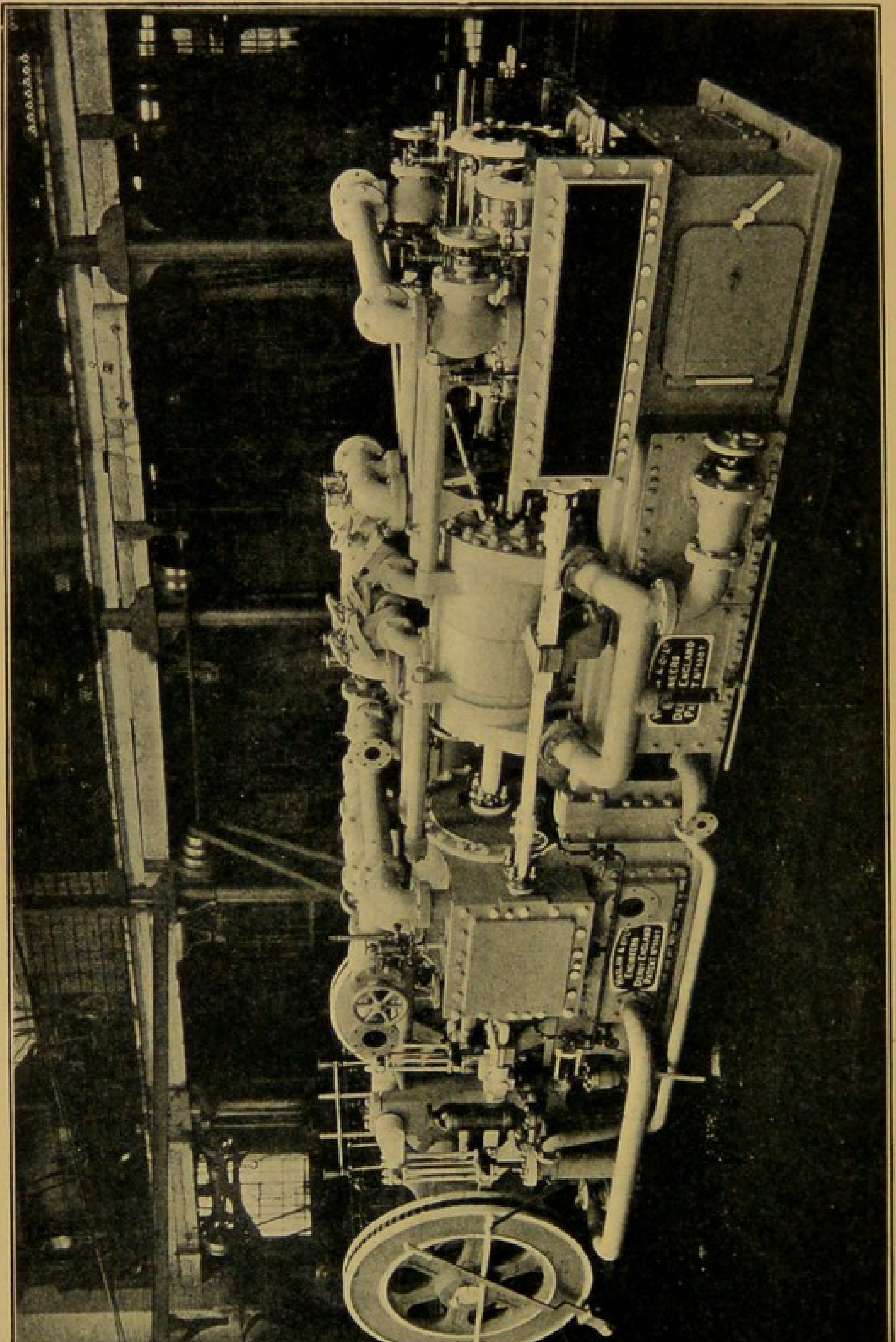

Fig. 30.

of which is 25¼ in. diameter, water jacketed, the water for this purpose being circulated by pumps from the coolers.

Each end of each compressor is fitted with four suction valves and five delivery valves.

The compressed air is passed to the coolers, each containing about 1000 tubes, around which water from the dock is pumped, the water passing (at a pressure of 24 to 30 lb. per sq. in. absolute) around the compressors and through the engine condenser before being returned to the dock.

The two expansion cylinders are each 19·5 in. diameter × 36 in. stroke, side by side and in line with the compressors, and helping to drive them by means of rods connected direct.

The air is delivered into the snow box at an average temperature of $-65°$ F., and is distributed through the cold chambers by a central wooden duct 24 in. × 22 in.

The return ducts are at the sides, each measuring 15 in. × 15 in. The air in the chamber is usually 18° to 22° F.

The indicated horse-power is given in the aggregate as 287.

Temperatures in Cold Air Machines.—The temperatures actually produced in cold air machines vary somewhat from that obtained by elementary theory—the lower temperature air so readily taking up heat, resulting in a higher temperature, while the heated compressed air readily gives up its heat, resulting in a lower temperature.

The work in Chapter IV. being read, a further step may be taken as follows :—

$$P_1V_1 = RT_1$$

$$P_2V_2 = RT_2$$

therefore

$$\frac{P_2V_2}{P_1V_1} = \frac{T_2}{T_1} \quad . \; . \; . \; . \; . \; . \; . \quad (1)$$

Again

$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

$$\frac{P_1V_1^{\gamma}}{P_2V_2^{\gamma}} = 1 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

Multiplying (1) and (2) we get—

$$\frac{T_2}{T_1} = \frac{P_2V_2P_1V_1^{\gamma}}{P_2V_2^{\gamma}P_1V_1}$$

$$= \frac{V_2V_1^{\gamma}}{V_1V_2^{\gamma}}$$

$$= \frac{V_1^{\gamma}}{V_1} \cdot \frac{V_2}{V_2^{\gamma}}$$

$$= V_1^{\gamma-1} \cdot \frac{1}{V_2^{\gamma-1}}$$

$$= \frac{V_1^{\gamma-1}}{V_2^{\gamma-1}}$$

$$= \left(\frac{V_1}{V_2}\right)^{\gamma-1} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Again

$$P_1V_1^{\gamma} = P_2V_2^{\gamma}$$

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{\gamma}$$

$$\frac{V_1}{V_2} = \left(\frac{P_2}{P_1}\right)^{\frac{1}{\gamma}}$$

$$\left(\frac{V_1}{V_2}\right)^{\gamma-1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Hence from (3) and (4) and writing

$$\frac{V_2}{V_1} = r$$

when r = ratio of expansion

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{r}\right)^{\gamma-1}$$

Again, taking example C, Chapter IV.

(1) In a cold air machine, air at 65 lb. per sq. in.

absolute and 70° F. is expanded, doing work to 14·7 lb. per sq. in. What is the final temperature?

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$= 531\left(\frac{14{\cdot}7}{65}\right)^{\frac{1{\cdot}4-1}{1{\cdot}4}}$$

$$= 531\,(0{\cdot}226)^{0{\cdot}2857}$$

$$\log T_2 = \log 531 + 0{\cdot}2857 \log 0{\cdot}226$$

$$= 2{\cdot}5406$$

$$T_2 = 347{\cdot}2^\circ \text{ F.}$$

$$t_2 = -113{\cdot}8^\circ \text{ F.}$$

(2) In a cold air machine, air at atmospheric pressure and 20° F. is compressed adiabatically to four atmospheres. What is the final temperature?

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$= 481\,(4)^{0{\cdot}2857}$$

$$\log T_2 = \log 481 + 0{\cdot}2857 \log 4$$

$$= 2{\cdot}8541$$

$$T_2 = 714{\cdot}7^\circ \text{ F.}$$

$$t_2 = 253{\cdot}7^\circ \text{ F.}$$

(3) In a cold air machine, air at 14·7 lb. per sq. in. absolute and 55° F. is compressed adiabatically to 65 lb. per sq. in. What is the final temperature?

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$= 516\left(\frac{65}{14{\cdot}7}\right)^{0{\cdot}2857}$$

$$\log T_2 = \log 516 + 0{\cdot}2857 \log 4{\cdot}42$$

$$= 2{\cdot}8970$$

$$T_2 = 788{\cdot}9^\circ \text{ F.}$$

$$t_2 = 327{\cdot}9^\circ \text{ F.}$$

The more advanced theory of the cold air machine would take into account the amount of moisture in the air before compression, and the effect of same during compression; the amount of moisture removed during cooling, and the effect of the remainder during expansion.

Cooling during compression and reheating during expansion would also be considered, as would the effect of clearance and waste spaces generally in the machine.

The useful refrigerating effect for any given machine can also be estimated, together with the work required to drive same.

VAPOUR COMPRESSION MACHINES.—Without going into the question of motive power—which may be any prime mover—we may say the essential parts of vapour compression machines are the—

(i.) compressor;
(ii.) condenser;
(iii.) evaporator (refrigerator).

These will be considered in the order given, and examples selected from the two best-known types of machines—ammonia and carbonic anhydride. The auxiliary machines (pumps, fans, etc.), very essential features, will be mentioned as occasions arise.

Compressor.—Compressors are divided into two classes—

(1) double-acting;
(2) single-acting.

Each class is again divided into two sections, which, from a practical standpoint and matter of detail, are equally important, viz.—

(i.) horizontal;
(ii.) vertical.

Broadly speaking, horizontal compressors are double-acting, and vertical compressors single-acting.

Apart from considerations of strength and general good design, two points stand out as being most important—

(*a*) clearance (to be as small as possible);
(*b*) vapour-tight working of the rod.

The methods adopted in practice with respect to these two points should be particularly well noted in the examples that follow.

Double-acting Horizontal Ammonia Compressor.—Fig. 31 illustrates the usual form of such a compressor. There are

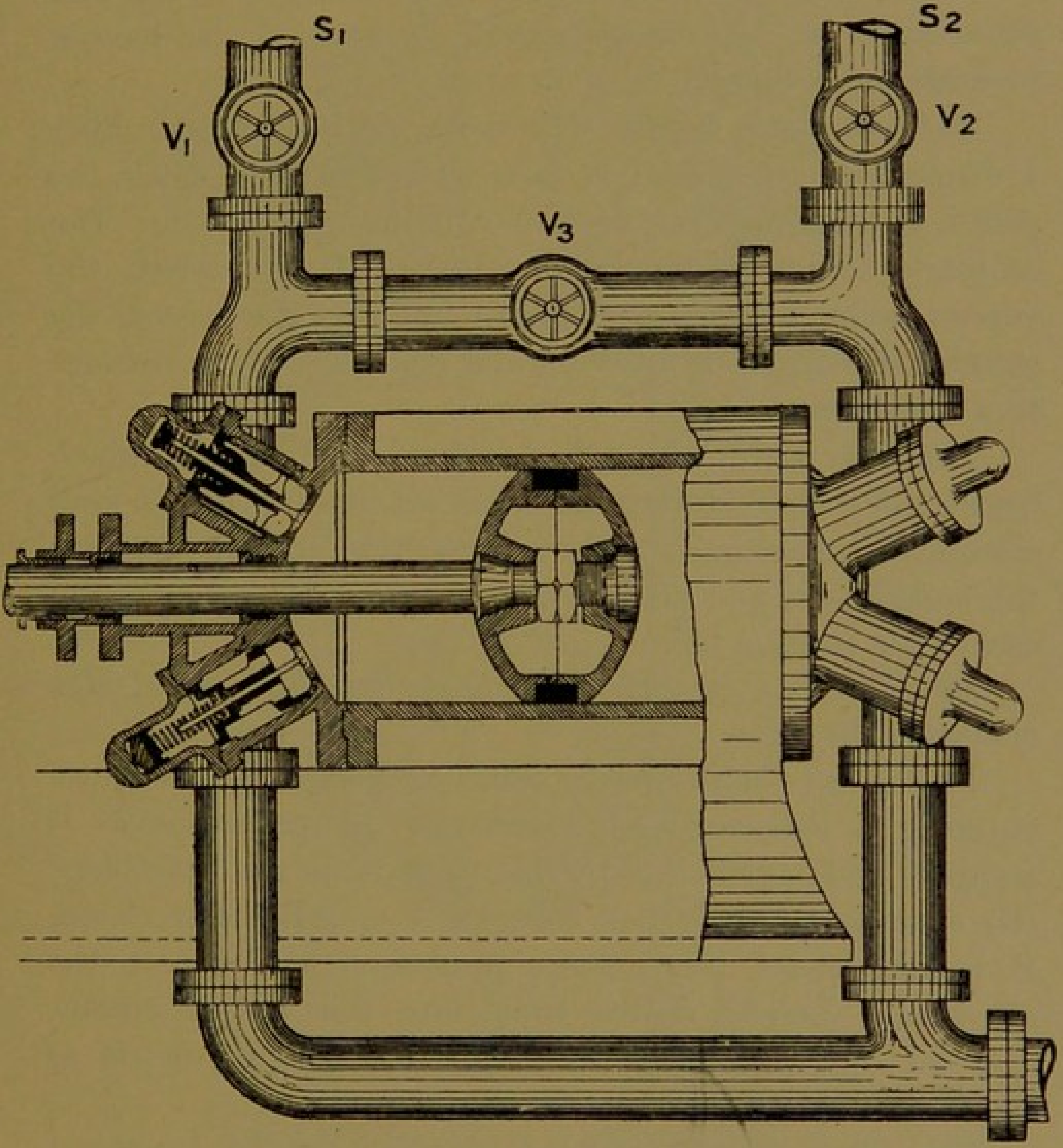

FIG. 31.

two suction pipes, S_1 and S_2. If the intermediate valve V_3 is closed, the rod end would draw from an evaporator in connection with S_1, and the other end from a second evaporator connected with S_2.

Thus the pressures and consequently the *temperatures* in each of the two evaporators can be kept different, an object often desired in practice.

By closing V_2 and opening V_3, both ends would draw from S_1; similarly, by closing V_1, opening V_3 and V_2, both ends would draw from S_2.

Both ends discharge into one common condenser connection, as no object would be gained in having separate condensers.

Two automatic valves—the one a suction and the other a discharge—are placed in each curved head or cover, the piston or plunger being made to suit this curved end. The ordinary action follows when the piston is moved, the vapour being alternately "drawn in" and discharged, the general construction allowing the clearance to be reduced to a minimum.

The rod passes through a special stuffing-box, which consists of a long lantern, in which oil (sealing oil) is kept circulated. Packing is used to keep this oil from *entering* the compressor, and also from coming *out* at the crosshead end of the stuffing-box.

The details vary with the maker, but the general idea is always the same.

In Fig. 28 the discharge from the compressor is shown entering a collector (A), where any oil passing over is trapped. The oil is, at intervals, passed into the "rectifier" (B), after which, the cock between A and B being closed, B is put under the inferior pressure—the bulk of the gas being thereby drawn back into the vapour circuit. The oil may be taken from the rectifier for re-use as required.

Fig. 32 is from a drawing supplied by the Liverpool Refrigeration Co., and shows one of their compressors.

Fig. 33 is from a photograph of a belt-driven compressor by the same makers. It will be noticed that the two suction and two delivery valves are connected at the top; the arrangement of suctions shown on Fig. 31 can, however, be readily fitted.

Fig. 34 shows a belt-driven compressor by Haslam & Co.

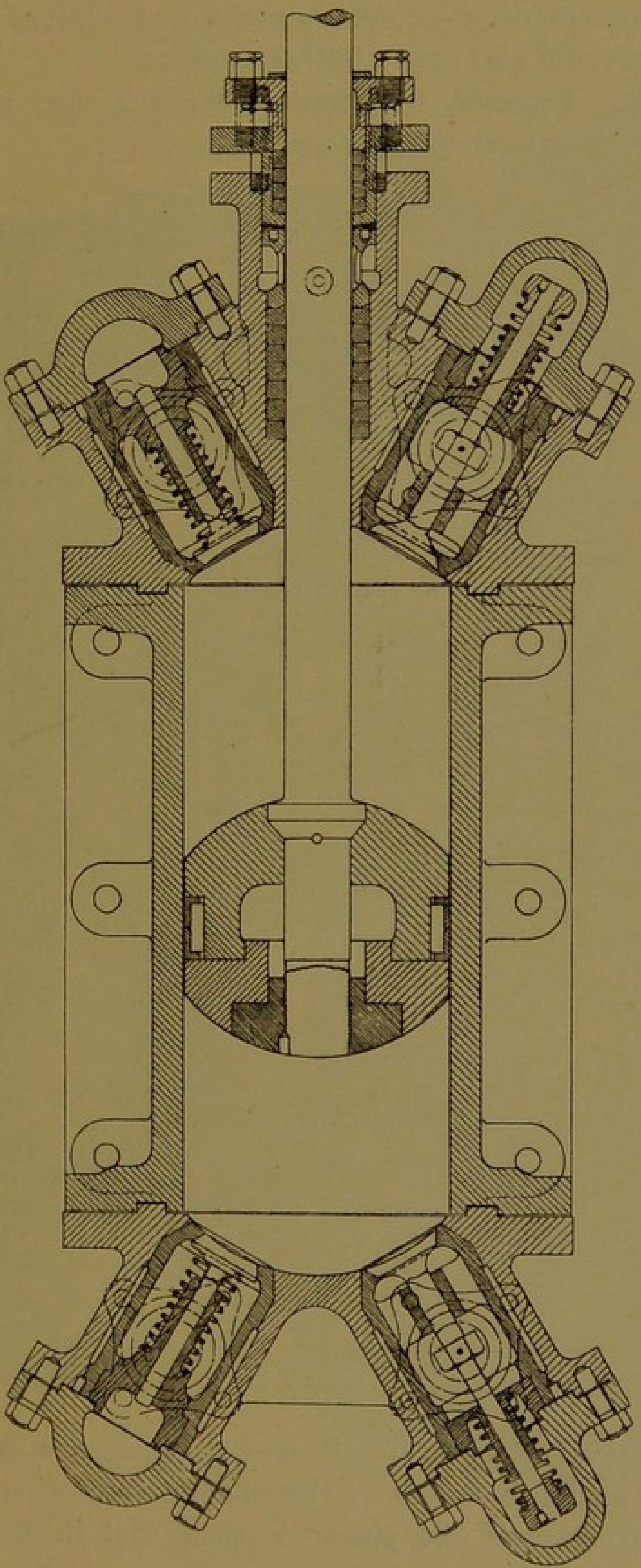

FIG. 32.

The same remark as to rearrangement of suction valves and pipes would also apply to this machine.

Vertical Ammonia Compressor.—Stern & Co. make a speciality of vertical compressors.

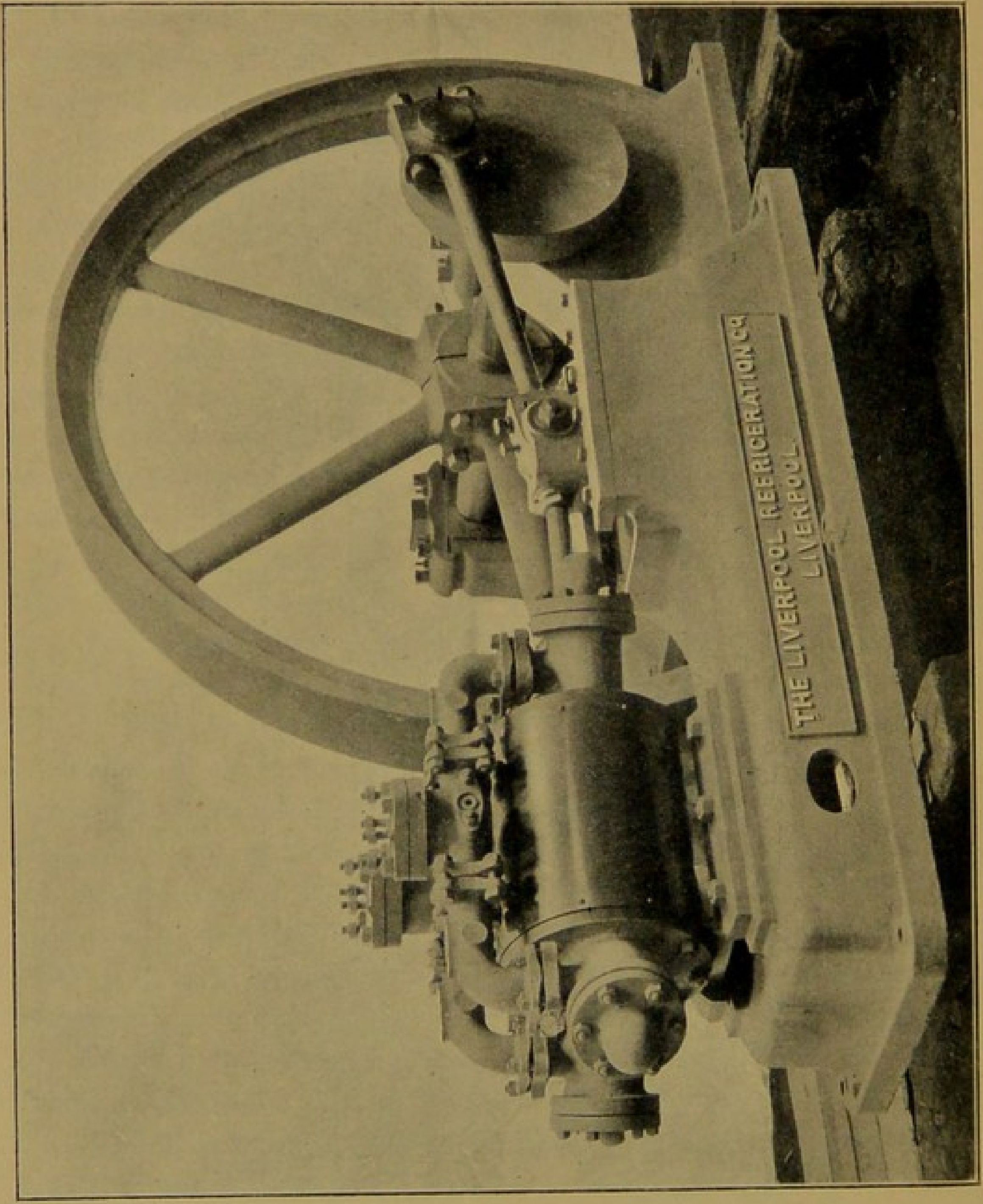

Fig. 33.

The section given in Fig. 35 may be taken as an example. Here the ammonia enters by the suction connection S, and the construction of the piston is such, that in the down

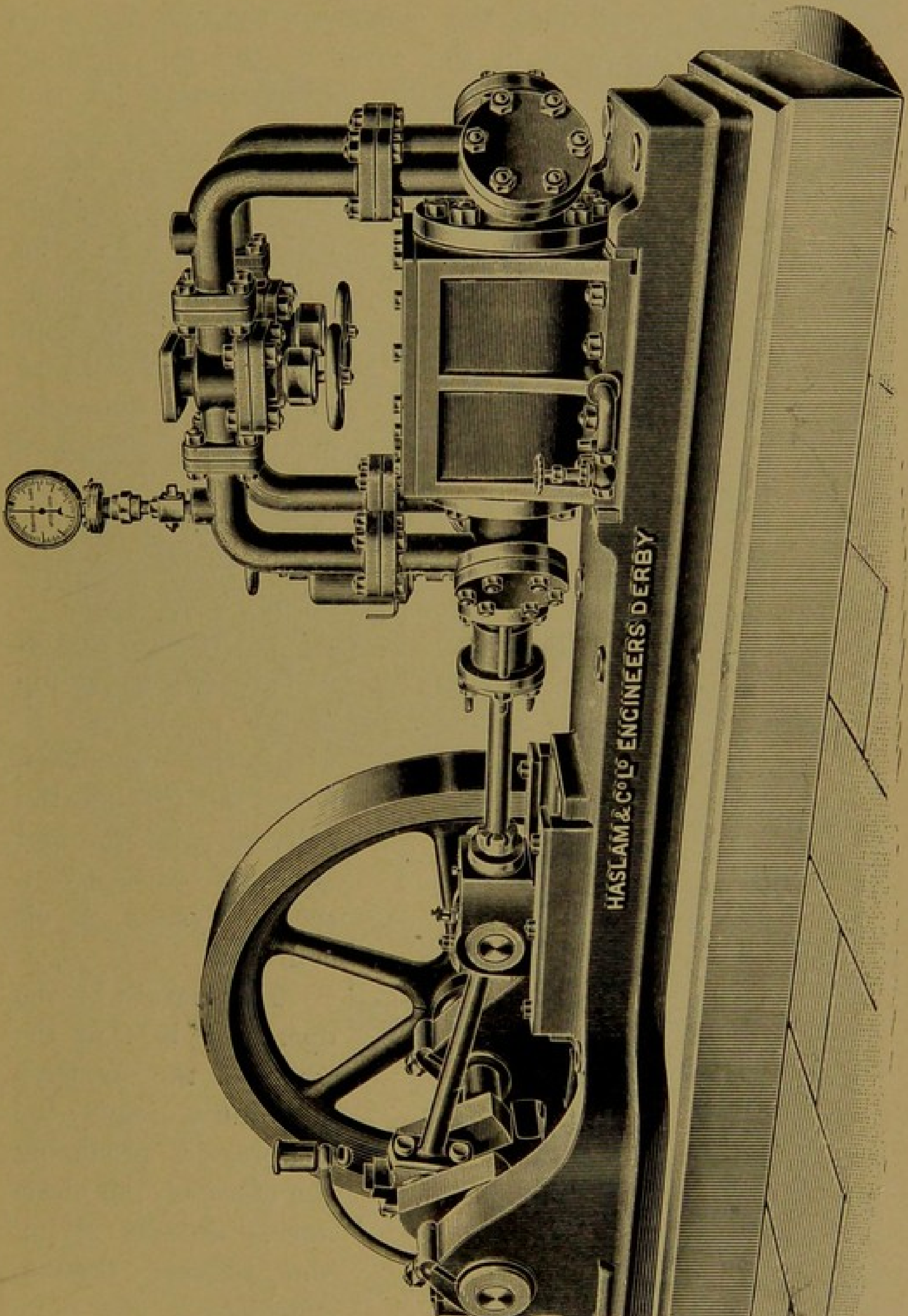

Fig. 34.

stroke, the vapour passes to the top. On the up stroke the ammonia is forced into the condenser through the connection D, the valve in the cover at the top opening automatically on the up stroke and closing on the down stroke.

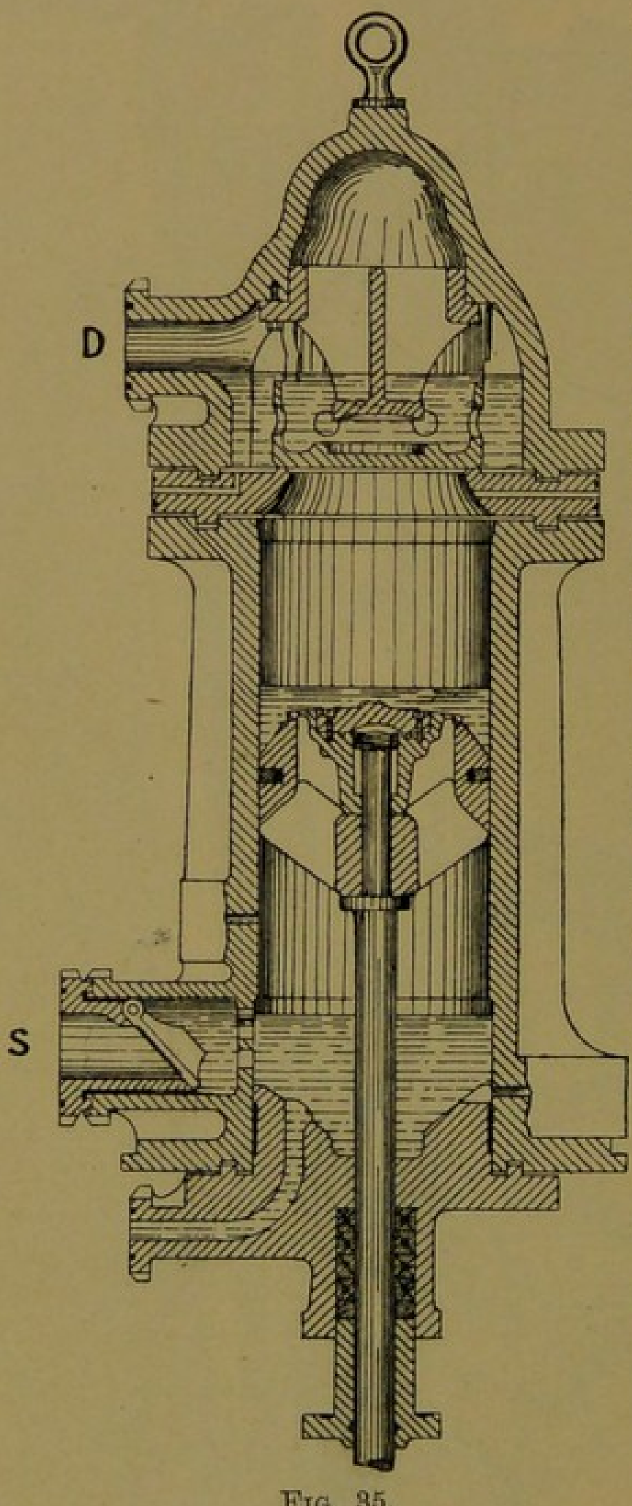

Fig. 35.

A quantity of oil will be noticed at the bottom of the compressor. This is kept at a constant level, and consequently the packing in the stuffing-box has only to deal with the oil under the low pressure in the refrigerator.

A portion of this oil finds its way to the top of the piston, and is, with the ammonia, forced out through the delivery valve, and is dealt with by a special system of oil collectors.

The feature of the operation is that the whole of the ammonia gas must leave the compressor, producing the effect of "no clearance," thereby giving the highest possible efficiency. The same firm also make a speciality of a high-speed vertical compressor.

Fig. 36 shows two compound horizontal engines each

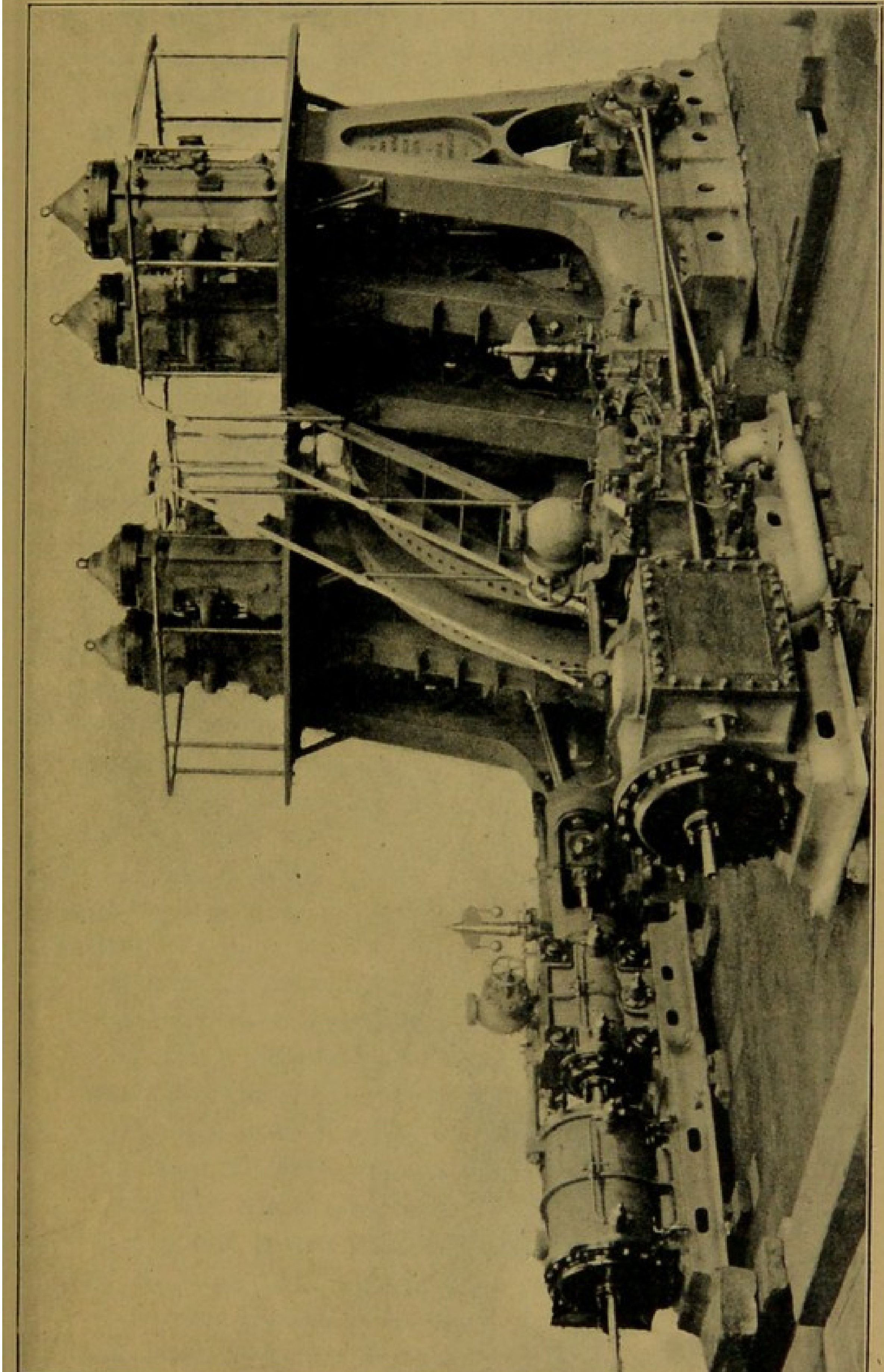

FIG. 36.

driving two vertical double-acting compressors, the whole forming a characteristic plant of Messrs. Stern.

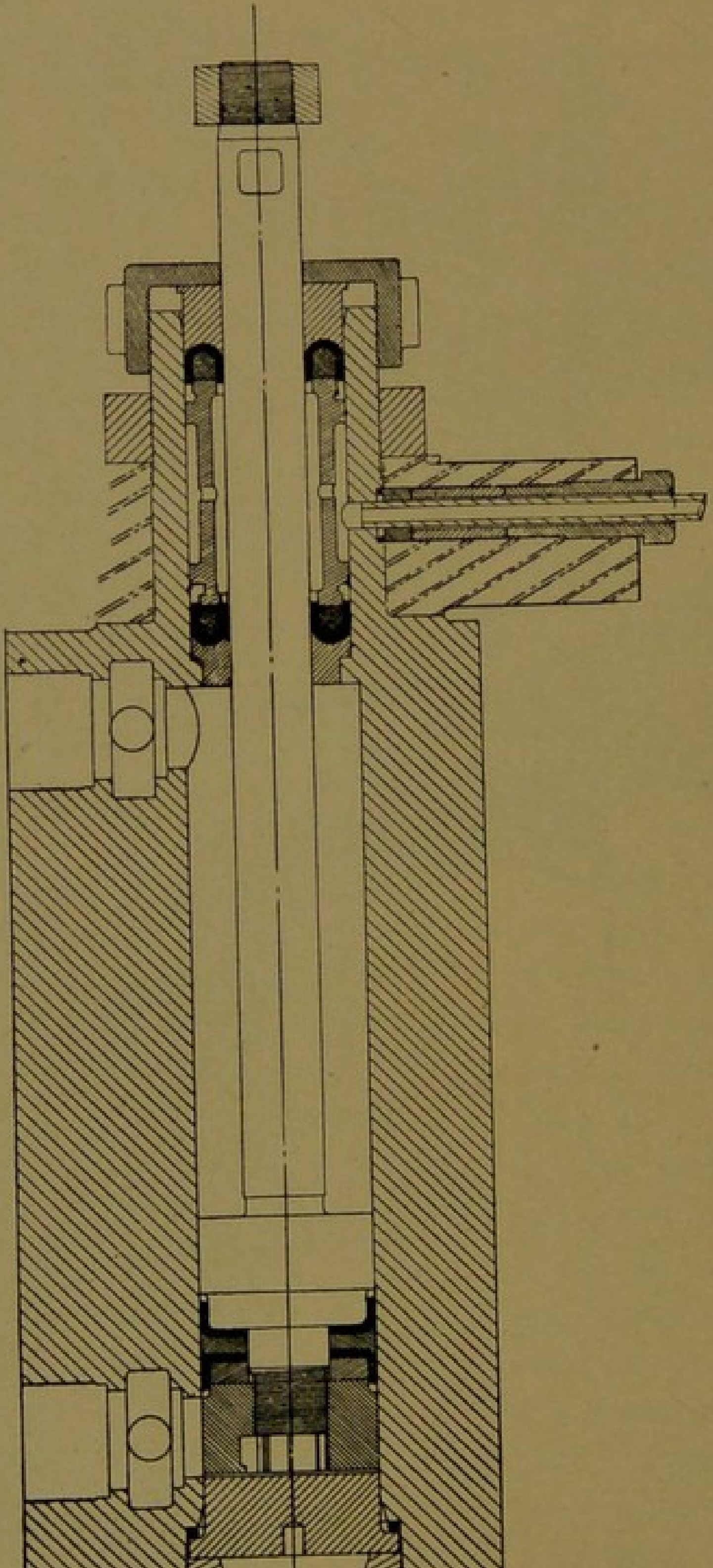

Fig. 37.

Carbonic Anhydride Compressors.—Figs. 37 and 37A show a compressor for CO_2 machines. Whereas close-grained cast-iron compressors are found to answer well with ammonia; the heavy pressures (1000 lb. sq. in.) necessary with CO_2 make it essential that mild steel should be used. This accounts, in a very large measure, for the simple construction shown in the figure, which is a design by Messrs. Hall. Suction and delivery valves are fitted at each end; the piston is packed by means of cup-leathers, and the special stuffing-box has also a series of cup-leathers, which are kept tight by the sealing fluid (oil or glycerine), which is pumped in at a slightly higher pressure than that found in the condenser of the machine.

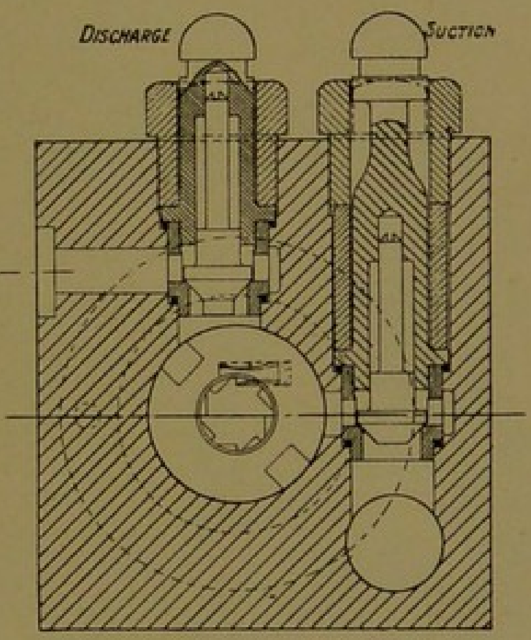

FIG. 37A.

The compressor has a safety-valve in the form of a copper disc, designed to give out at a prearranged pressure, generally a little under 2000 lb. sq. in.

Small CO_2 compressors may be made of bronze, CO_2 (unlike NH_3) having no effect on copper or its alloys.

Fig. 37B represents Hall's patent dry air, carbonic (CO_2) machines, Nos. 5 and 6, belt-driven land type.

This is a very compact machine, and the simple construction of the compressor is clearly shown.

Fig. 37C is also a CO_2 machine by the same makers, being their No. 8 vertical marine type.

Fig. 37D is a CO_2 machine by The Liverpool Refrigeration Co., and is intended for marine use. The condenser and evaporator are contained in the box bed—the latter being well insulated by cork and placed in an air-tight compartment, the whole forming a most interesting design.

Both the machines, 37C and 37D, are driven by steam engines which form part of the machine itself.

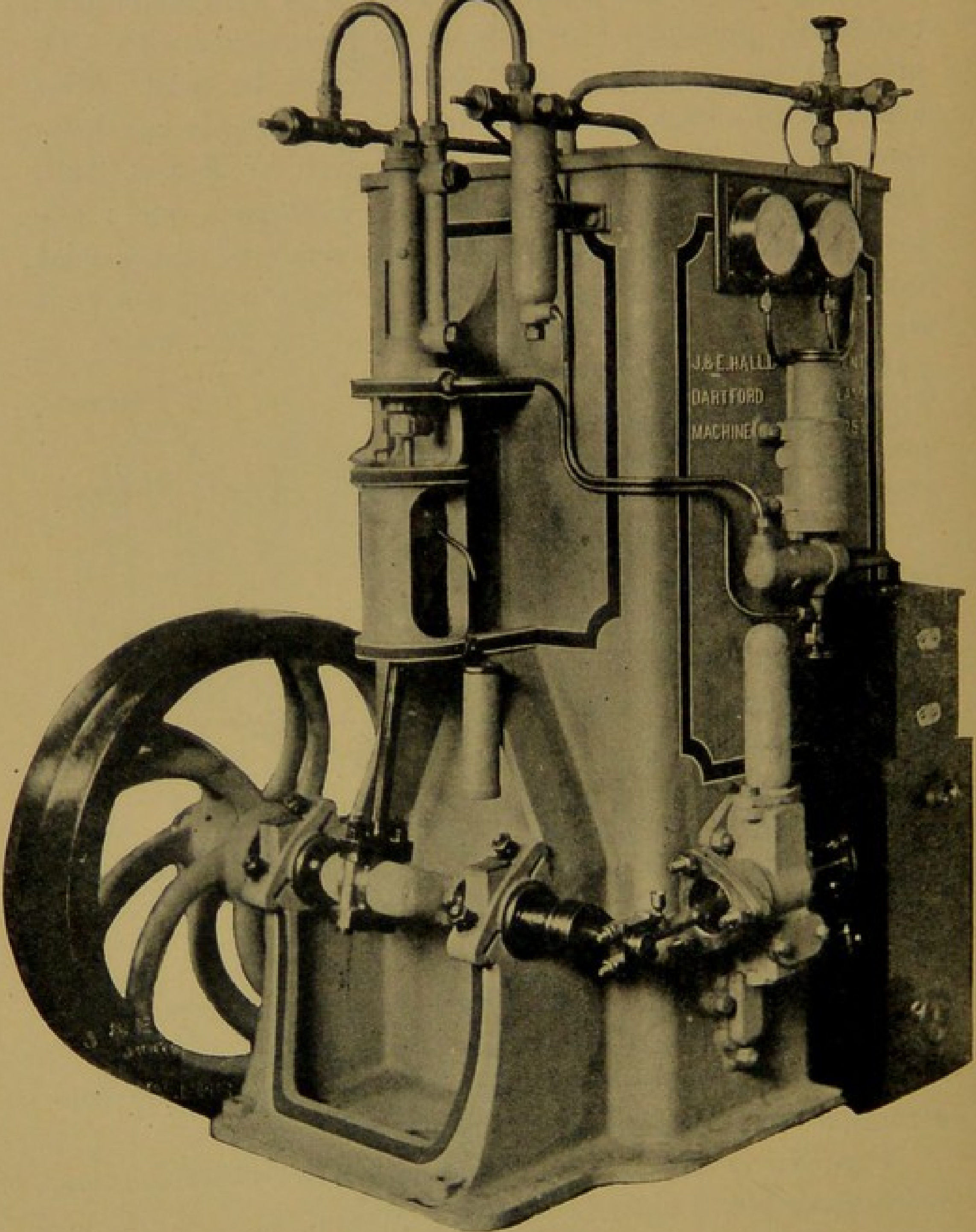

FIG. 37B.

Condensers.—The condensers for vapour compression machines may be divided broadly into two classes—

I. submerged.
II. atmospheric.

The submerged condenser takes various forms according to the size and position of the machine. The circular form consists of a thin vertical tank—of steel or iron—in which are placed a number of concentric coils (through which the refrigerant passes) connected together at the top and bottom by a "header" or "manifold."

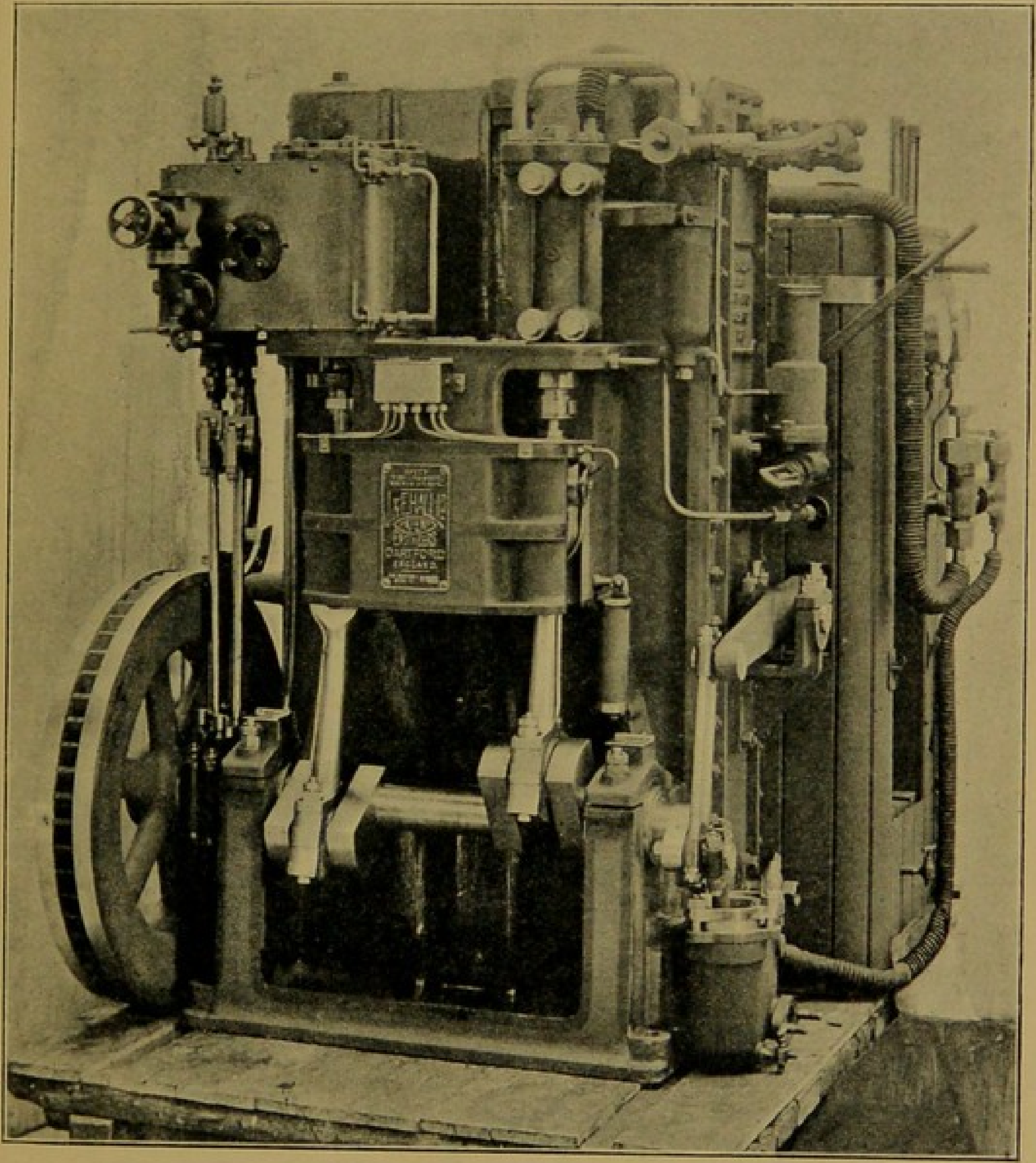

FIG. 37C.

The pitch of the outer coil is greater than the innermost coil, so that the length of tube in each may be kept as nearly as possible the same.

The hot vapour to be condensed enters the coils by the top manifold—the liquid coming away from the bottom. The condensing water enters the tank at the bottom, and passes around the coils, and away at the top—this ensures the refrigerant being cooled to the *lowest* possible *temperature*—a most important feature.

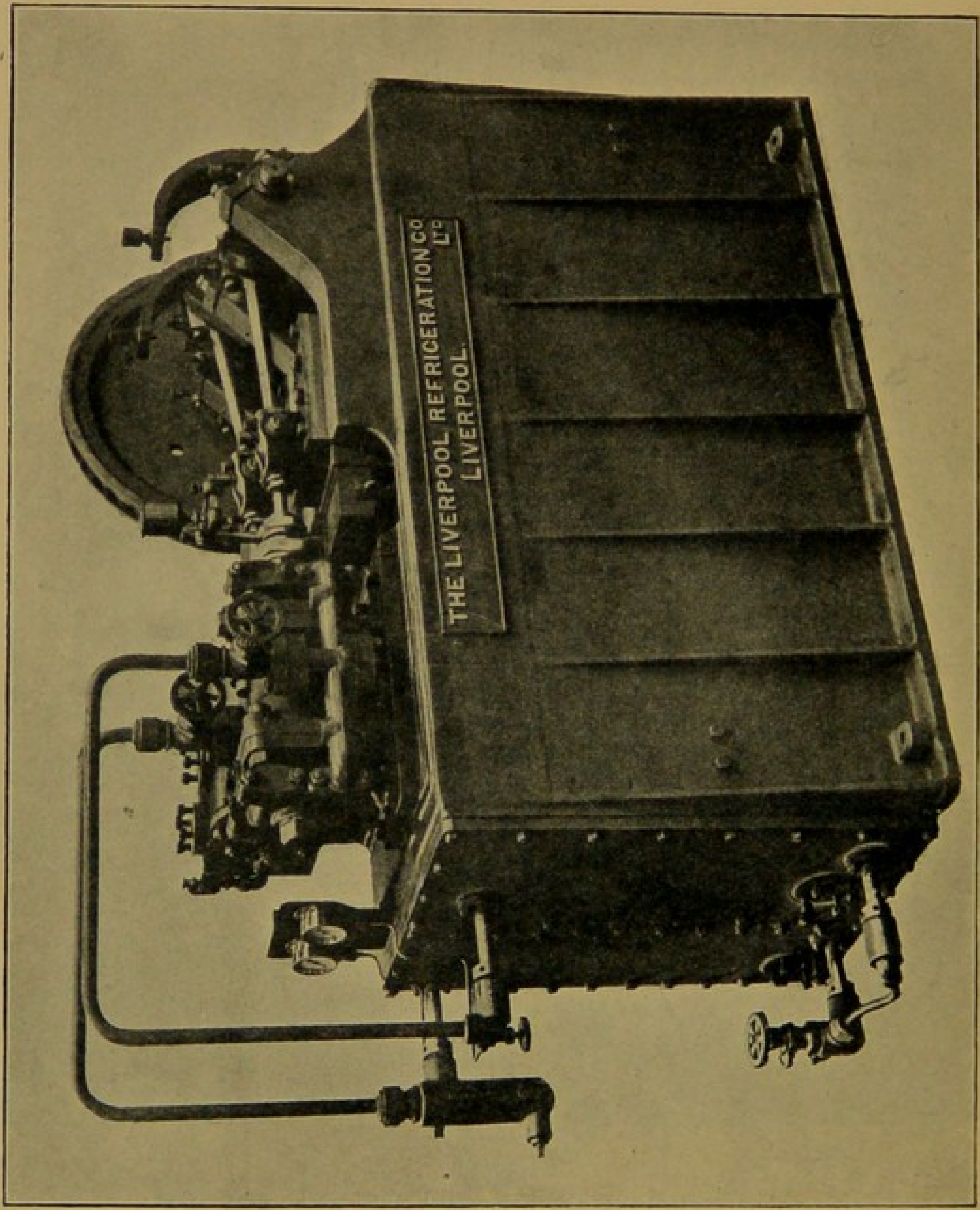

Fig. 37d.

The submerged condenser may also be built with grid coils into an ordinary rectangular-shaped tank, and in marine machines is often placed in the bed plate (Fig. 37D).

The coils may be of iron or steel, and in CO_2 machines copper coils are also used.

The atmospheric condenser consists of stacks or grids of pipes placed in an open position, water being allowed to trickle or fall over the coils by suitable distributing pipes.

The grids may be made of continuous lengths (welded) of rather small pipe—1 in. to 1½ in. diameter—or of large pipe—2 in. to 2½ in. built up in sections.

An example of the latter is shown in Fig. 38, and is thus described by the makers, Haslam & Co.—

"The figure illustrates an open-air evaporative surface ammonia condenser in a nest of five sections. The compressed ammonia gas passes into these condensers at the bottom, and as it rises is cooled by the water flowing over the surface of the pipes. As the gas is cooled it liquefies and leaves the condenser by means of small pipes which are shown at the near end of the condenser. By this arrangement the greatest possible efficiency is ensured, as the hottest gas comes in contact with the hottest water, and immediately the ammonia is liquefied it passes away without travelling through the remainder of the condenser, as is necessary in some systems.

"These condensers are constructed in sections for convenient transport, and to give easy access to all parts of the apparatus for repairs. Each section is provided with independent valves and cocks, so that any particular section may be shut off at any time if desired."

Fig. 39 shows an open-air condenser by The Liverpool Refrigeration Co. at Messrs. Ruddin & Sons, Central Cold Stores, Liverpool.

Here the pipes are in continuous lengths—four separate coils forming each grid—three grids forming the whole condenser.

The ammonia gas comes from the compressor in a pipe

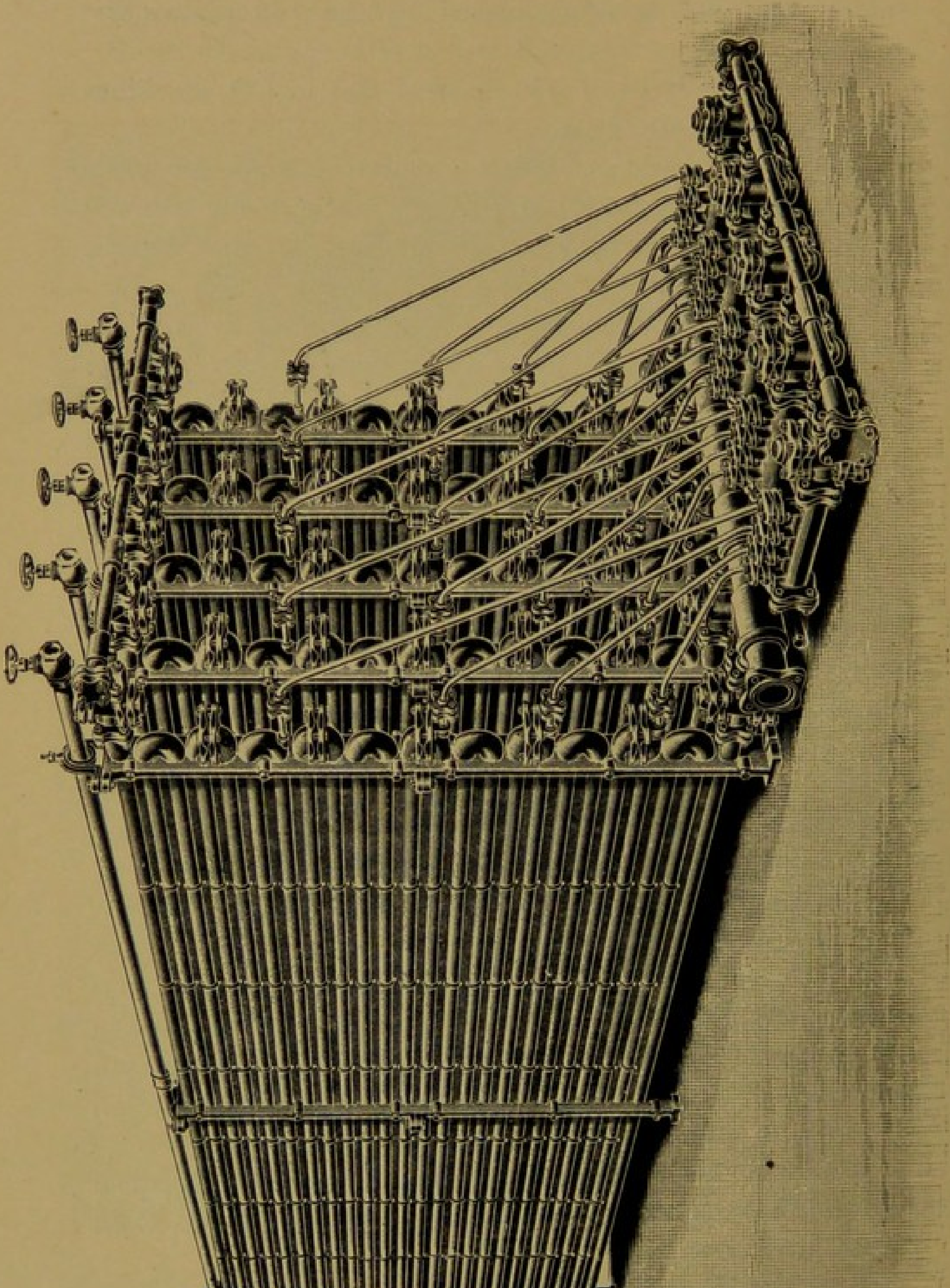

Fig. 38.

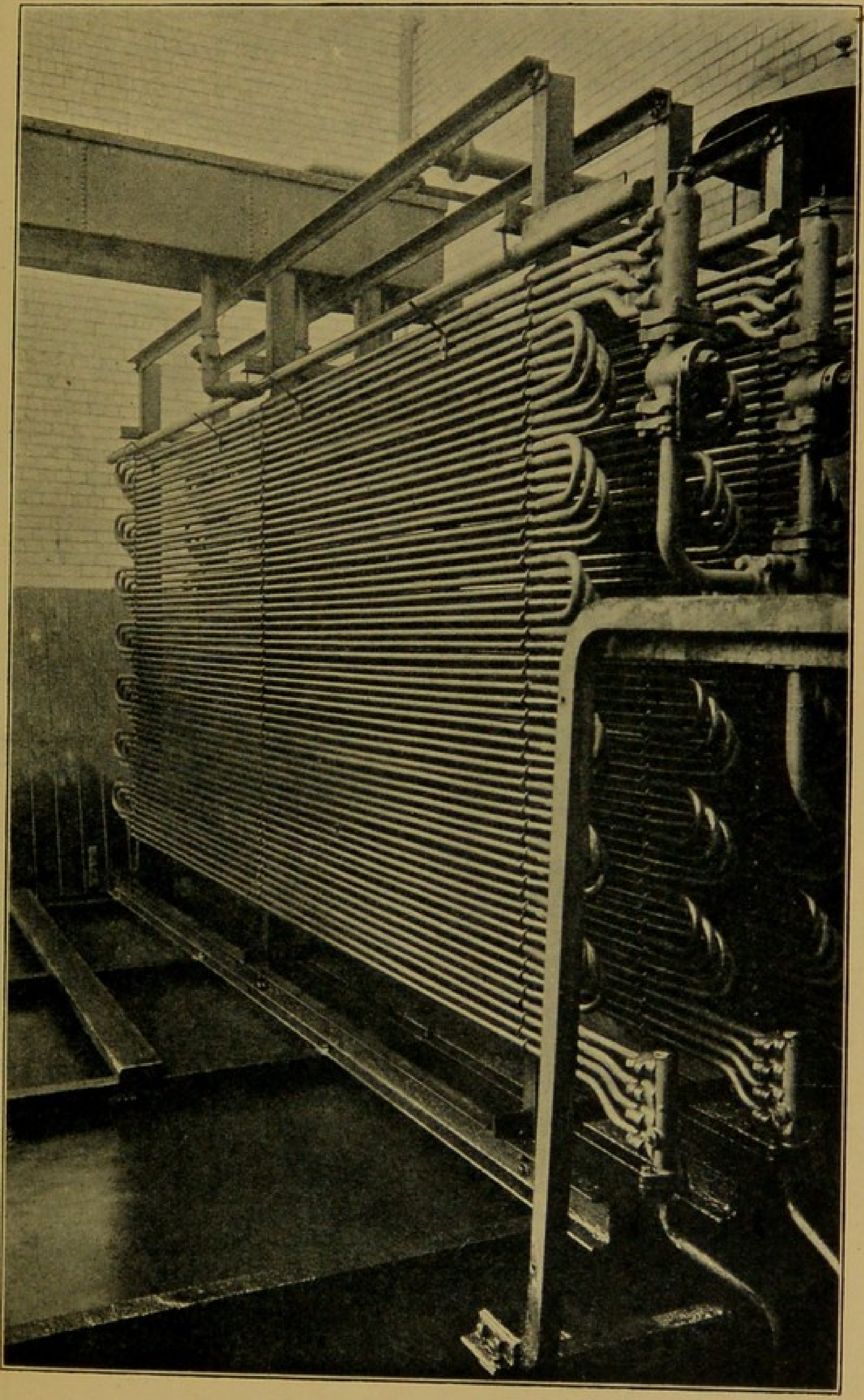

Fig. 39.

shown about halfway up the photo. It then divides into three sections, each section having a cock, so that any section may be put out of circuit if required.

Each of these three sections again divide by means of a manifold into four coils. The same arrangement is used for collecting the liquid at the bottom, the gas entering at the top.

A very large tank (22 ft. × 11 ft. × 2·5 ft. deep) is fitted below the coils, and a circulating water-pump keeps such a good supply of water running over the coils (Fig. 40), that the difference of temperature of the water at the top and at the bottom is very small.

This large tank, fitted under the specification of the author, has proved most economical. The water increases in temperature during the day, but falls sufficiently every night to ensure good regular working—a small loss only from evaporation taking place.

The condenser illustrated is in a " pocket " on the north side of the building, and hence louvres, which would be required in positions exposed to the sun, are not fitted.

Evaporators—(Refrigerators).—The object of the evaporator is to allow the liquid refrigerant to vaporize—extracting the heat necessary for this operation from the surrounding medium—this action, in fact, constituting the *refrigerating effect* of the machine.

The surrounding medium may be air, water, or brine in general refrigeration; in special machines, it may be milk, beer, etc.

In general (leaving out the exceptions), the refrigerant vaporizes on the inside of the tubes or pipes, the medium to be cooled being on the outside.

The *difference of temperature* between the two is seldom more than 20° and often less, so the *greatest possible care* must be taken to ensure *effective circulation* of the refrigerant and proper *agitation* (or circulation) of the medium, in order that the greatest efficiency may be obtained.

The evaporators used for ice making generally have the coils submerged in brine.

Such an evaporator is shown in Fig. 41, and forms part of the equipment at the Liverpool Cold Storage and Ice Co.'s

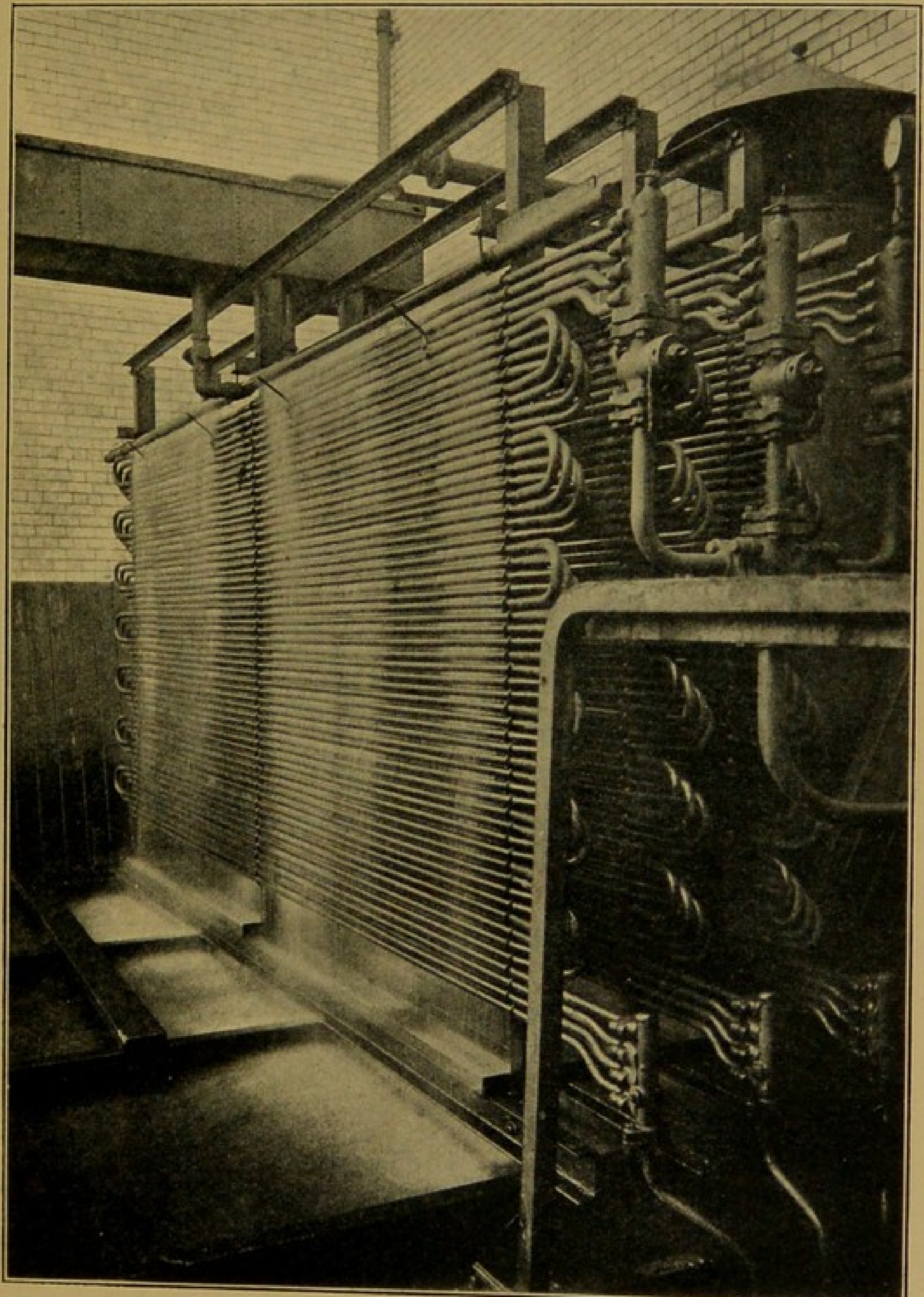

Fig. 40.

factory (Linde machines), and is used in connection with ice making on the Siddeley process (p. 147).

Ammonia is the refrigerant circulated through the ten coils—in two groups of five, each group being so arranged as to connect with separate compressors if so desired.

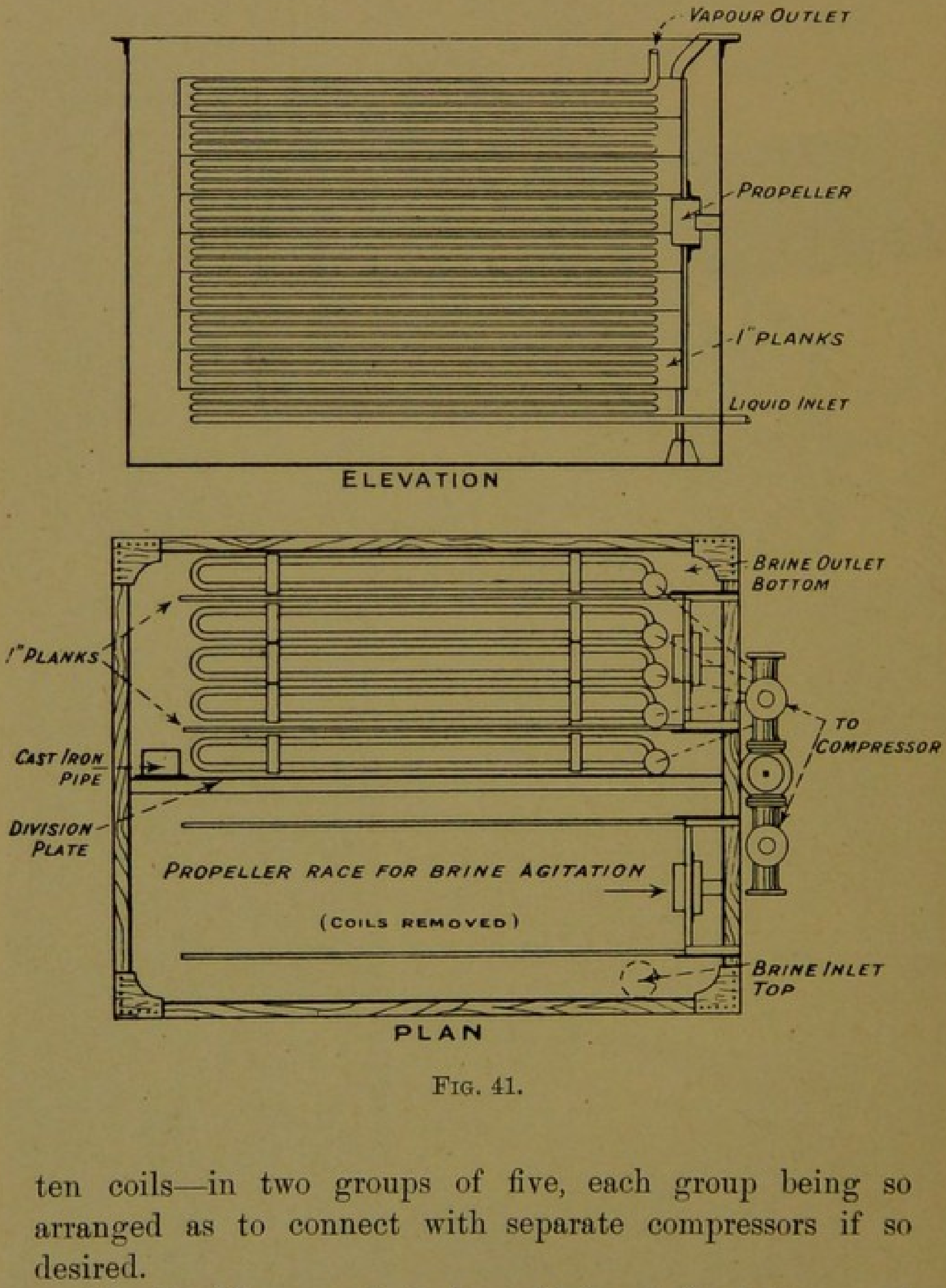

Fig. 41.

The liquid ammonia is brought in at the bottom, and distributed to the several coils by means of a header or manifold. A similar connection is made at the top, and is indicated in outline on the plan.

The brine to be cooled is brought in at the top (called the brine return) in one corner of the tank, and is baffled by an arrangement of 1 in. planks, and agitated by means of a propeller. Passing outside the first set of five coils, the brine enters the second division of the tank by means of a cast-iron square pipe—open at the bottom to the first division only—the brine overflowing at the top into the second division.

After being baffled and agitated in a similar way, the brine is drawn by a pump from the bottom far corner, and becomes the " cold brine feed " for the ice-making tanks.

The tank is 12 ft. long, 9 ft. wide, and 8 ft. 6 in. deep, the coils being 9 ft. 6 in. long, and of $1\frac{1}{2}$ in. external diameter pipes.

Evaporators, like condensers, are often made circular in form, particularly for marine work.

Types of evaporators used for cooling chambers are described in Chapter X.

Sizes of Compression Machines.—The following sizes are given by F. W. Wolf Co., of Chicago, for their Linde ammonia compression machines :—

No. of Machine.	Tons Refrigerating Capacity 24 Hrs.	Compressor.				Approx. H.P. required.	Condenser.					
										Space required.		
		Diameter.	Stroke.	Dia. of Connections.	R.P.M.		No. of Sections.	No. of Pipes.	Length of Pipes.	Length.	Width.	Height.
12	25	$9\frac{7}{8}''$	$16\frac{5}{8}''$	$2\frac{1}{2}''$	70	25	2	24	20′ 0″	21′ 6″	3′ 6″	11′ 9″
15	50	$12\frac{13}{16}''$	$21\frac{1}{4}''$	3″	66	50	4	24	20′ 0″	21′ 6″	7′ 3″	11′ 9″
19	100	$18\frac{1}{2}''$	$27\frac{9}{16}''$	5″	50	100	8	24	20′ 0″	21′ 6″	16′ 0″	11′ 9″
23A	500	TWO 22″	48″	6″	50	500	40	24	20′ 0″	21′ 6″	64′ 0″	11′ 9″

Haslam & Co. give the following for ammonia compression machines :—

No. of Machine.	Ice Making Tons per 24 Hrs.	Cubic Feet of Storage kept at 32° F.	Horse-power required.	
			Temperate Climate.	Hot Climate.
1	½	1,500 to 3,000	2	2½
2	1	3,000 to 6,000	4	5
6	5	42,000 to 85,000	16	18
9	10	90,000 to 180,000	32	38
14	25	260,000 to 550,000	78	88
17	50	460,000 to 940,000	155	180
20	100	1,000,000 to 2,000,000	300	360

L. Sterne & Co. give for double-acting ammonia compressors :—

Ice melted per 24 Hrs. (Refrigerating Capacity).	Ice Making per 24 Hrs.	Horse-power required.	Size of Compressor at 40 R. P. M. Diameter and Stroke.
12 cwt.	6 cwt.	⅔	One 2¼″ × 4½″
64 ,,	32 ,,	5	,, 4½″ × 9″
9 tons	5 tons	12	Two 6″ × 12″
18 ,,	10 ,,	23	,, 8″ × 16″
35 ,,	20 ,,	42	,, 10″ × 20″
50 ,,	30 ,,	60	,, 11″ × 22″
100 ,,	60 ,,	119	,, 14″ × 28″
220 ,,	130 ,,	250	,, 18″ × 36″

Wm. Douglas & Sons, Ltd., give for SO_2 machines :—

No. of Machine.	Ice Making per 24 Hrs. Cwts.	Cubic Ft. the Machine will cool.		Produce Machine will cool per 24 Hrs. in Cwts.		B. Th. U. eliminated per Hour.	H.P.	R.P.M.
		To 35° F.	To 24° F.	To 35°	To 24°			
1	3	250	125	10	5	7,500	1	120
3A	15	2,000	1,000	50	25	32,000	3¾	146
5	44	4,000	2,000	100	50	60,000	8	90
7	95	13,000	6,500	200	100	130,000	18	58
8	130	20,000	10,000	300	150	190,000	26	48
8A	160	25,000	12,500	360	180	220,000	31	56

The above tables could be extended *ad lib.*, but those given will furnish ample food for the thoughtful student.

ABSORPTION PLANTS.—When a liquid will vaporize under conditions that can easily be maintained, and the resulting vapour readily absorbed by another fluid, we have all the conditions necessary for what is termed an "absorption plant," or "absorption machine."

Thus, if a vessel partly filled with water has the air in the remaining part exhausted, the aqueous vapour that will, in consequence, be given off may be absorbed by sulphuric acid contained, say, in a separate vessel. The heat required for the vaporization of the water is drawn from the water itself, the whole being thereby cooled—in fact, it may be frozen.

Here advantage is taken of the affinity of sulphuric acid for water, and we have an absorption machine.

The fact that a partial vacuum has to be maintained in order that the water may vaporize makes this particular type more often spoken of as a "vacuum machine," the sulphuric acid simply dealing with the vapour that would otherwise require a very large "air pump" (see p. 152).

The machine just described is due to Edmund Carré, whose brother, Ferdinand, invented the "ammonia absorption machine," which has been improved by various inventors and manufacturers until at the present moment it must be regarded as an important type. Its action is due to the—

(1) affinity of water for ammonia;
(2) vaporization of the ammonia from the water and subsequent condensation into anhydrous ammonia;
(3) vaporization of the anhydrous ammonia producing the refrigerating effect, the resulting vapour being once more absorbed by water.

In describing the action of this machine, it must be understood that the details of construction and names of the parts vary in practice, and, further, the temperatures and pressures (absolute) selected must not be taken as more than reasonable figures, the reader by this time being aware how greatly both depend on circumstances and methods of working.

Generator.—The generator, or still, may be either a horizontal or vertical vessel, fitted with steam heating coils.

Aqua ammonia fortissima (or water containing 38 per cent. by weight of pure anhydrous ammonia, specific gravity 0·88) is introduced into the generator, and its temperature raised by means of steam at 60 to 75 lb. (absolute) pressure (the resulting water draining away through a steam trap), ammonia gas being thereby driven off—the water not being able to retain so large a percentage with the increased temperature (see p. 120).

Analyzer.—Aqueous vapour is also driven off with the ammonia gas, and the object of the analyzer is to prevent, as far as possible, the passage of this vapour, but, at the same time, to allow a free passage for the gas. This end is accomplished (generally) by baffle plates, the temperature of which is kept down below that of the escaping vapour by circulating the ammonia liquor feed, at about 180° F., on its way to the generator.

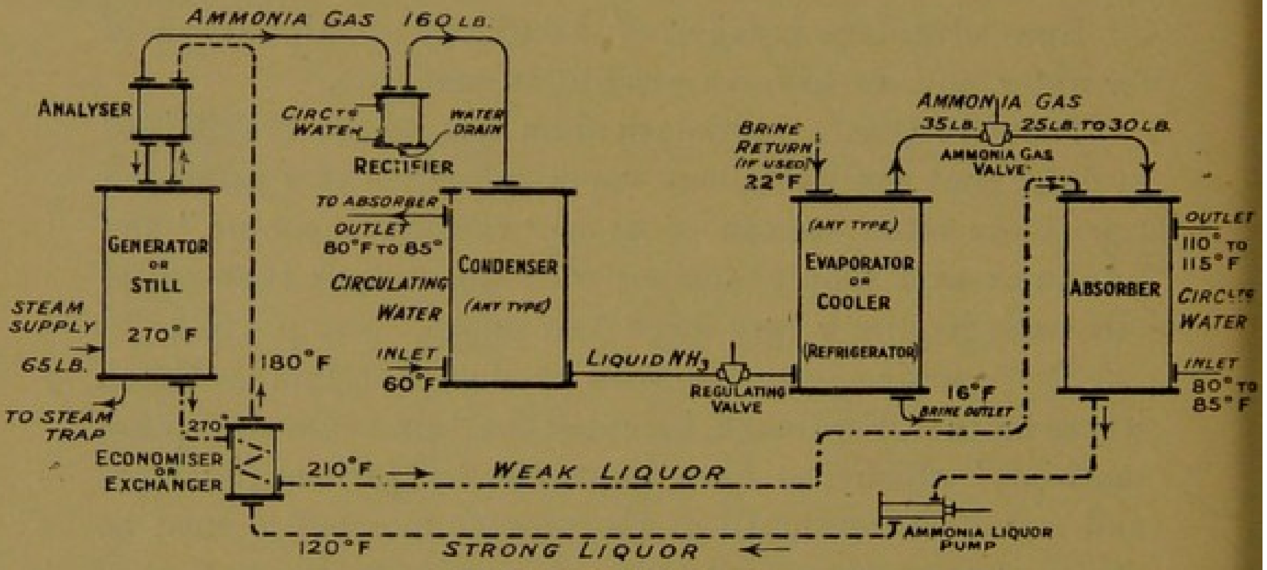

FIG. 42.

Rectifier.—The ammonia gas, after leaving the analyzer, is certainly not free from water vapour, and as this vapour is bound to condense later on in the circuit—perhaps freezing up in the cooler—the gas is passed through a rectifier, where the temperature is further reduced by means of circulating water, condensing the remaining water vapour, which drains back into the generator, the cooling surface not being sufficient to condense the ammonia.

Condenser.—The now *almost* anhydrous ammonia passes away to the condenser, which may be any of the types previously described.

Cooler or Evaporator (Refrigerator).—The liquid ammonia from the condenser passes through a regulating valve which reduces its pressure from say 160 lb. per sq. in. absolute to say 35 lb., and then evaporates in the coils of the cooler, taking the heat necessary for the process from the surrounding medium, this giving the refrigerating effect.

The cooler may take various forms: in ice making, brine would be the immediate medium cooled. For cold storage work, the cooler may consist of pipes placed in the chambers, the air being cooled by direct contact, this arrangement being known as the "direct expansion system."

The ammonia vapour or gas, after leaving the cooler, has its pressure further reduced 2 lb. to 10 lb. by means of a valve, and enters the next vessel (the absorber) at say 20 lb. to 30 lb.

Absorber.—The arrangement in the absorber is such as to allow the weak liquor (which has had its ammonia driven off in the generator) to take up the ammonia gas coming from the cooler.

This is done by allowing the weak liquor to trickle over pipes while being surrounded by the ammonia gas.

Through the pipes water is circulated to keep down the temperature, heat being generated by the combining of the gas with the weak liquor.

The strong liquor at about 110° F. to 130° F. is drawn off from the bottom of the absorber, and by means of a pump sent back to the generator, on its way passing through the "exchanger," and then through the "analyzer."

Exchanger or Economizer.—In the exchanger the weak liquor, at high temperature (say 270° F.), on its way to the absorber, meets (separated by coils) the strong liquor at a lower temperature (say 120° F.) on its way to the generator—an economical interchange of heat being the result; the strong liquor being increased to say 180° F., and the weak liquor reduced to say 210° F. The flow of the liquors, being in contrary directions, facilitates the interchange of heat.

In Fig. 42 the ammonia circuit is shown in full lines, the strong liquor circuit in dotted lines, and the weak liquor circuit in dotted and dashed lines.

Circulating Water.—The circulating water first enters the condenser at the bottom, at say 60° F., leaving at the top, at say 85° F.; it then passes to the bottom of the absorber, leaving the top at say 115° F.—the heat units rejected at the absorber being roughly 10 per cent. to 20 per cent. greater than those rejected at the condenser.

If the temperature of the supply is high (80° F. to 90° F.) separate circuits may be made with advantage through the condenser and absorber.

The amount of ammonia in the strong liquor leaving the absorber at 120° F. and 33 lb. absolute pressure per sq. in. is about 31 per cent. and 27° B. (Beaume's hydrometer, pure water being 10° B.); and in the weak liquor leaving the generator at say 270° F. and 160 lb. per sq. in. absolute about 18 per cent., or 20° B.

Steam Supply.—With respect to the steam supply for heating purposes in the generator, exhaust steam has been and is extensively used, and, when available, should not be ignored. Live steam, direct from the boiler, can, however, be used with most economical results.

With the temperatures and pressures given in Fig. 42, the water from the steam coils in the generator should be returned to the boiler at a temperature not lower than 260° F.

Stanley, in "Ice and Cold Storage," vol. ii. p. 67, gives the following dimensions and particulars for machines making (I.) 15 tons, (II.) 25 tons of ice per twenty-four hours.

No.	Capacity of Machine.				Condensing Water per Hour at 50° F.	Aqua Ammonia to Charge.	Power required H.P.	
	Tons of Ice per 24 Hrs.	Water cooled 1° F. per Hr.	Water cooled 1° C. per Hr.	Air cooled 20° F. per Hr.			Boiler.	Engine.
		Gallons.	Litres.	Cub. Ft.	Gallons.	Gallons.		
I.	15	55,100	138,900	1,251,000	1900	500	15	6
II.	25	80,100	202,000	1,901,000	2500	610	20	7

No.	Dimensions—Diameter × Length.							Gross Weight of Machine.
	Generator.	Analyzer.	Heater or Exchanger.	Refrigerator or Cooler.	Absorber.	Condenser.	Receiver.	
								Tons.
I.	2′ 10″ × 14′ 0″	2′ 4″ × 13′ 8″	1′ 3″ × 5′ 4″	2′ 5″ × 10′ 4″	2′ 7½″ × 7′ 0″	5′ 2″ × 20′ 0″	2′ 1″ × 3′ 0″	45
II.	3′ 3″ × 14′ 3″	2′ 10″ × 12′ 5″	1′ 5½″ × 9′ 6½″	3′ 0″ × 13′ 0″	3′ 3″ × 8′ 0″	5′ 10″ × 23′ 0″	2′ 1″ × 3′ 0″	60

CHAPTER VIII

WATER—HYDROMETERS—BRINE—AIR—LIQUID AIR

Water.—The most elementary considerations of water from a general view would take more space than can be devoted in this volume—we can view them only from a refrigeration standpoint.

Composition.—Pure water is a chemical combination of the elements oxygen and hydrogen, in the proportion, by volume, of two of the latter to one of the former, the chemical symbol being H_2O.

Colour.—Water is a transparent liquid, which, in its pure state, is practically colourless; when seen in bulk it has a bluish-green appearance.

Purity.—As water is one of the best solvents known, it is never found naturally pure. The nearest approximation is that collected in the country or at sea during a heavy rainstorm, after the fall has continued some time.

Drinking waters are generally broadly classed into *hard* and *soft*. These qualities are determined by the amount of "curd" that is produced when soap is used. Dr. Clark introduced a *standard* soap solution, which is employed by chemists to determine the *hardness* of the water in terms of parts, by weight, of carbonate of lime per 100,000 parts of water, or *degrees Clark.*

Hardness is generally due to calcareous and magnesian salts.

In order to determine if a water (which is not to be distilled) is fit for drinking or ice making, it should be subjected to a

(*a*) chemical
(*b*) bacteriological

analysis.

The following are portions of the results of analyses, expressed in parts per 100,000, carried out by Dr. Campbell Brown, of the University of Liverpool, for the Water Committee of Liverpool.

DESCRIPTION. WATER OBTAINED FROM.	TOTAL SOLID MATTERS.	ORGANIC CARBON.	ORGANIC NITROGEN.	AMMONIA.	NITRATES.	TOTAL COMBINED NITROGEN.	CHLORINE.	HARDNESS.
Vyrnwy . .	5·04	0·218	0·033	0·002	0·000	0·035	0·9	0·9°
Rivington .	10·12	0·166	0·026	0·003	0·000	0·029	1·6	3·9°
Green Lane Well . .	32·40	0·025	0·006	0·000	0·707	0·713	3·3	18·9°

The first two may be taken as very excellent waters. The third is an example where a rigid bacteriological examination should be made, as the nitrates may point to past pollution by sewage, and the total nitrogen, and also the chlorine, to existing direct pollution from the same source.

Aëration.—Water has a remarkable power for absorbing gases. Ordinary drinking water contains air to a greater or less extent; in fact, this aëration makes the water palatable. For ice making, aëration is a distinct drawback, for such a water when frozen is milky-white in appearance, and special precautions have to be taken if *clear* ice is required, which will be briefly discussed under "Ice Making."

The following table is given by Siebel in his "Compend of Mechanical Refrigeration."

One Vol. Water dissolves Vols. Gas.	32° F.	39·2° F.	50° F.	60° F.	70° F.
Air	0·0247	0·0224	0·0195	0·0179	0·0171
Ammonia . . .	1049·6	941·9	812·8	727·2	654·0
Carbon dioxide .	1·7987	1·5126	1·1847	1·0020	0·9014
Sulphur dioxide .	79·789	69·828	56·647	47·276	39·374
Marsh Gas . . .	0·0545	0·0499	0·0437	0·0391	0·0350
Nitrogen. . . .	0·0204	0·0184	0·0161	0·0148	0·0140
Hydrogen . . .	0·0193	0·0193	0·0191	0·0193	0·0193
Oxygen	0·0411	0·0372	0·0325	0·0299	0·0284

Two important points should be noted from this table: (1) the higher the temperature of the water the less the volume of gas absorbed; (2) the great amount of ammonia absorbed. It should be further mentioned that "pressure" is also a factor. The figures are given for atmospheric pressure. If the pressure should be greater than this, the volumes absorbed will be greater.

In the ammonia absorption system of refrigeration, described in outline in the previous chapter, advantage is taken of the affinity of water for ammonia.

Solubility of Salts in Water.—Special mention will be made of solutions of salt and water in this chapter, under the heading of "brine," but while dealing with water, we may say that 100 parts of water at 0° C. will dissolve about 51 parts of calcium chloride, or 55·5 parts of anhydrous magnesium chloride (forming a saturated solution); the specific gravity in either case will be, approximately, 1·36.[1]

A percentage solution of 17·5 of calcium chloride, or 14·3 of magnesium chloride, is sufficient to raise the boiling point from 100° C. to 104° C. (Engel).

Effect of Heat on Water.—If a unit volume of water be taken at its maximum density (39·1° F., 4° C.) and heated to boiling point under the ordinary atmospheric pressure its volume will be 1·043, at freezing point the volume will be 1·00013, if converted into ice 1·09; approximately, we can say that 10 volumes of water become 11 volumes of ice.

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[1] *Engel* gives 60·3 parts of calcium chloride and 52·2 parts of anhydrous magnesium chloride at 0° C. (*Journal Chemical Society*, vol. lii. p. 771).

This increase of volume during freezing is to be particularly noted.

One volume of water at 4° C., heated and converted into steam at atmospheric pressure, will occupy 1654 volumes.

It is one of the wisest provisions of nature that these changes of state take place gradually, the latent heat being a most important factor. If a pound of water at 212° F., occupying say 0·0167 cub. ft., *suddenly* changed into steam occupying 26·5 cub. ft., the danger attending even the domestic boiling of water would be great. The 1 lb. must absorb 966 B.Th.U. before the change can be completed.

Specific Heat.—Water has been taken as a standard of comparison for measuring the capacities for heat of all bodies. The specific heat of water at freezing point is the unit; at 70° F. it is a minimum, being barely 0·99; at 212° F. it is 1·03; as ice it is 0·504; and as steam 0·478.

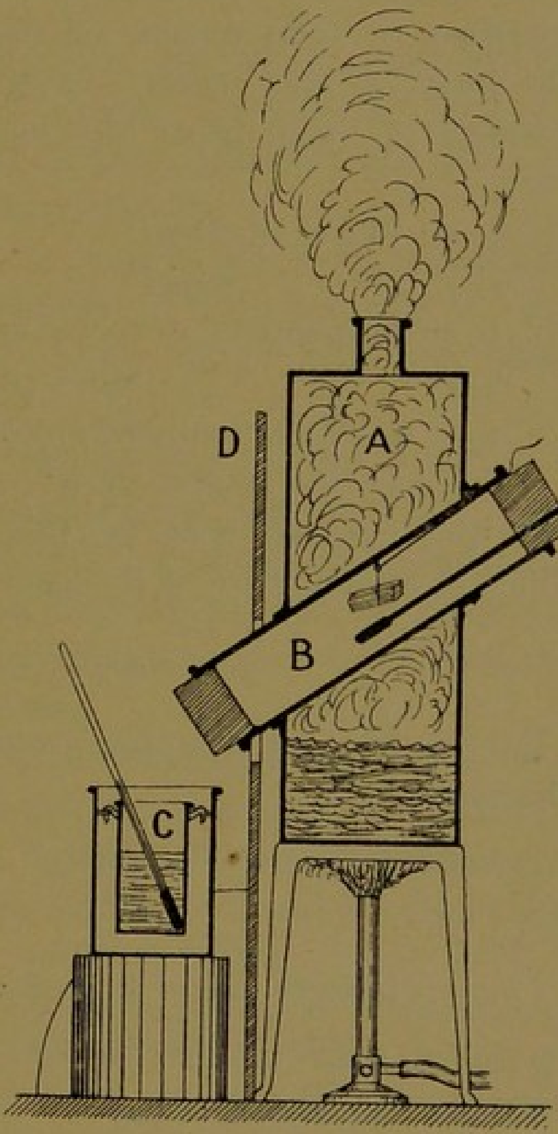


Fig. 43.

An interesting experiment which, with a little care, will give approximate values for the specific heat of solids, can be carried out by means of the apparatus illustrated in Fig. 43.

A vessel, A, is penetrated by a cylindrical vessel, B. In the former steam is generated, thereby heating a small block of metal say of known weight, to a temperature that can be determined by a thermometer.

In the insulated vessel C is a known weight of water at a known temperature.

If the block is lowered by a thread into the vessel C, the increase in temperature of the water will give the specific heat of the metal. D is a shield to prevent the passage of heat from one vessel to the other by radiation.

Let w_1 = weight of metal
w_2 = „ water
t_1 = temperature of metal after heating
t_2 = „ „ water (initial)
t_3 = resulting temperature of metal and water
k = specific heat of metal.

Now, the gain of heat by the water = its weight × difference of temperature × its specific heat

$$= w_2(t_3 - t_2)$$

since the specific heat of water is unity.

Similarly,

$$\text{loss of heat by the metal} = w_1(t_1 - t_3)k$$

clearly,

$$\text{loss of heat by metal} = \text{gain of heat by water}$$
$$w_1(t_1 - t_3)k = w_2(t_3 - t_2)$$

from whence, the specific heat

$$k = \frac{w_2(t_3 - t_2)}{w_1(t_1 - t_3)}$$

The temperature of gases in a flue can be determined in a similar manner by immersing a piece of suitable metal, whose weight and specific heat is known, and which has been placed in the flue, into water whose weight and temperature is known. In the above equation, t_1 would be the only unknown, and can be determined by the equation—

$$t_1 = \frac{w_2(t_3 - t_2) + w_1 t_3 k}{w_1 k}$$

It is assumed that the metal has remained in the flue long enough to be practically the same temperature as the gases.

Specific Gravity.—Water is also used as the standard for the relative density of bodies. At 4° C. or 39·1° F. the specific gravity of water is 1·00 ; one cub. cm. (c.c.) weighs 1 gram, a cub. ft. weighs 62·425 lb.

At 62° F. the cub. ft. weighs 62·35 lb., and the gallon 10 lb. Ice at 0° C. weighs 57·5 lb. per cub. ft., and its specific gravity 0·92. A cub. ft. of saturated steam at 212° F. weighs 0·037 lb.

A very simple but instructive experiment can be made by weighing cubic centimetres of, say, metals. A c.c. of water weighs, as just stated, 1 gram, so that the weight of the cubes in grams gives, directly, the specific gravity. For instance, a c.c. of brass weighs 8·4 grams—8·4 is, therefore, the specific gravity of brass.

Density of Liquids.—The density of liquids can be found by weighing a known quantity in a special vessel called a "density bottle." The weight of the same quantity of water is known or can be determined, and the ratio between the two will give the required density.

Supposing a flask held (to a mark on the neck) 50 c.c., the weight of water up to this mark would be 50 grams. If oil, say, was poured in up to the same mark and, on being weighed, was found to be 41 grams, then

$$\begin{aligned}\tfrac{41}{50} &= \text{relative density or specific gravity of the oil}\\ &= 0{\cdot}82\end{aligned}$$

Another method is to weigh a solid body and then ascertain its loss when

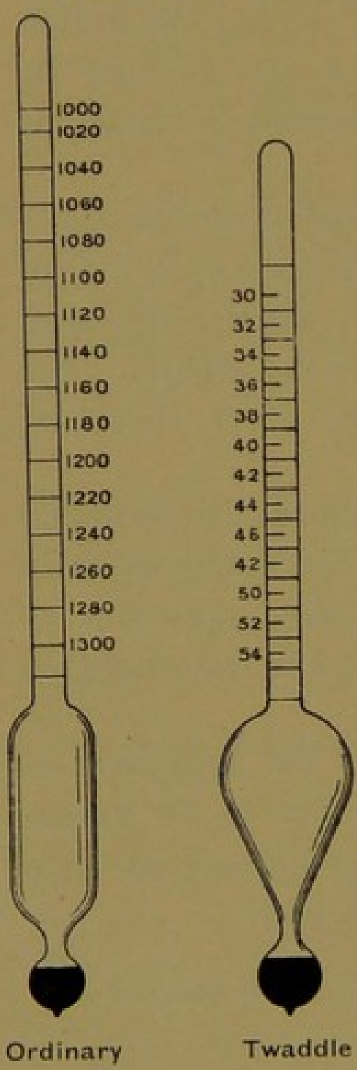
(1) weighed in water ;
(2) weighed in the liquid whose density is required.

Assume, for example, that the loss in the first case was 30 grams, and in the second 26 grams.

The 30 grams represent the weight of the volume of water displaced by the solid; the 28 grams represent the weight of the volume of liquid displaced by the solid, therefore

$$\frac{\text{density of liquid}}{\text{density of water}} = \text{specific weight of the liquid}$$
$$= \tfrac{26}{30}$$
$$= 0{\cdot}866$$

The Hydrometer.—The foregoing explains at once the reason why a body that is capable of floating, floats at different levels in liquids of different densities.



HYDROMETERS

Fig. 44.

Hydrometers are simple instruments (Fig. 44) designed to show, by the height at which they float, the density of the liquid in which they are immersed.

They are generally arranged in sets to show the densities of liquids or solutions—

(1) greater than that of water;
(2) less than that of water.

The ordinary hydrometer has the level at which it floats in distilled water marked at 1000. Should it float in another liquid so that the level is at a point marked 1200 on the graduated scale, the specific gravity or density of that fluid is 1·2. In the same manner 750 would mean 0·75.

Hence, sometimes, specific gravities are given as 1000, 1200, 750, etc., *i.e.* the reading on the ordinary hydrometer.

The scales on other types of hydrometers are often marked in "degrees." These degrees vary—in Beaumé's, for instance, the degree means one thing if constructed for use in liquids *lighter* than water, and quite another meaning if used for liquids *heavier* than water.

In Twaddle's hydrometer the scale is marked in degrees which can be converted into the ordinary scale by multiplying the reading by 5 and adding 1000.

Hence 40 degrees Twaddle is 1200 on the ordinary scale and the specific gravity 1·200.

In refrigeration, hydrometers are generally used for liquids heavier than water, and the following table is given for comparison :—

TABLE SHOWING SPECIFIC GRAVITIES

And corresponding readings on the Ordinary, Beaumé, and Twaddle Hydrometers.

LIQUIDS HEAVIER THAN WATER.

SPECIFIC GRAVITY.	READING ON		
	ORDINARY.	TWADDLE.	BEAUMÉ.
1·000	1000	0	0
1·060	1060	12	8
1·100	1100	20	13
1·150	1150	30	19
1·180	1180	36	22
1·190	1190	38	23
1·200	1200	40	24
1·210	1210	42	25
1·220	1220	44	26
1·230	1230	46	27
1·250	1250	50	29
1·300	1300	60	34

Sea Water. Brine.—It has already been stated that water is an excellent solvent and never found in a pure state. Sea water, for example, contains solids to the extent of about 38 parts per 1000—chiefly chlorides of sodium and magnesium, sulphates of magnesia, lime, and potash : average specific gravity 1·025 ; a cub. ft. weighs 64 lb.

The boiling point of sea water is slightly higher and the freezing point slightly lower than pure water.

Great advantage is taken in practice of the fact that a solution of salt in water (brine) has a lower freezing point than pure water. Sodium chloride (common salt) and calcium chloride solutions are both extensively used in refrigeration; other solutions, such as magnesium chloride, are used, but not to the extent of those named.

The brine (when used) is cooled in the refrigerating machine, generally to many degrees below the ordinary freezing point, and then circulated around the ice cells if for ice making, or through pipes for cooling stores, etc.

Calcium Chloride ($CaCl_2$).—This salt is readily dissolved in water at ordinary temperatures, and a mixture of about 25 per cent., by weight, of salt should be used for making brine; the resulting specific gravity will be about 1·22, *i.e.* 44° Twaddle, 26° Beaumé, and 1220 ordinary, hydrometers

The freezing point of such a mixture is about $-18°$ F., and with ordinary care no trouble will arise in a refrigerating machine on account of the brine freezing.

The specific heat may be taken as 0·75, and the gallon to weigh 12·2 lb., it being remembered that both the specific heat and specific gravity must be determined if scientific accuracy is desired at the temperatures at which it is used. For ordinary purposes the capacity of brine for heat may be taken as 9 B.Th.U. per gallon per degree difference of temperature.

Sodium Chloride ($NaCl$).—This salt is not so extensively used as calcium chloride for brine making, owing to the fact that it is difficult to keep the brine of such a density as to prevent freezing.

Guthrie found in 1876 that when brine made with 10 per cent. sodium chloride was cooled to 18° F. or $-8°$ C., formation of ice took place, which was free from salt. This left the remaining brine of greater density, but further cooling resulted in the further formation of ice, and at $-8°$ F. or $-22°$ C. the whole was frozen, forming *cryo-hydrate*, consisting of crystals of ice and salt in juxtaposition, expressed by the formula $NaCl + xH_2O$.

If a 15 per cent. solution is taken, pure ice is not formed until a temperature of 11° F. or −11·7° C. is reached, but still at −8° F. or −22° C. the whole will freeze.

With a 20 per cent. solution 0° F. or −17·8° C. is reached before ice is formed; but, again, at −22° C. or −8° F. the whole will freeze.

With a 23·5 per cent. solution the lowest possible temperature that sodium chloride brine will stand, viz. −22° C. or −8° F., is reached without any ice formation, but the whole will then freeze.

If we take a common practical example, brine is made at ordinary atmospheric temperature, with a specific gravity of 1·200 which represents a little over 25 per cent. salt.

This percentage will hold good until −12·2° C. or 10° F. is reached, when *salt will separate out.* On further cooling further salt will separate, until 23·5 per cent. is reached and −22° C., when the whole will solidify into crystals of cryo-hydrate.

In an evaporator (refrigerator) working with low temperatures for cold storages, consisting of vertical sheets of pipes through which air is blown for cooling the chambers, and over which sodium chloride brine is allowed to fall, it is almost impossible to prevent the formation of cryo-hydrate, on account of the brine being brought into contact with the very lowest temperature in the circuit.

The solid substance so often found in the tray of this type of evaporator may, therefore, be a mixture of salt and cryo-hydrate; the latter when once formed will not readily melt, even at temperatures much higher than required for its formation.

It is evidently useless attempting to work with this brine higher than 1200 or 40° Twaddle, for even ordinary refrigeration.

Magnesium Chloride ($MgCl_2$).—This salt is finding increasing favour for brine making. A 25 per cent. solution may be used for ordinary refrigerating purposes, the freezing point of which is about −22° F., specific gravity 1·22, *i.e.* 44° Twaddle and 26° Beaumé; the specific heat may be taken as 0·70.

Magnesium chloride brine has, for some purposes, advantages over either of the other brines (NaCl, $CaCl_2$). The following table will help to explain two of these points; it gives the pounds of salt required per gallon of water to make saturated solutions at the temperatures selected:—

TEMPERATURE.		$MgCl_2$.	$CaCl_2$.	NaCl.
F.	C.			
65°	18·3°	5·65	7·10	3·60
55°	12·8°	5·60	6·40	3·55
0°	−17·7	5·30	3·60	3·20
−10°	−23·3	5·20	3·50	Frozen

The first point in favour of $MgCl_2$ is that the solution is much more stable than $CaCl_2$, and the second point is that it can be used for much lower temperatures than NaCl.

Taking a concrete example, we have, where the *Poetsch* system of shaft sinking is used by forming an ice wall (see p. 179), long vertical brine pipes inserted into the ground, with the object of freezing the water in the water-bearing strata.

The supply of brine to these vertical pipes is by means of a smaller pipe, concentric with the first, the larger pipe having the bottom end closed, the small pipe having its bottom end open.

When operations (which extend over months) are started, the brine is sent down at a much higher temperature than towards the finish, in fact, the final temperatures may be below 0° F. Sodium chloride brine could not be used for the purpose at all, while, if calcium chloride brine was used, the risk of stoppage from the separated salt collecting at the bottom of the pipes would be great. With magnesium chloride brine no such difficulties arise, and therefore we find it used for this particular process, a 26 to 28 per cent. solution being generally employed. It may be mixed at 55° F. to 65° F., or even higher, without the slightest fear of separation taking place at the lowest temperature met with in the circuit (*i.e.* say −10° F. on the pipes in the evaporator).

It is often a difficult matter to mix brine to the required density, warm water being frequently used. An inspection of the table shows the danger with respect to $CaCl_2$; if the operator neglects the use of the hydrometer, a very strong solution may be made at the outset, and the after deposit serious.

Concentrators.—If brine of any kind is used for spraying over air coolers, the moisture deposited by the air rapidly weakens the brine. Concentrators, which are generally simple tanks with steam coils (or other means of heating), may be used for concentrating the brine by driving off vapour.

AIR. THE ATMOSPHERE.—Air is a mechanical mixture of nitrogen and oxygen, the proportion by weight being 77 of the former to 23 of the latter, by volume 79 and 21, or nearly 4 to 1.

It is taken as the standard of comparison for the densities of gases, which are considered perfect.

Gas.	Symbol	Density.	Gas.	Symbol.	Density.
Oxygen . .	O_2	1·105	Sulphurous Acid .	SO_2	2·211
Nitrogen .	N_2	0·971	Carbonic Acid . .	CO_2	1·520
Hydrogen .	H_2	0·069	Ammonia . . .	NH_3	0·589

These gases, however, can no longer be considered perfect—all having been liquefied—but at the ordinary temperature and atmospheric pressure they are so far removed from their liquid state that they may be considered as obeying the laws of the perfect gases.

One pound of air at 32° F. occupies 12·387 cub. ft, 1 cub. ft. will, therefore, weigh 0·0807 lb.

The Atmosphere.—The atmosphere contains traces of many impurities mixed with the air, carbonic acid (CO_2) being found to the extent of three parts in 10,000 even in the purest air.

Aqueous vapour is always present, but in ever varying quantities.

The pressure of the atmosphere is usually taken as 14·7 lb per sq. in., or 2116 lb. per sq. ft. This pressure is equivalent to that produced by a column of mercury 29·92 in. or 760 mm. high, or a column of water 34 ft. high.

Heavy pressures are generally taken in terms of atmospheres; for instance, in a carbonic acid refrigerating machine the pressure in the evaporator would be about 20 atmospheres, and 65 in the condenser.

Very light pressures are registered in mm. of mercury or inches of water, *i.e.* equivalent to pressures produced by columns of the given height.

Hygrometry.—Hygrometry is a branch of physics which treats of the amount of moisture in the air.

The amount of moisture in a given volume of atmospheric air depends on the pressure and temperature. As the pressure (for our purpose) varies between such very small limits, temperature only need be considered, and it is found that the higher the temperature the greater the amount of moisture the air is capable of retaining.

Dew Point.—Air at ordinary temperatures may not be saturated with aqueous vapour (*i.e.* may not contain all the vapour it is capable of retaining), but if cooled, a saturation point is reached, called the "dew point," and very fine beads of moisture will be deposited, which can readily be observed on suitable surfaces.

Dew Point Hygrometers are instruments in which a smooth bright surface is cooled, and on which the first indication of the formation of dew can be observed.

The following table, taken from "Ventilation and Heating" (Sturtevant Engineering Co.), should be most carefully studied in order to understand the general principles governing the amount of moisture contained in air. It gives the weight of air, vapour of water, and saturated mixtures of air and vapour at temperatures 0° F. to 92° F. (also at 212°) under the ordinary atmospheric pressure of 29·921 in. of mercury.

TEMPERATURE FAHRENHEIT.	VOLUME OF DRY AIR, VOLUME AT 32° BEING 1·00.	WEIGHT OF A CUBIC FOOT OF DRY AIR, IN POUNDS.	ELASTIC FORCE OF VAPOUR IN INCHES OF MERCURY. REGNAULT.	MIXTURES OF AIR SATURATED WITH VAPOUR.					
				ELASTIC FORCE OF THE AIR IN MIXTURE IN INCHES OF MERCURY.	WEIGHT OF CUB. FT. OF THE MIXTURE OF AIR AND VAPOUR.			WEIGHT OF VAPOUR MIXED WITH 1 LB. OF AIR.	WEIGHT OF DRY AIR MIXED WITH 1 LB. VAPOUR.
					WEIGHT OF THE AIR. LB.	WEIGHT OF THE VAPOUR. LB.	TOTAL WEIGHT OF MIXTURE LB.		
0°	0·935	0·0864	0·044	29·877	0·0863	0·000079	0·086379	0·00092	1092·4
12	0·960	0·0842	0·074	29·849	0·0840	0·000130	0·084130	0·00155	646·1
22	0·980	0·0824	0·118	29·803	0·0821	0·000202	0·082302	0·00245	406·4
32	1·000	0·0807	0·181	29·740	0·0802	0·000304	0·080504	0·00379	263·81
42	1·020	0·0791	0·267	29·654	0·0784	0·000440	0·078840	0·00561	178·18
52	1·041	0·0776	0·388	29·533	0·0766	0·000627	0·077227	0·00819	122·17
62	1·061	0·0761	0·556	29·365	0·0747	0·000881	0·075581	0·01179	84·79
72	1·082	0·0747	0·785	29·136	0·0727	0·001221	0·073921	0·01680	59·54
82	1·102	0·0733	1·092	28·829	0·0706	0·001667	0·072267	0·02361	42·35
92	1·122	0·0720	1·501	28·420	0·0684	0·002250	0·070717	0·03289	30·40
212	1·367	0·0591	29·921	0·000	0·0000	0·036820	0·036820	Infinite	0·000

Supposing the inlet air to an evaporator of a cold store was 22° F. and the outlet 12° F., being saturated in both cases, the water deposited per cub. ft. of air would be 0·000072 lb.

A store of a capacity of 200,000 cub. ft. would probably have fans sufficiently large to circulate the whole of the air every two hours, *i.e.* 100,000 cub. ft per hour.

With the above conditions this would mean a deposit of 7·2 lb. of water per hour, or 17 gallons per day of 24 hours.

This would weaken and overflow the brine when working continually, and great care must be exercised in keeping the solution up to standard by the addition of more salt.

It is seldom found that the air returning to the evaporator is saturated, but, on the other hand, the outlet air is frequently super-dried, so that the above calculation may be taken to hold good in extreme cases.

The weakened brine from the overflow may be boiled in a concentrator, the excess of moisture being driven off, and the concentrated brine, after cooling, sent back to the evaporator.

It is much better, for a given refrigerating effect, to circulate large quantities of air through the cooler, lowering the temperature but a few degrees, than to send small quantities through, lowering the temperature to a greater extent.

In the latter case the air will be super-dried, and the goods in the store "mummified," as the air will endeavour to reach its saturation point, and will extract moisture (if possible) from all available material.

For this reason, many engineers cool chambers intended for bacon and similar goods with brine pipes—a method which does not super-dry the air.

Cold Air Evaporators, Refrigerators or Coolers.—Coolers are generally placed on the top floor of a cold chamber, because the cold air will naturally drop and the warmer air rise.

Taking for example the same temperatures as before, 12° and 22° F., we find that for a cold store 100 ft. high the difference of pressure—causing the natural rise—in the inlet and outlet shafts would be 0·18 lb. per sq. ft. This would call for less than 1 per cent. extra work on the fan if the cooler was placed on the ground floor; therefore, in the more modern buildings we find the evaporator side by side with the main machinery, the engineer thereby having all his plant close at hand (p. 156).

The student should refer to the drying of air for blast furnace purposes, page 181.

Liquid Air.—Liquid air can be obtained from the atmosphere by machines that work on what is known as the "self-intensive refrigerative method."

One of these machines (Linde's) is described by Ewing in the *Journal of the Society of Arts*, March 11, 1898. A description is also given in *Engineering* of the same date, from which the following extract is made :—

> "The apparatus in question is based on a classical experiment made many years ago by Lord Kelvin and Joule, in which compressed air was allowed to escape through a porous plug, and its temperature measured on both sides of the same. With a thermo-dynamically perfect gas the two thermometers would have shown no temperature difference, as the air under these conditions expanded without doing work, but actually under the conditions of the experiment a slight cooling effect, amounting to about ¼ deg. per atmosphere was exhibited. Linde causes the air, which has undergone this cooling by being made to flow through a constricted orifice, to pass back through a long pipe surrounding a second pipe conveying the unexpanded air to the orifice. Hence, when the apparatus has been working some time, the unexpanded air reaches the orifice at a lower temperature than that of the atmosphere, and is further cooled on its escape and expansion.
>
> "This, again, still further cools the in-coming air to be expanded, and an accumulative effect is thus attained, which rapidly reduces the temperature at the point of escape below the critical temperature for air. A certain portion of the latter is then liquefied, and can be collected in a vacuum vessel in the usual way."

Another of these machines is due to Dr. Hampson, a description and illustration of which appears in "Ice and Refrigeration," April, 1899.

Improvements in details have been effected in these machines, but the principle remains exactly the same.

The critical data of air and other fluids has been given in Chapter V., but the following additional data will serve to show how oxygen can be obtained from liquid air:—

Substance.	Boiling Point or Temperature of Saturated Vapour at Atmospheric Pressure.		Freezing Point.	
	C	F	C	F
Air	−191·4	−312·6	−207	−340·6
Argon	−187	−304·6	−189·6	−309·3
Nitrogen . . .	−194·4	−318	−214	−353·6
Oxygen . . .	−181·4	−294·5	—	—

Air, it will be remembered, is simply a mechanical mixture of (chiefly) nitrogen and oxygen, and liquid air, when newly made, will contain 21 per cent. of oxygen and 79 per cent. of nitrogen.

When the air boils it is found that the nitrogen is "distilled" from the oxygen, owing to its boiling point being 13° C. lower. Thus, after a period, the liquid air will have a greater percentage of oxygen than of nitrogen; a percentage of 75 can readily be obtained.

Value of Liquid Air.—Liquid air has been, and will continue to be, of very great value in carrying out scientific researches at very low temperatures, but the whole theory of thermodynamics is against it ever being of value for commercial refrigeration, where temperatures below 0° F. are not required.

The temperature of liquid air at ordinary atmospheric pressure is −312·6° F.; it would, therefore, be just as absurd to use this to obtain the 0° F. just mentioned, as it would be to go down 312 ft. for water that could be obtained at the ground-level.

Storing Liquid Air.—The greatest possible care must be exercised in storing liquid air: firstly, in order to retain it in the liquid state; secondly, to minimize the danger from explosion. The latter is met at once by only using open-mouthed vessels—closed vessels being impossible.

To meet the first demand, many devices have been framed, but Dewar's bulbs, described in Chapter III., and illustrated in Fig. 16, is the type of vessel most frequently used (p. 35).

CHAPTER IX

ICE MAKING

Natural Formation of Ice.—When the air above a pond or lake is below freezing point, the top layer of water is cooled, and will sink in consequence of the increased density.

This will go on until the whole pond is cooled to 4° C., or 39·1° F., which is the point of maximum density of water.

The top layer, on being further cooled to say 3° C., will, therefore, still remain on the top (the water below being of greater density), and eventually will be reduced to freezing point.

The main body of water will remain at 4° C., or perhaps a little lower.

A thin layer of ice being once formed, it must be noted that before the next layer of water below is frozen, the heat must pass from the water through the ice already formed, consequently, the thicker the ice grows, the slower its subsequent growth.

If the water underneath is still, opaque ice will be formed; if the water is moving, or even in a gentle state of agitation, clear hard ice will result.

Each molecule of water in freezing sets free the particle of air it contains; the small bubble thus formed adheres to the surface of the newly formed ice.

This bubble may be built around by the growing ice and become imprisoned, the ultimate result of myriads of similar cases making the ice opaque.

On the other hand, if the bubble is *washed off* the surface of the newly formed ice by the movement (agitation) of the water, the ice will be kept clear.

Assuming the article on "Water" (Chapter VIII.) has been read, it may be said without further explanation that pure, clear, hard ice is generally demanded by the consumer from ice factories, and elaborate means have to be adopted to ensure its production. The two principal ways are—

(1) distillation,
(2) agitation.

(1) **Distillation.**—Distilled water for ice making has long been in common use in the United States; the use in this country has, however, been the exception rather than the rule, although more distilling plants are being fitted now than formerly.

The exhaust steam from the main and auxiliary engines, treated in a special apparatus, may be used, but the quantity of water thus produced is generally on the small side, and, broadly, it is desirable that an entirely separate plant should be employed.

In either case, great care has to be exercised to ensure cleanliness, and also to prevent the water from being re-aërated in its transit to the ice cans.

Assuming great care in the working, distilled water produces clear, hard, and crystal-like ice.

(2) **Agitation.**—The reason why agitation is necessary has been mentioned under "the natural formation of ice." Further practical considerations will be treated under—

Artificial Production of Ice.—With very few exceptions, what is known as "artificial ice" is produced by constantly extracting heat from a thin wall of metal, which is in contact with the water to be frozen.

The arrangements adopted in practice for extracting the heat from the thin wall, and for keeping the water agitated (if clear ice is required—distilled water not being used) is always interesting, and easily understood by those having a knowledge of first principles, which may be explained by reference to Fig. 45.

A is the thin wall of metal;
B a fluid (brine) kept at a low temperature;
C the water to be frozen.

The heat from C passes through A to B, and given B at a sufficiently low temperature (12° to 25° F.) ice will be formed on the water side of A.

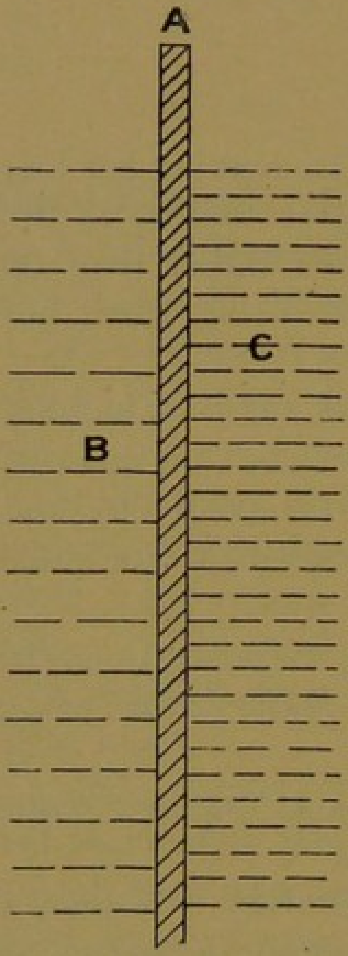


FIG. 45.

If the water is pure and free from air, clear ice will be formed; or, being ordinary town water, if kept agitated, so as to brush off the air-bubbles and impurities from the newly formed ice surface, the same effect will be produced, otherwise opaque ice is formed.

Time of Freezing.—The first layers of ice will form very quickly, say 1 in. thick in one hour, or less, according to the temperature. Taking an average temperature of 20° F., and ice forming on two walls and meeting to form the given thickness, the following rule may be taken to hold good:—

To estimate the time in hours that will be required to produce n *inches of ice (cell or can), find the sum of the first* n *natural numbers.*

Thus, to make ice 6 in. thick, $1 + 2 + 3 + 4 + 5 + 6$, *i.e.* the sum of the first six natural numbers $= 21$; 21 hours is, according to this rule, required for 6 in. ice.

Expressed as a formula—

$$\text{Time in hours} = \frac{n(n + 1)}{2}$$

The following is a table from this formula :—

4 in. ice	…	10	hours to freeze	(cell or can)
6 in. „	…	21	„	„
8 in. „	…	36	„	„
10 in. „	…	55	„	„
12 in. „	…	78	„	„

If the ice is formed from *one* wall only, as in plate ice, the above rule will still hold, if modified accordingly, thus—

$$\text{Time in hours} = \frac{2n(2n+1)}{2}$$

or

4 in. ice	…	36	hours to freeze	(plate)
6 in. „	…	78	„	„
8 in. „	…	136	„	„
10 in. „	…	210	„	„
12 in. „	…	300	„	„

Temperature for Ice Making.—In practice, the temperatures carried (brine) vary very much ; 12° to 25° F. would, however, cover the range. For thick (10 in. to 14 in.) plate ice, the former figure, 12°, would not be too low, whereas for the *best* clear, hard, can ice, 25° would not be too high. With reason, the higher the temperature the better the ice ; but 18° to 20° F. would be safe figures to use.

Purity of Ice.—There can be no question that ice during its formation endeavours to throw off the impurities contained in the water, but the conditions under which ice usually grows is such, that we can at once say that contaminated water produces contaminated ice. The greatest care should, therefore, be exercised to see that the water supply to an ice factory is pure, as suggested in the previous chapter on " Water."

Consumers of ice would do well to have the ice tested (*i.e.* water formed by melting the ice), particularly when natural ice is intended for table use.

Ice Factories.—There are, in practice, three principal systems of ice making—

(1) can,
(2) cell,
(3) plate.

These will be explained diagrammatically, with references to one or two actual plants.

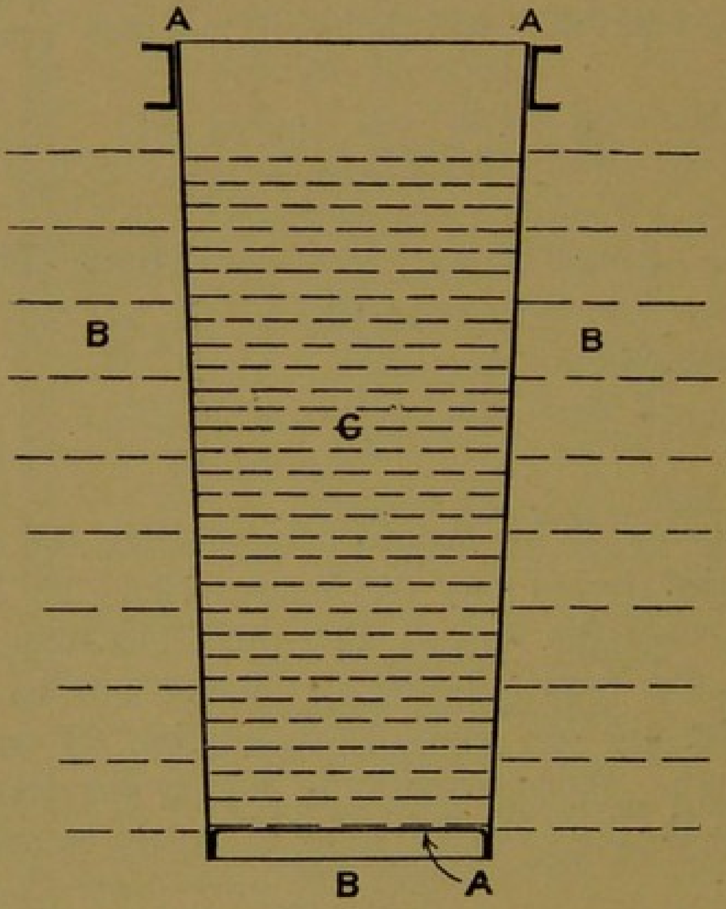


FIG. 46.

(1) **CAN SYSTEM.**—A tapered can (various sizes are made) of terned, tinned, or galvanized iron or steel, is nearly filled with cold water and placed in a tank of cold brine.

Following in Fig. 46 the same notation as in Fig. 45, it will be noticed that there are five walls (four sides and bottom) on which ice may form.

With distilled water, good clear, hard ice can be made by this method.

If town water is used, and no agitation employed, opaque ice is formed, and may be used, when crushed, for cooling railway refrigerating vans, trawlers, etc.; it has no commercial value for table use, and its lasting properties are inferior to clear ice.

If clear ice is required, the water must be agitated by some mechanical means—many ingenious methods being employed. One type takes the form of a very thin piece of wood (paddle), which is kept moving backwards and forwards in the water, and removed before the ice freezes across.

Another method, shown in Fig. 47, is by means of a double-necked bottle-shaped vessel, one end of which is placed in the water, the other end connected by means of rubber hose to a pipe in which the pressure is alternately slightly higher and slightly lower than the atmosphere. The water is drawn in and partly forced out of the bottle, thereby keeping the water in the can in a constant state of agitation.

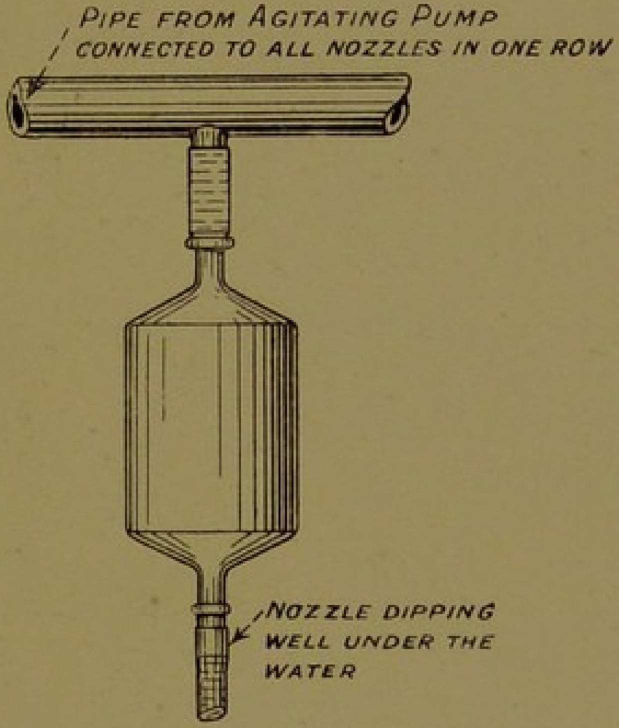


FIG. 47.

The nozzles must, of course, be withdrawn before the ice "closes," by lifting the connecting pipe bodily up. This can be better understood by noting the arrangement shown at the bottom of Fig. 48.

The can system in operation at the Liverpool Cold Storage and Ice Co. (fitted by The Linde British Refrigeration Co.), shown in Figs. 48, 49, and 50, may be taken as a good typical example.

Here, twenty ice cans (or moulds) are placed in one row on two carriers (Fig. 49). The cans are first taken to one end of the factory and (partially) filled with water from a special tank, divided internally into twenty small tanks,

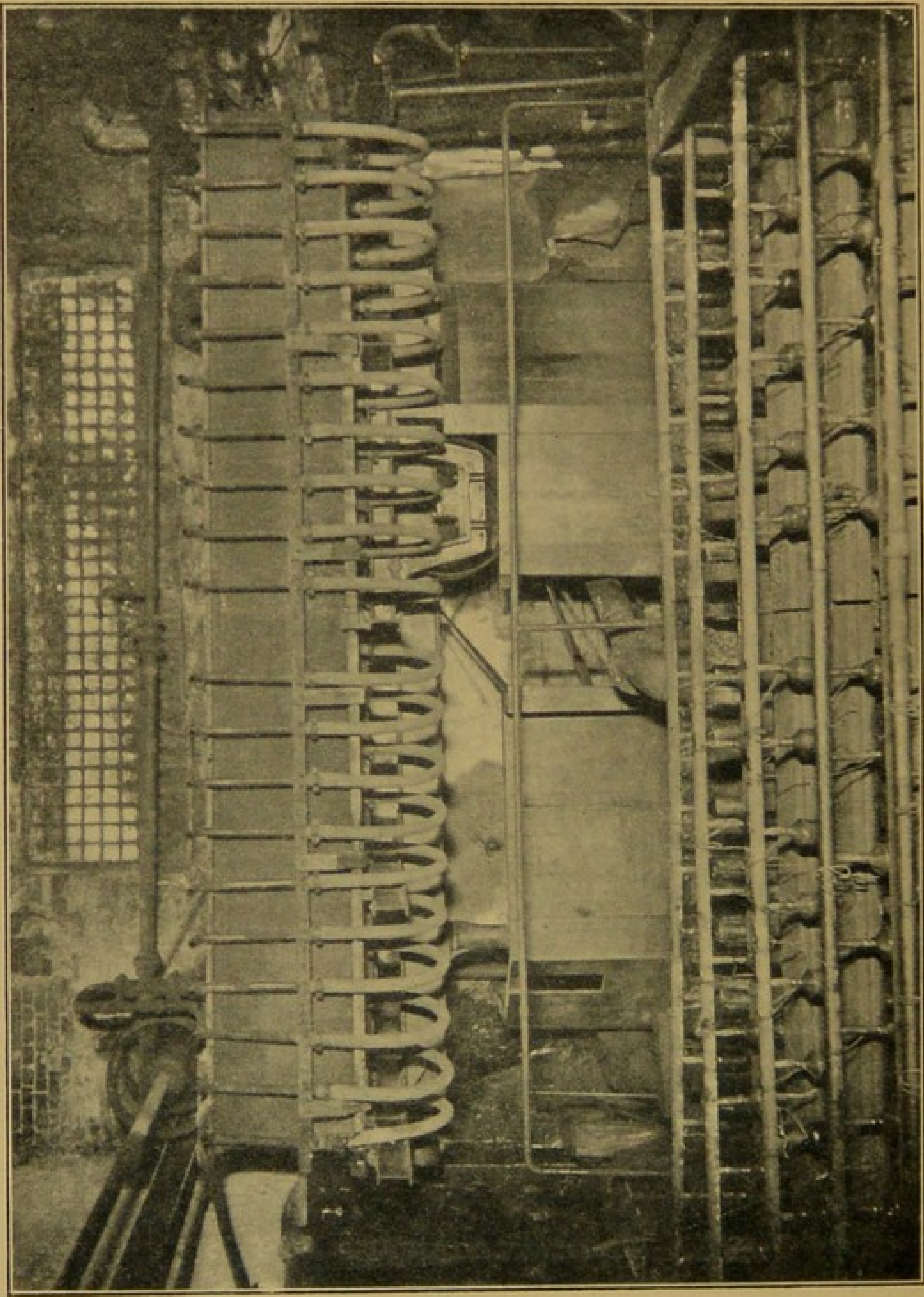


Fig. 48.

each arranged to hold sufficient for one mould. From the bottom of each small tank is a short rubber pipe connecting to a metal nozzle. The whole twenty nozzles are clipped to one iron bar, and can be raised or lowered all together.

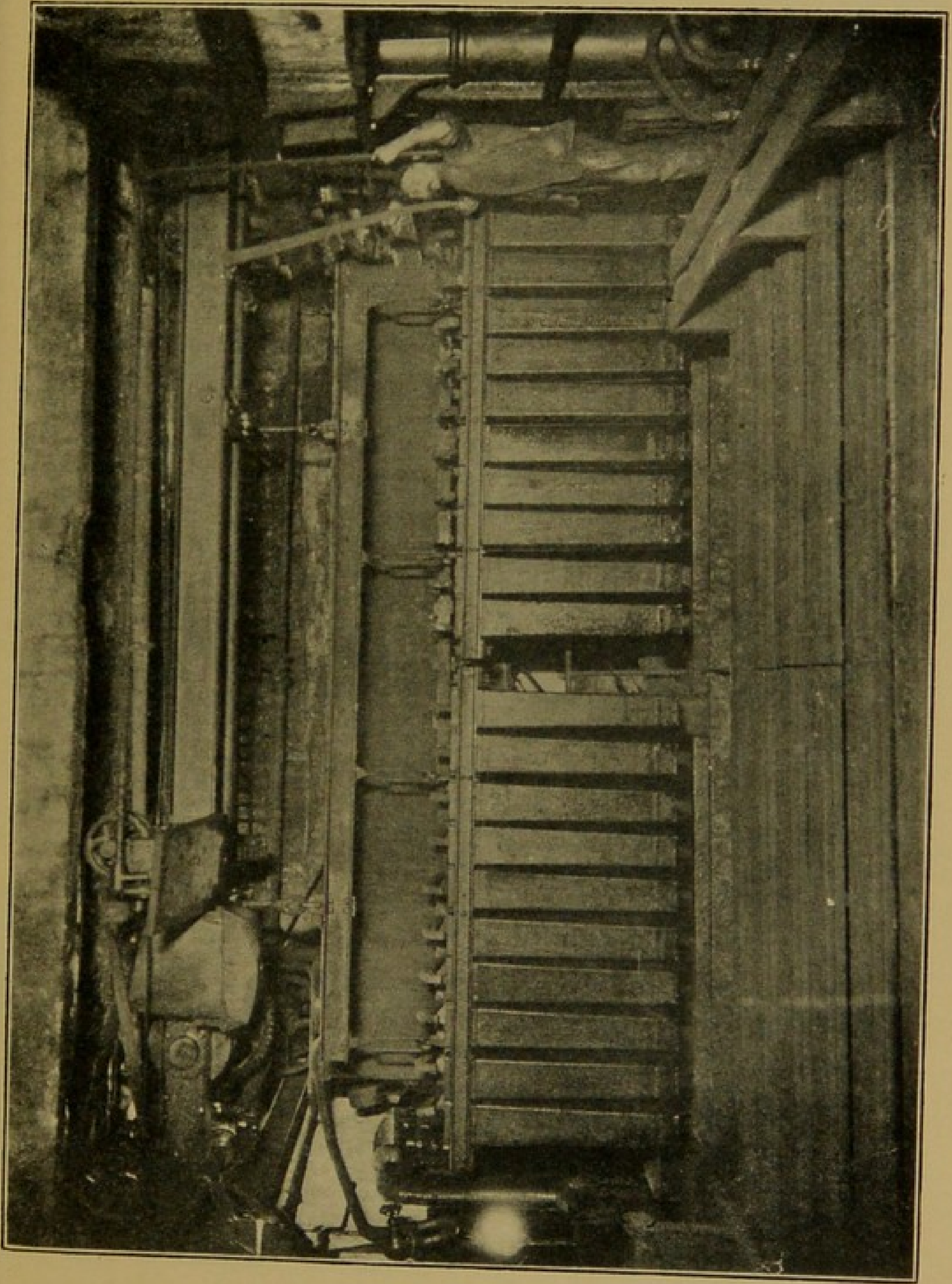


Fig. 49.

When the large tank (or series of small ones) is being filled, the ends of the nozzles are kept (Fig. 48) above the water-level, and are brought over into the ice moulds, while the latter are still elevated on the crane; the whole is then lowered into the brine tank, the moulds filling, and the tank (or tanks) emptying (Fig. 49).

The agitating nozzles in the cans that have been previously treated are lifted, and all the carriers are mechanically moved forward (by rams) a space equal to that occupied by one row; the agitating nozzles are then once more lowered.

The operation has dislodged a row of moulds at the far end of the tank, where the ice in the cans is "made up."

The crane lifts the carriers and places these moulds into a tank of warm water known as the "thawing off" tank. This loosens the ice ("thawing off"), and the whole 20 are tipped over by means of a special rocking-bed, the operation being governed by the craneman. Fig. 50 shows the moulds half over, and in this figure details of the carrier, etc., can be noted.

There are 48 rows of ice cans, 20 in a row; each block weighs 1¼ cwt. (average size 7 in. × 13 in. × 48 in.), giving a total capacity of 60 tons.

Forty-eight hours are required to freeze, thaw off, and fill, giving a daily output of 30 tons.

The following table gives particulars of a few dimensions of ice blocks from cans that may be taken as typical in size:—

WEIGHT OF BLOCK. LB.	MEAN THICKNESS. IN.	MEAN WIDTH. IN.	DEPTH. IN.
56	3	18	33
112	5½	18	36
112	6	24	24
168	6	30	30
224	8	30	30
336	7	18	42
336	8	30	30

Evaporator or Refrigerator for Can Ice Making.—The brine for can ice making may be cooled in separate evaporators, or the evaporator coils may be placed in the ice-making tank itself. In the case of the plant just described,

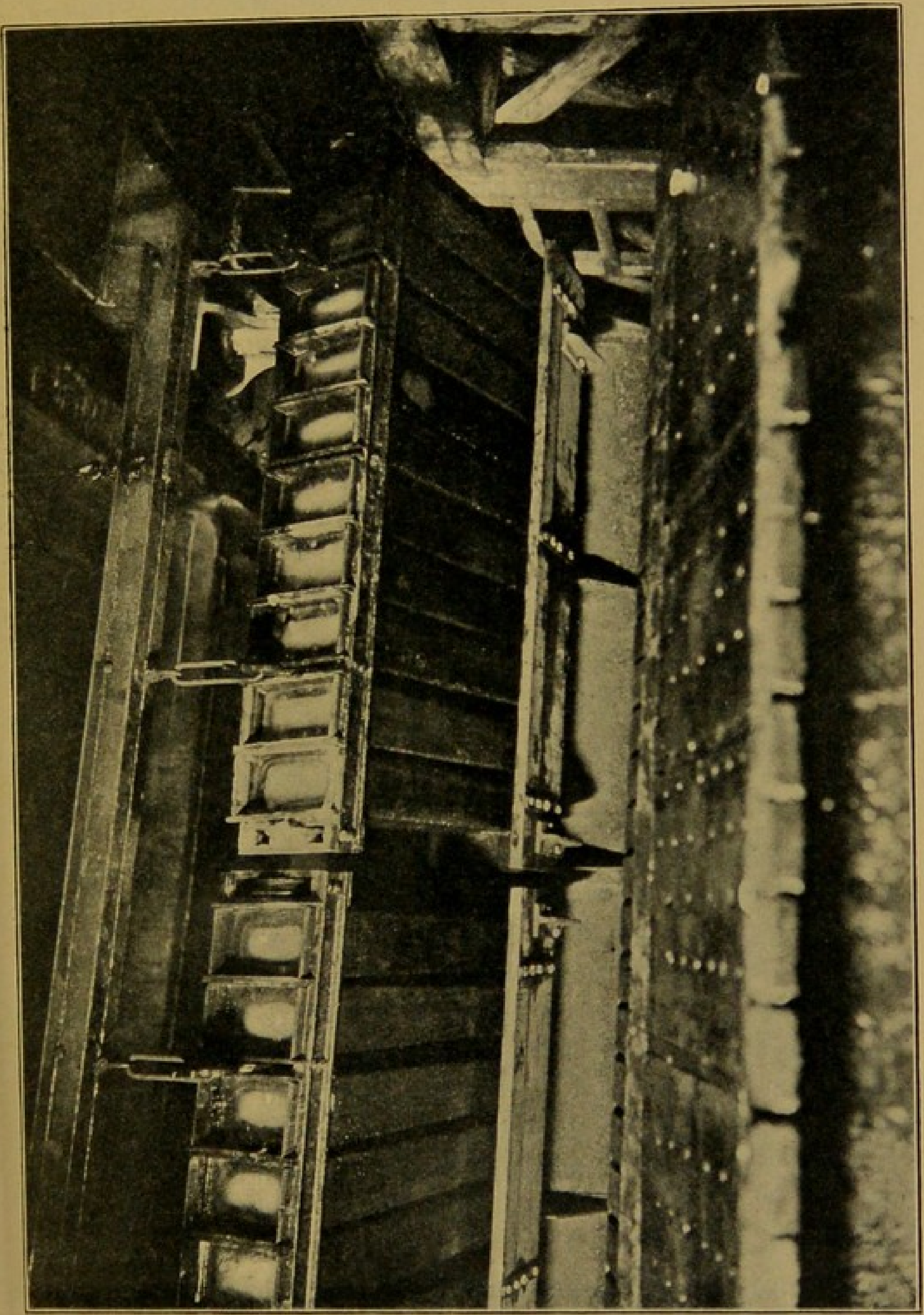


Fig. 50.

the coils (ammonia) are under a false bottom, having openings at each end. Propellers circulate the brine—first, around the coils, under the false bottom, then over the false bottom, around the ice cans, returning at the far end of the tank to the coils.

American Practice in Can Ice Making.—The American practice differs from the English, inasmuch as each can is lifted separately—generally by a quick-acting pneumatic hoist—and deposited on a sloping table, where a series of warm water sprays act on it to "thaw off," the ice, when released, sliding into the ice store. An automatic can filler (at the end of a hose) is used, the can being filled, in position, to any required height with distilled water. Agitation in this case is not necessary. The following table gives usual sizes :—

Weight of Block. Lb.	Mean Thickness. Inches.	Mean Width. Inches.	Depth. Inches.
50	8	8	31
100	8	16	31
200	11	22	31
300	11	22	44

(2) **CELL SYSTEM.**—In this country, the best known cell system is that of Siddeley's. A number of thin hollow castings are placed in a tank in such a way as to make cells—a diagram of which is shown in Fig. 51.

Following the same notation as before, A shows the thin walls, B the cold fluid (brine), and C the water to be frozen. The paddle or plunger D is worked up and down a short distance, and keeps the water C_1 in constant motion, thereby moving the water C through holes in the false bottom of the wooden tank. The ice grows on the four walls, the formation working towards the centre, consequently the agitation is kept up almost until the block closes.

When the ice blocks are "made up," the water is drained away from the false bottom, and warm brine (50° to 70° F.) from a special tank is circulated through the cells, which loosens the ice, and the block can be lifted by means of a becket (a piece of rope with an eye at one end) which has been frozen in.

Fig. 52, which is from the factory of the Liverpool Cold Storage and Ice Co., gives an excellent idea of the general arrangement of such a plant, which in this case consists of 12 tanks, each having 20 cells, the blocks of ice weighing 5 cwt., giving a capacity of 5 tons in each tank, or a total capacity of 60 tons.

The blocks are 4 ft. deep, 2 ft. 6 in. wide, and 12 in. thick, and the best results are obtained when three days are allowed for freezing, thawing off, cleaning and re-filling.

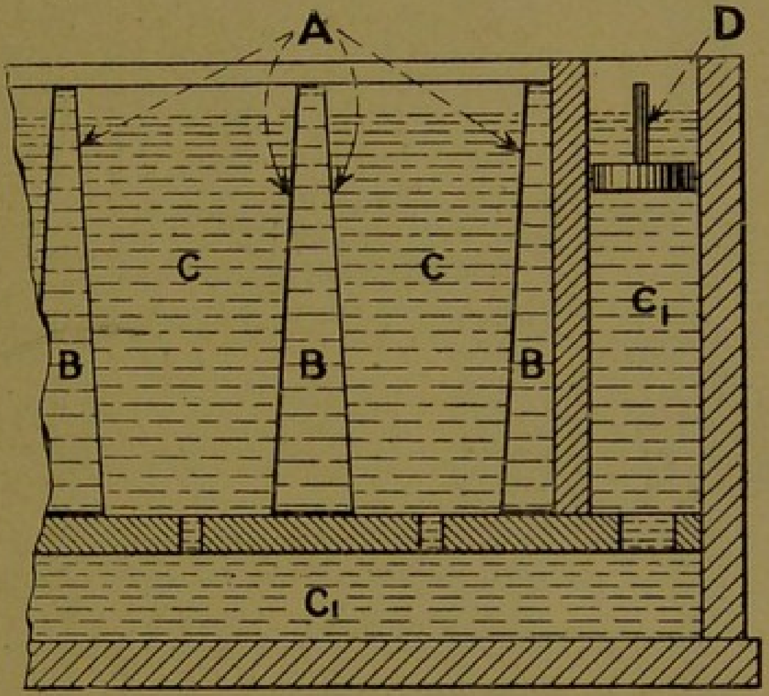


Fig. 51.

The evaporator for these cells is described on p. 110.

Fig. 53 is a plan and elevation of a complete tank of cells as arranged by the Liverpool Refrigeration Co.

Referring to the plan, the brine enters at one end of a hollow wall that forms part of three cells.

From the elevation it will be seen that the wall has internal divisions that deflects the brine backwards, forwards, and downwards, until the bottom front end is reached, when it ascends an internal pipe, and passes over by means

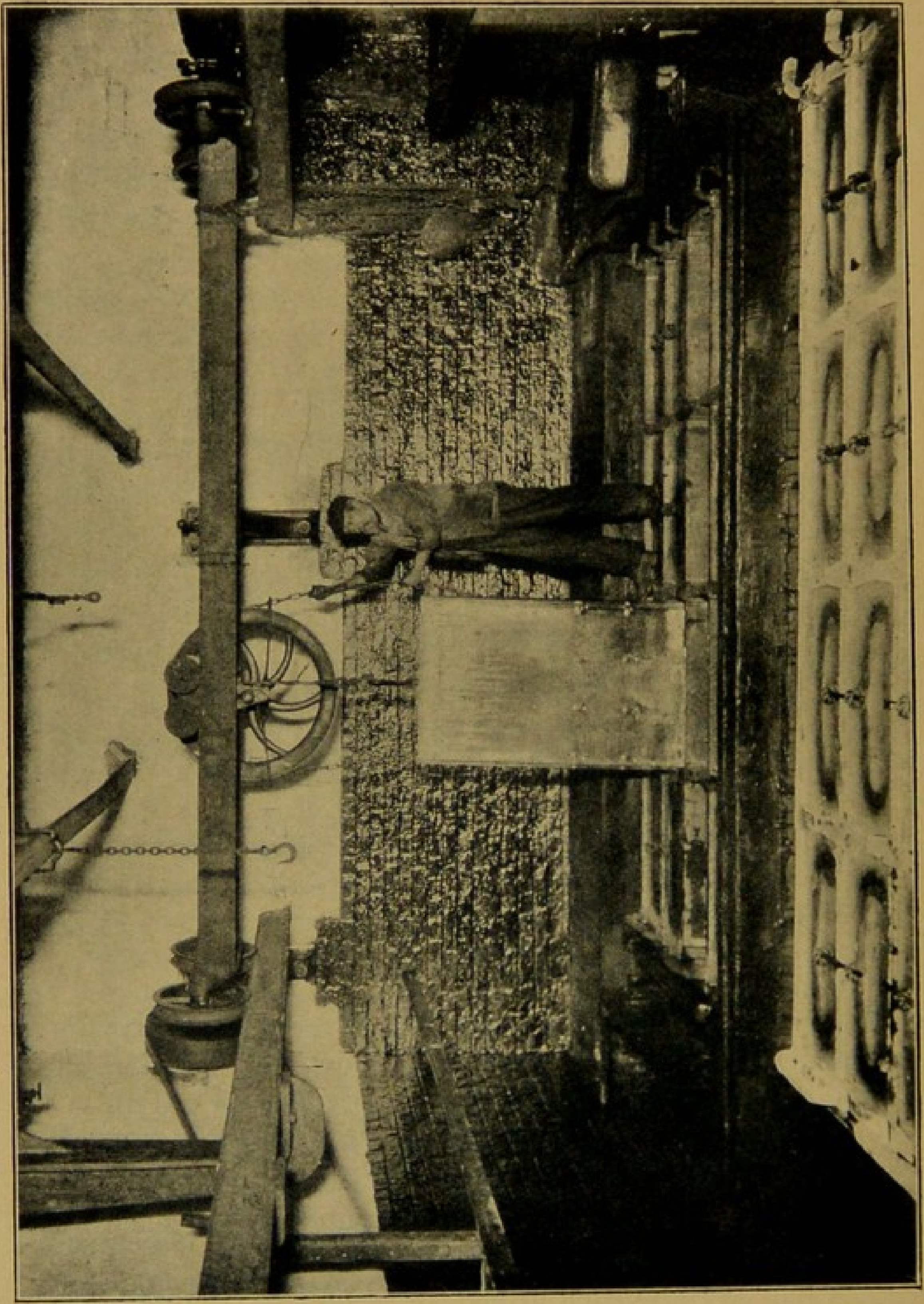
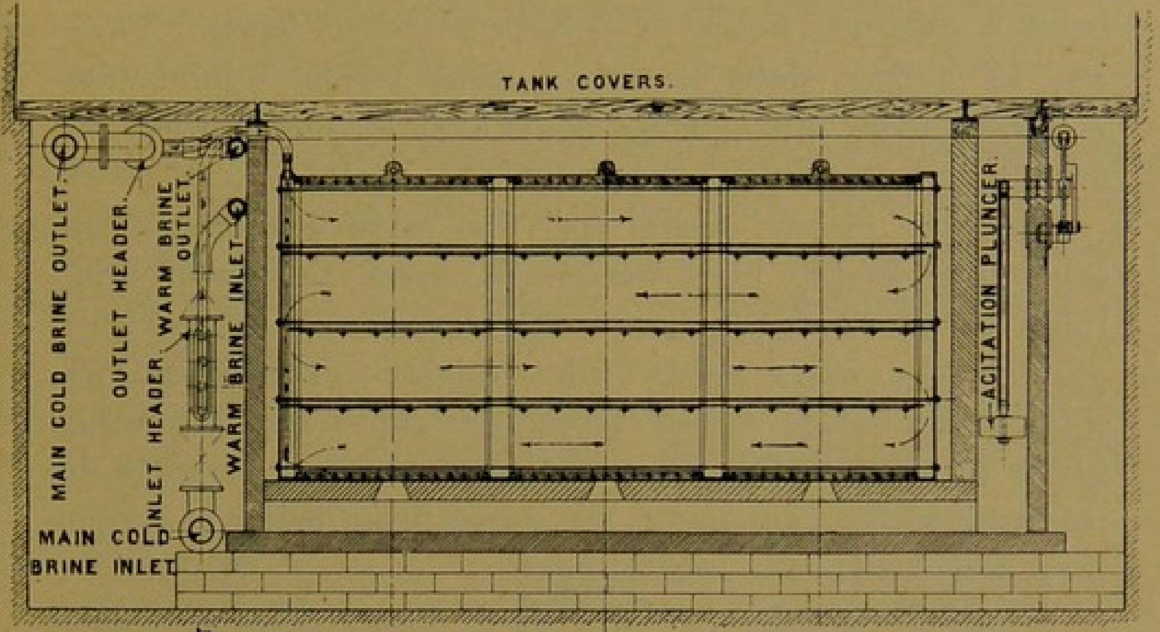
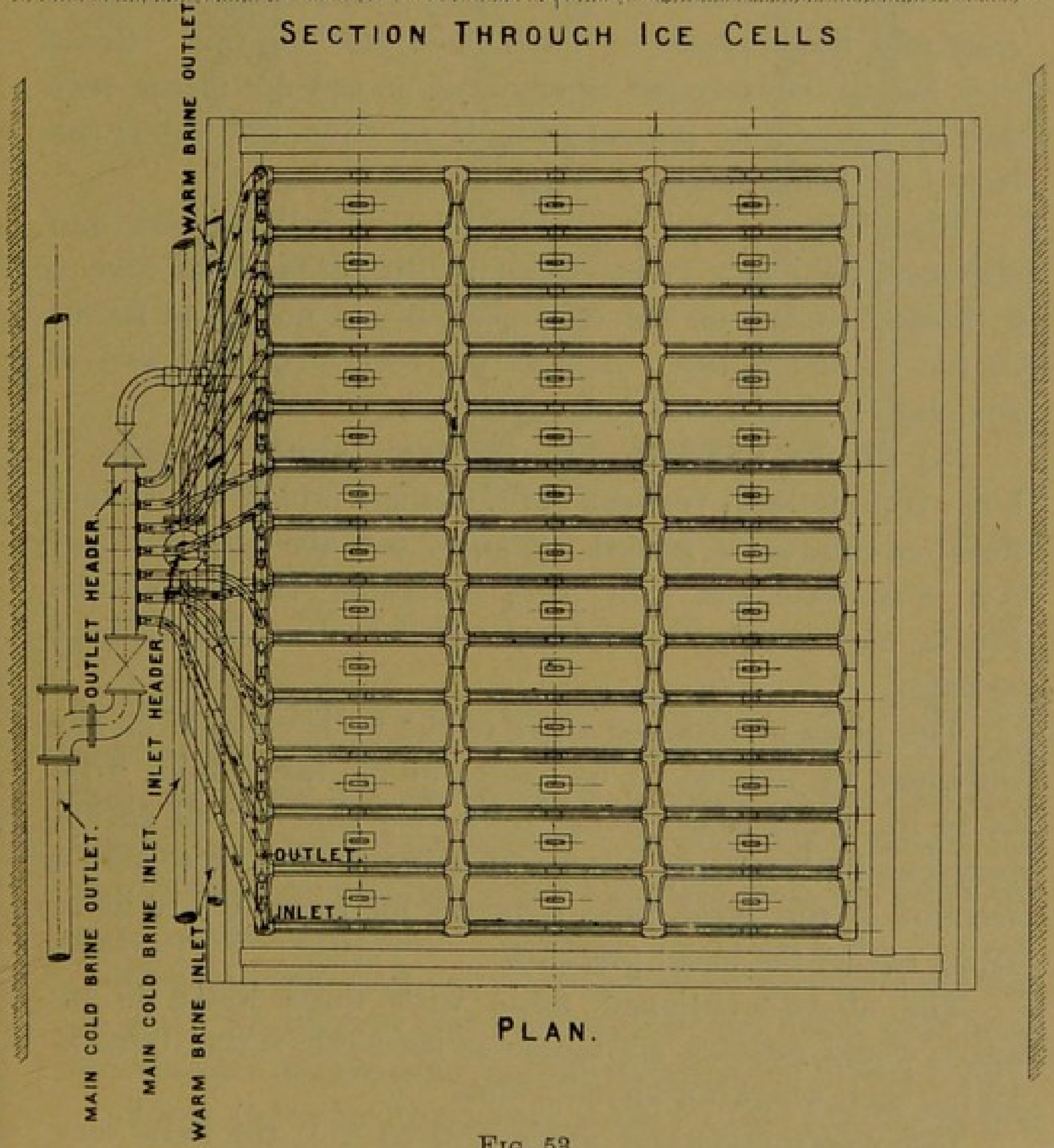


Fig. 52

of a rubber pipe connection to the second hollow wall. After passing through this wall in a similar manner, the



SECTION THROUGH ICE CELLS



PLAN.

Fig. 53.

brine is returned to the evaporator to be re-cooled. There are 14 hollow slabs or walls, which means 7 inlets and 7 outlets—the inlets being controlled by one header, and outlets collected by another header.

The ice being "made up," the valve connecting the inlet pipe to the inlet header is closed, the warm brine inlet valve being opened (see elevation). After a few minutes the warm brine outlet valve is opened and the cold brine outlet valve closed, the short interval being given to allow the greater portion of the cold brine to be returned to the evaporator, the warm brine being in proper time deflected to the warm tank.

The hollow walls are built up by means of special castings and large plates of galvanized steel or iron. Great care has to be exercised in erecting, on account of the very narrow joints that separate the brine from the water, the least leak being fatal.

Excellent ice can be made by this cell method, and although used to a great extent in British factories, and to a limited extent on the continent, it has not found favour in the United States. Almost the reverse may be said of the plate system about to be described.

(3) **PLATE SYSTEM.**—In the plate system a series of long, thin, hollow, vertical walls, through which the cooling fluid circulates, is placed in tanks, say about 16 ft. long, 8 ft. 6 in. wide, and 7 ft. deep, containing the water to be frozen, and which, in order to make clear ice, is kept agitated.

The pitch or distance apart of the walls depends on the thickness of the ice to be made, which varies from 6 in. to 14 in., the former being much too thin for all except very small plants, and the latter being seldom exceeded on account of the great time required for freezing; 10 in. to 12 in. covers the usual practice.

The above-mentioned tank, with three walls 30 in. apart, would produce six blocks of ice 15 ft. × 6 ft. 6 in. × 12 in., each weighing about 5 tons.

The construction and method of cooling the walls vary greatly in practice, the principal systems being shown in Fig. 54, A, B, and C.

In A the pipes are placed very close together, or a thin strip of iron fitted between. Brine or the refrigerant is circulated through the pipes, and when "thawing off" is required warm brine is circulated, or the refrigerant (warm) direct from the compressor is sent through on its way to the condenser.

B represents an effective method, and consists of grids or coils of pipe through which the refrigerant circulates enclosed by two plates, against which the ice forms, the intervening space being filled with brine. For thawing off, the cool brine can be replaced by warm brine (specially heated in a tank) by means of a pump. Or a steam coil can be fitted so that the pipes alternate with the ammonia pipes, steam being turned through for thawing off.

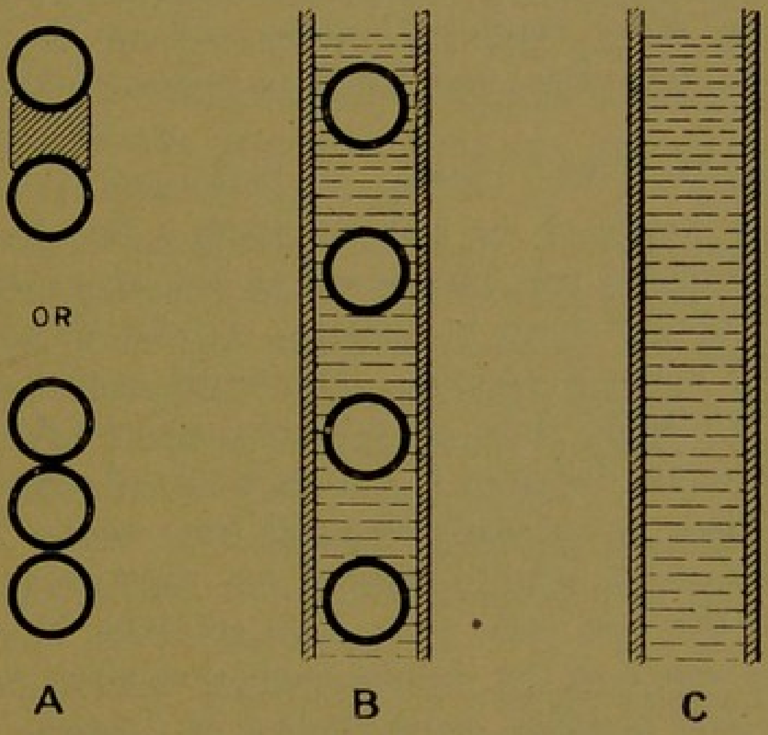


Fig. 54.

C is a plain wall, very similar in construction to that shown in the elevation of Fig. 53, through which cool brine is circulated for freezing, and warm brine for thawing off.

From the table previously given in this chapter it will be seen that nine to twelve and a half days are required for 10 in. and 12 in. ice. Where, as in America, high-class ice is demanded for table use, this great length of time is, perhaps, justified, because plate ice is better than any other artificial clear ice. Good cell ice, however, is so very good that one cannot wonder that the plate system has not found favour with British manufacturers, the difference between three and twelve days for 12 in. ice being so very great.

Plate ice may be harvested in the large plates just as they are formed, or they may be cut by special saws (steam saws being often employed) while still in the vertical position on the plate, and lifted in pieces of about half a ton.

Vacuum Ice.—Mr. Patten, of Baltimore, U.S.A., has patented a system of ice making, where a very fine jet of water, or series of jets, rotates and at the same time moves vertically up and down in a closed circular vessel (called the former) under a vacuum. The result is that a hollow cylinder of opaque white ice is formed, about 6 ft. external and 4 ft. internal diameter, 6 ft. high, blocks of a commercial size and shape being easily obtained from same. The ice, although opaque, is quite equal, if not superior, in lasting powers to the best clear ice. The ordinary white ice is opaque by reason of the minute bubbles of air it contains; such ice soon becomes honeycombed or "rotten," and is without lasting power. The vacuum ice is white because it is built up by myriads of ice crystals, the faces of which have a refractive influence.

A very high vacuum is required for ice making by this method, and as the volume of vapour given off is very great, the size of the "air" pump is kept within practical limits by using sulphuric acid for absorbing the aqueous vapour, the weakened acid being treated in a concentrator for re-use.

It is interesting to note that a supply of cold drinking water, for use in the engine-room, can easily be obtained by taking (say) a stone jar and insulating it with felt and canvas and making a connection, by means of a "rubber" cork and pipe (with cock) to the steam condenser. The evaporation of a portion of the water will cool the remainder, with the desired result.

Storage of Ice.—Care must be exercised in the storing of ice, best results being obtained by placing the blocks on battens on the floor, and thin strips of wood between each block.

The store itself should be well insulated and kept at about 22° F. by means of brine pipes.

The air circulation method can be advocated, if a separate air cooler is fitted, where the air will not be super-dried, otherwise the ice will gradually disappear, without, of course, going through the process of melting; the air taking up vapour direct from the ice.

Working an Ice Factory.—It is an open question whether an ice factory should consist of a relatively small plant and large store, where ice could be made all the year round, and stored during the months of small demand, or a large plant designed to meet the maximum demand, with perhaps a small store to meet daily requirements.

As a matter of fact, each particular case of proposed ice factory demands individual consideration, and no hard and fast rule can be laid down.

In engineering generally, the storage system (to meet maximum demands or "peaks"), if an effective method can be devised, has, at all times, been found most economical, and is always sought for and arranged if possible. Refrigeration is no exception, and a small plant with large store, properly designed and arranged, should, as a rule, prove more economical—the ice being properly made, and "robbing" tanks (taking the ice away before the block is finished) prevented.

Cost of Ice Making.—In Chapter VII. tables, given by various manufacturers, serve to indicate the approximate horse-power required for ice making, the figures differing according to whether the main engines only or main engines, pumps, agitating gear, etc., are included.

A very fair estimate is that a 100-ton plant will require 300 horse-power, all inclusive.

The following table gives the horse-power required for driving the compressors only for the tons of ice stated :—

Tons of Ice made per 24 Hours.	H.P. for driving Compressors.	Tons of Ice made per 24 Hours.	H.P. for driving Compressors.
5	17	60	130
10	27	70	150
20	50	80	170
30	70	90	190
40	90	100	210
50	110		

A method often adopted for indicating the efficiency of ice-making plants is to state the pounds of ice produced per pound of coal burnt, 10 lb. of ice per 1 lb. of coal being a very fair average; much greater values, however, have been registered, particularly during trials.

The author, in testing the vacuum machine in Baltimore (previously mentioned) during the very hot summer of 1906, found that, under quite ordinary working conditions, it made 16 lb. of ice per pound of coal.

It is difficult to give reliable figures as to the actual cost, conditions varying so much; but four shillings per ton, delivered at the tipping platform from the factory, may be taken as a fair average figure.

With a 100-ton can ice plant, working, say nine months in the year, the cost should not exceed two shillings and sixpence per ton.

Wastage, labour, and cost for storage, delivering, etc., are not included in the above figures.

One or two general arrangements of ice plants are given in Chapter XII.

CHAPTER X

CONSTRUCTION AND INSULATION OF COLD STORES AND CHAMBERS, WITH METHODS OF COOLING

In constructing a cold store, it must ever be remembered that any device or arrangement that will *keep heat out* is greatly to be desired; the refrigerating machine, as a heat pump, will then have less work to do, and even temperatures can be the better maintained.

The best construction is one where the building is of a square or rectangular (with but little difference in the length of the sides), box-shaped form, the working entrance or entrances being from the top only, all the goods being lifted on the outside, and then lowered into the interior, extra openings or shoots to meet special demands being fitted to the lower floors.

One of the most economical stores in the kingdom—that of Messrs. Eastmans, Ltd., Derby Rd., Liverpool—was constructed (1887) on this principle by the author's sometime chief, the late J. K. Kilbourn, a celebrated American refrigerating engineer.

The engine-room is built of brick, and is detached from the cold stores, which are constructed for the main part of timber only, with flake charcoal insulation.

Modern bye-laws would prohibit such a building now in a town, but in the colonies, on a foundation wall 1 ft. 10 in. to 2 ft. thick, the timber walls may be built, consisting of a 11 in. × 3 in. sill-piece, with similar sized uprights, with two boards (T and G), with two layers of paper between, placed on either side of the uprights; the outer face to be further protected by weather-boards nailed on 1½ in. strips.

A selected insulating material such as flake charcoal, silicate cotton, pumice, granulated cork, kieselguhr or peat-dust (according to locality, cost, etc.) should be filled in the 11 in. space.

Working openings to be all on the top.

Most owners and managers of cold stores have a rooted objection to these openings and the entailed methods of working, and Fig. 55 shows a sectional elevation of a typical modern building.

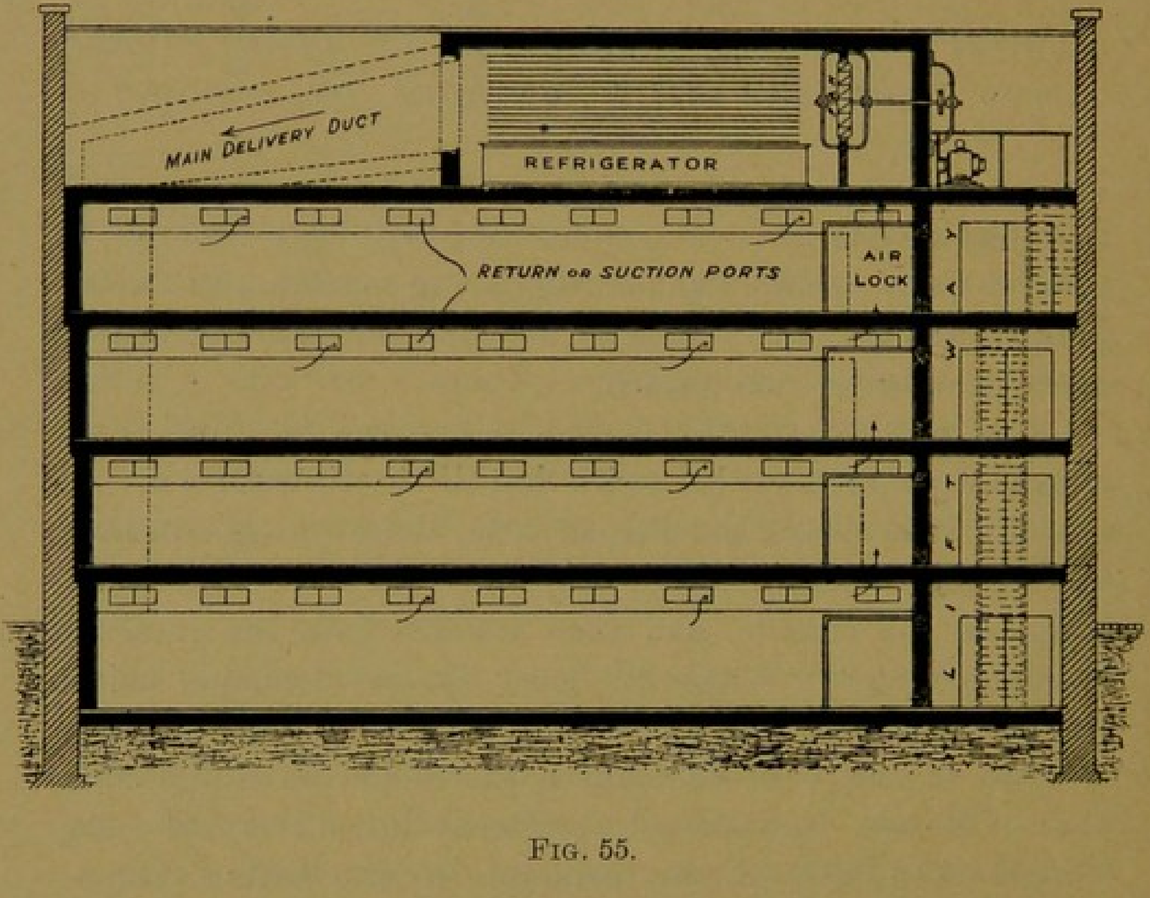


Fig. 55.

The front is provided with a lift-way and stairs—doors with air-locks being fitted to the cold chambers on each floor.

The evaporator or refrigerator is placed on the top floor, and the cold air distributed by means of a fan and air ducts.

An obvious improvement, and one that should be adopted, is to place the evaporator on the floor of the lowest room to be cooled, provided the machinery is in the basement. The engineer has then all the main parts of the plant under his immediate control (p. 132).

Further, it may be placed in *any* convenient position—the illustration assumes that it is placed in the centre of a queen-post roof truss.

Fig. 56 is the plan, and indicates that only a very few small windows are allowed, and those only in the lift and stair-way; most of these could be dispensed with, if the better method of working from the top was adopted.

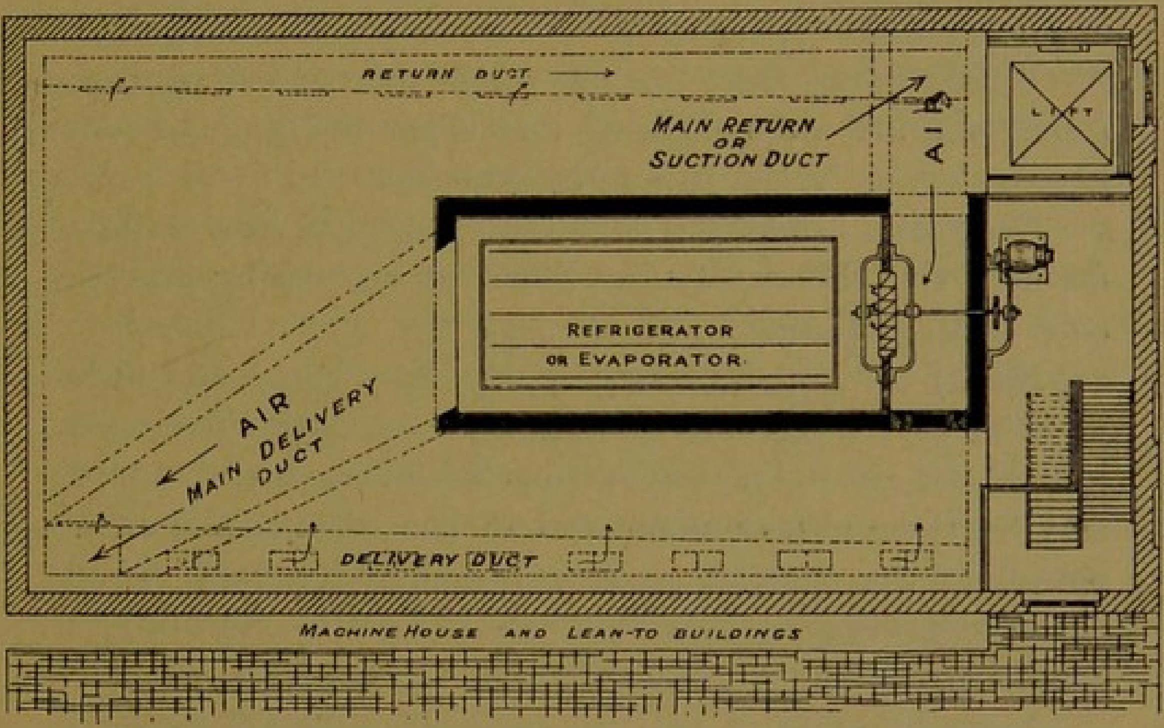


FIG. 56.

The delivery duct in each room has the supply ports on the under side, while the suction or return ports are on the vertical side.

The air supply to each chamber is thus sent direct to the floor, and "filters" through the stored goods to the top of the chamber on the opposite side.

In large chambers a convenient method of distributing the air is to have a supply duct on either side, and a return duct in the centre of the room, the latter with ports on either side, or *vice versâ* (p. 87).

Great care should be taken to avoid "pockets" in the rooms, or dead-air spaces, and if such should exist after the construction of the otherwise most suitable arrangement of ducts, auxiliary ducts should be laid, and a good circulation assured.

Figs. 55 and 56 assume the air circulation method of cooling, and up to, say 100,000 cub. ft. capacity, one evaporator would be sufficient.

With certain classes of goods, or rather mixture of goods, this is not altogether satisfactory, and special rooms, such as for fish, are sometimes set apart and cooled either by means of pipes (direct expansion or brine) or a separate evaporator.

Whole stores may be, and often are, cooled by brine pipes or brine walls (Messrs. Hall's patent), and for some goods, such as bacon, it is to be preferred.

For general storage this method lacks one very essential feature, viz. the sweetening effect of circulating air over cold damp surfaces.

Nearly all stored goods give off heavy gases, and where pipes alone are used for cooling, however good the circulation of the air by means of suitable arrangement of pipes may be, these gases remain, and in fact often collect at the bottom of the chamber, and, in consequence, goods resting on, or parts hanging near, the floor will not be kept in good condition.

A combination of the two methods, although not often carried out, gives excellent results. The fan and the air ducts assure an efficient circulation of the air, while the brine in the pipes, in addition to performing the ordinary cooling, acts as a "reserve of cold," or, in other words, helps to keep a uniform temperature by providing a large bulk of very cold material, which must be "heated" before the room can experience a serious rise.

This most important question of uniform temperatures, so essential for really good storage, is obtaining the attention it merits, as shown by the recent advances in methods of construction, cooling, management and methods of storage adopted, on both land and sea.

Refrigerators or Evaporators for Cold Stores.—In Figs. 55 and 56 the type of refrigerator shown is that of an ordinary evaporator, fitted in a tank (*i.e.* the refrigerant evaporates in coils which are surrounded by brine), and the brine circulated through vertical grids or sheets of pipes, over which a small spray of brine is allowed to fall, and the air blown through the grids by means of a fan.

This type is fitted by the Liverpool Refrigeration Co., and the advantage claimed is that the air is not super-dried, coming in contact with surfaces only a few degrees colder than itself.

The brine is circulated in the vertical grids by means of a pump, the suction for same being taken from the back end, each grid discharging at the front end, a good circulation of brine being thus maintained.

The spray of brine prevents the formation of frost on the pipes, the surfaces being thus kept in the most efficient state.

Another very efficient cooler, for which the same advantage may be claimed, is made by the Linde Co., and is shown in Fig. 57. It consists essentially of a large tank, in the bottom of which ammonia coils are placed and practically covered in by a horizontal division or floor, provided with openings at each end.

Brine is cooled by the evaporation of the ammonia in the coils, and kept in active circulation by the propeller, as shown in the elevation.

A large number of thin circular plates are threaded on to a series of horizontal shafts, and the whole so arranged, that the bottom portions of the vertical plates are in the brine.

The shafts are rotated (generally by means of an electric motor and suitable gearing), and consequently the thin plates are always kept wet and cold.

The whole being suitably boxed in, air is blown through the top portions of the plates and thereby cooled to the required degree without being super-dried.

The same company more commonly fit a cooler composed of vertical sheets of pipes *in* which ammonia evaporates and *over* which brine is circulated, the latter falling into a shallow tray below for re-circulation. Air is blown by a fan through the grids formed by the pipes, and thereby cooled.

This forms a most efficient refrigerator and always gives excellent results. It is necessary to point out that if the ammonia is carried to a very low pressure and temperature, the air will be super-dried. For some purposes (such as drying air for blast furnaces) this is an advantage; but for cold storage work it would mean careless working.

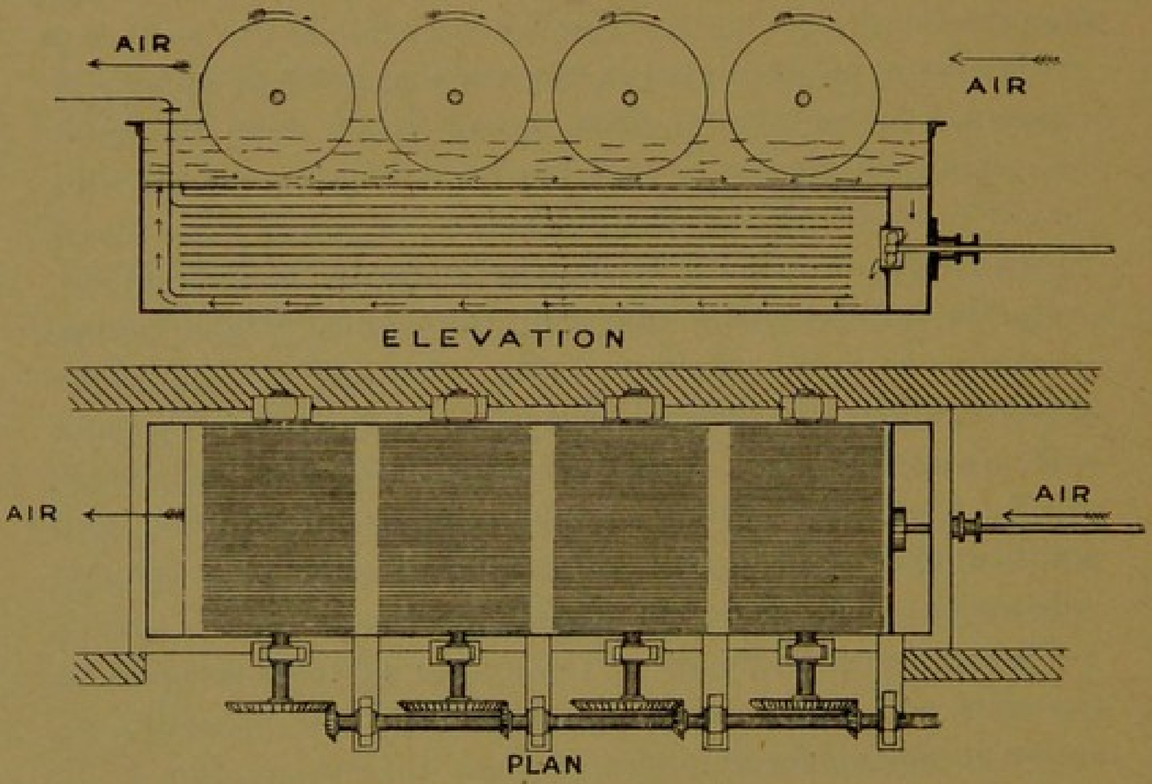


FIG. 57.

Still another method of cooling is by what is known as "direct expansion."

Liquid ammonia (this is the only refrigerant used to any extent for this process) at low pressure, say 30 lb. absolute, is passed direct into coils placed in the chambers, and the heat necessary for its evaporation is taken from the air in the rooms. All the regulating valves for the various sections can be placed in or near the main engine-room, and the return pipes serve as indicators of the work performed, by virtue of the amount of frost they carry.

The direct-expansion method is more efficient and more economical than any other method, but it calls for the very highest workmanship in the construction and great care in working. Only special firms with great experience and repute should be trusted with work of this class, as even the slightest leak of ammonia would be fatal to the reputation of a cold store; if properly erected no trouble will be experienced.

INSULATION.—Whatever the construction of the shell of a cold store may be—stone, brick, with steel or re-enforced concrete beams, etc., etc.—the interior must be lined with an efficient "insulator." Such insulators should have—

(1) a low coefficient of conductivity at low temperatures and small temperature differences;
(2) a high specific heat;
(3) high density or specific gravity.

It further should be—

(4) practicable and sanitary;
(5) non-hygroscopic.

Taking these various points in order, we have—

(1) that those heat insulators which give good results with tests at high temperatures and with great differences of temperature may not (seldom do) give anything like the results when used at low temperatures and small temperature differences, and, of course, *vice versâ.*

It is generally admitted that tests and researches, to be of any value, must be carried out under conditions as near those obtaining in actual practice as possible; yet we frequently see the value of insulators for cold storage based on tests carried out on a steam pipe, with a temperature difference of at least 250° F., and conditions that do not test the damp-resisting properties of the material at all.

Very few reliable tests have been published in this country—the best being that of Messrs. Lamb & Wilson, of Cambridge, whose results are tabulated on p. 36.

The late Dr. Howard, of the Physics Department, University of Liverpool, commenced a research on this subject, being the outcome of tests carried out for a report by the author. He had only obtained relative results when death intervened.

The following are his results, and give the relative number of heat units lost or gained (*i.e.* transferred by the material) per minute for each degree difference in the temperature of its faces as compared with the amount which would be transferred in the same time through an equal thickness of air with its faces differing by one degree.

Table I. is in the Metric system of units, and Table II. in the British system.

TABLE I.

Heat lost per minute per one degree Centigrade. Excess Temperature at specified excess Temperatures.

MATERIAL.	NO. OF KILOGRAMS PER CUBIC METER OF SPACE.	RELATIVE HEAT UNITS LOST AT THE EXCESS TEMPERATURE GIVEN. RECKONED PER DEGREE CENTIGRADE OF EXCESS.						
		15° C.	25° C.	35° C.	45° C.	55° C.	65° C.	75° C.
Air, dry	—	1·00	1·11	1·22	1·39	1·55	1·78	1·96
Air, damp	—	1·50	1·63	1·78	1·90	2·20	2·40	2·70
Sall asbestos—								
AA yellow, dry . .	200	1·42	1·49	1·52	1·54	1·61	1·64	1·67
C yellow, 1 % damp .	268	1·52	1·58	1·61	1·64	1·74	1·78	1·82
" "	224	1·40	—	—	—	—	—	1·50
" "	330	1·70	—	—	—	—	—	1·87
Silicate cotton—								
Ordinary, 3 % damp .	254	1·07	1·08	1·09	1·08	1·08	—	—
B, dry	179	1·00	1·00	1·00	1·00	1·00	1·00	1·00
S, dry	115	1·00	1·00	0·99	1·01	1·00	0·99	0·99
Flake charcoal, dry .	182	1·00	1·05	1·17	1·32	1·38	—	—
Hair felt—								
6 % damp	96	1·41	—	—	—	—	—	1·72
Dry	96	1·00	1·04	1·12	1·25	1·28	1·30	1·33
Kemps—								
8 % damp	49·6	1·56	—	—	—	—	—	1·48
Dry	80	0·90	0·92	0·98	1·02	1·07	1·23	1·35
Sawdust (pine)—								
Damp	173	1·55	—	—	—	—	—	2·60
Dry	200	1·04	1·08	1·26	1·40	1·43	1·49	—

TABLE II.

Heat lost per minute per one degree Fahrenheit. Excess Temperature at specified excess Temperatures.

Material.	Pounds per Cubic Foot of Space.	Relative Heat Units lost at the Excess Temperatures given. Reckoned per Degree Fahrenheit of Excess.						
		20° F.	40° F.	60° F.	80° F.	100° F.	120° F.	140° F.
Air, dry	—	1·00	1·10	1·19	1·39	1·55	1·79	1·97
Air, damp	—	1·44	1·59	1·76	1·90	2·21	2·41	2·72
Sall asbestos—								
AA yellow, dry . .	12·5	1·39	1·48	1·52	1·54	1·61	1·64	1·68
C yellow, 1 % damp .	16·8	1·49	1·57	1·61	1·64	1·75	1·78	1·83
” ”	14·0	1·39	—	—	—	—	—	1·52
” ”	20·6	1·68	—	—	—	—	—	1·88
Silicate cotton—								
Ordinary, 3 % damp .	15·9	1·07	1·08	1·09	1·08	1·08	—	—
B, dry	11·2	1·00	1·00	1·00	1·00	1·00	1·00	1·00
S, dry	7·2	1·00	1·00	0·99	1·01	1·00	0·99	0·99
Flake charcoal, dry .	11·4	1·00	1·04	1·15	1·32	1·39	—	—
Hair felt—								
6 % damp	6·0	1·39	—	—	—	—	—	1·73
Dry	6·0	1·00	1·04	1·10	1·25	1·28	1·31	1·34
Kemps—								
8 % damp	3·1	1·56	—	—	—	—	—	1·48
Dry	5·0	0·90	0·92	0·97	1·02	1·07	1·24	1·36
Sawdust (pine)—								
Damp	10·8	1·52	—	—	—	—	—	2·63
Dry	12·5	1·03	1·08	1·23	1·40	1·43	1·50	—

Kemps, it may be explained, is a waste material in the manufacture of silk hats, and is a near approach to short natural hair.

One must note how the results of Dr. Howard agree with those obtained by Messrs. Lamb & Wilson with respect to the materials in general use—silicate cotton, flake charcoal, and sawdust.

Dr. Howard's figures further show the importance of temperature differences, and indicates how the various materials differ in their behaviour.

Supposing certain materials give (nearly) *equal* results with respect to *conductivity*, we come to—

(2) specific heat,
(3) specific gravity.

The higher the product of these values the more valuable the material as an insulator.

Taking, for example, air, silicate cotton, and flake charcoal, and considering 1 sq. ft. of insulating face 1 ft. thick, we shall have 1 cub. ft. of each material—the enclosing walls being neglected, being supposed the same in each case.

The air will weigh 0·0807 lb., and its specific heat being 0·237, it will only require 0·0191 B.Th.U. to increase its temperature 1° F. The relative figures for silicate cotton are 11·2 lb. (from Dr. Howard's table), 0·200, and 2·240 B.Th.U.; for flake charcoal 11·4 lb., 0·242, and 2·758 B.Th.U.

Supposing three stores insulated with the materials named respectively and the refrigerating machinery stopped. Before the air in the chambers could increase 1° F. by heat passing through the insulation, the insulation itself would be raised (approximately) 1° F. To do this the following amounts of heat would be required:—

air insulation	0·0191	B.Th.U.
silicate cotton insulation	2·240	„
flake charcoal „	2·758	„

The value of the "reserve of power" in the two latter materials is very important.

It is a matter of common knowledge that air can be quickly heated and as quickly cooled—we have practical illustrations every day in summer in the atmosphere itself, which cools so quickly after sundown, and, taking the above reserve of power into account, air, as a practical insulator, leaves a great deal to be desired.

Air, as an insulator, is not used to any great extent in this country, although small air spaces are often left in the insulation.

In the United States, a series of air spaces with the necessary lumber to enclose them, generally makes up the sum total of insulation, although recent practice shows a tendency to British methods—cork, mill shavings, and sawdust being packed between the lumber.

The above figures should also show the student the fallacy of testing insulating materials by placing blocks of ice inside cubical boxes, packed with various materials (not often even the same thicknesses) and noting how much ice is melted in a given time and taking the amount as a measure of the thermal units *passing through* in a given time. The first ice melted is by the heat contained in the material itself.

In such a test, as in practice, time should be allowed for the insulation to "cool down" before readings are taken.

From the figures just given, flake charcoal would take the most "cooling down," before it could demonstrate its insulating properties.

We now come to

(4) the insulator must be practicable and sanitary.

What may be termed the "mechanical properties" of an insulator are important. The methods necessary to hold the material in position for the particular purpose in mind must be duly considered.

If, for example, a pipe is to be insulated, hair felt would claim consideration, because of the fact that it can be "wrapped round" and covered with a waterproof covering. Cork, moulded into shape by means of a waterproofing material, could also be used; most other materials would, however, require a clumsy casing.

The material should be sanitary. Any vegetable matter liable to decay should be excluded, or anything liable to harbour vermin.

The material should be, if possible,

(5) non-hygroscopic.

All materials used for insulating take up moisture from the air, however small that quantity may be, and one that takes up an abnormal quantity must be avoided.

Of the materials mostly used in this country silicate cotton and hair felt are far removed from being non-hygroscopic, and, in consequence, when used, the greatest possible care should be taken, by means of tongued and grooved boarding and waterproof paper, to case them in air-tight casings.

Finally, *cost* must always be an important factor. If a reasonably good insulator can be obtained at a low price, other insulators, perhaps on account of importation, being very high, it may, perhaps, be commercially sound to use such material.

The following, then, may be taken as a list of possible insulators:—

Flake charcoal
Silicate cotton
Hair felt
Cork (granulated, slab, or moulded)
Pumice stone
Kieselguhr
Charcoal (small lump)
Sawdust and mill shavings.

Not forgetting the value of coke breeze, ashes, and concrete for floor formation, or timber and paper used for casing purposes.

Other points are urged for and against various insulators, which have not been considered. For example, the splendid fire-resisting properties of slag wool (silicate cotton) is often quoted in its favour; but again, Professor Lorenz, in his "Modern Refrigerating Machinery" (authorized translation by T. H. Pope, B.Sc.), says, "So-called *slag-wool* should be avoided, on account of the hydrogen sulphide formed by the partial decomposition it always undergoes."

Increasing quantities of *cork* are being employed, but reliable data is lacking comparing it with *flake charcoal* or *silicate cotton;* it is much superior, according to American tests, to either *sawdust* or *mill shavings.*

In the latest Cunard steamers, *Lusitania* and *Mauretania,* which have each cold chambers totalling to 43,000 cub. ft., *granulated cork* is used as the insulator, white boards and waterproof paper being used for the casings.

Types of Insulation.—Referring to Figs. 55 and 56, the insulation *generally* adopted for a building of this kind, would be a 2-in. air space next to the walls (obtained by fixing 2-in. battens to the wall), then two layers of $\frac{3}{4}$-in. tongued and grooved (T & G) boards with waterproof paper between, then 7 in. of *either* flake charcoal *or* silicate cotton, then a $\frac{3}{4}$-in. board, paper, and finally an inch board—T, G, and V (V meaning veed, *i.e.* the edge chamfered off, so that when two boards come together a V is formed).

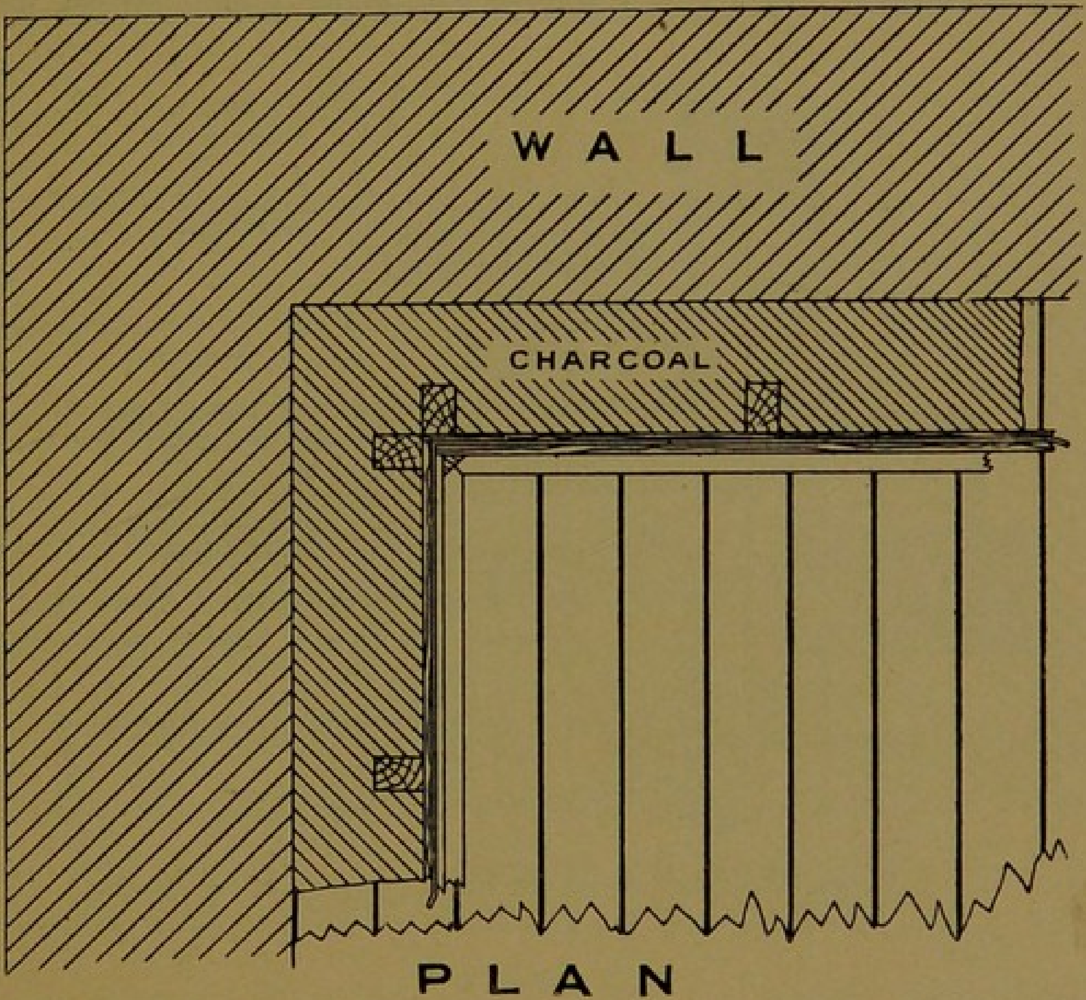


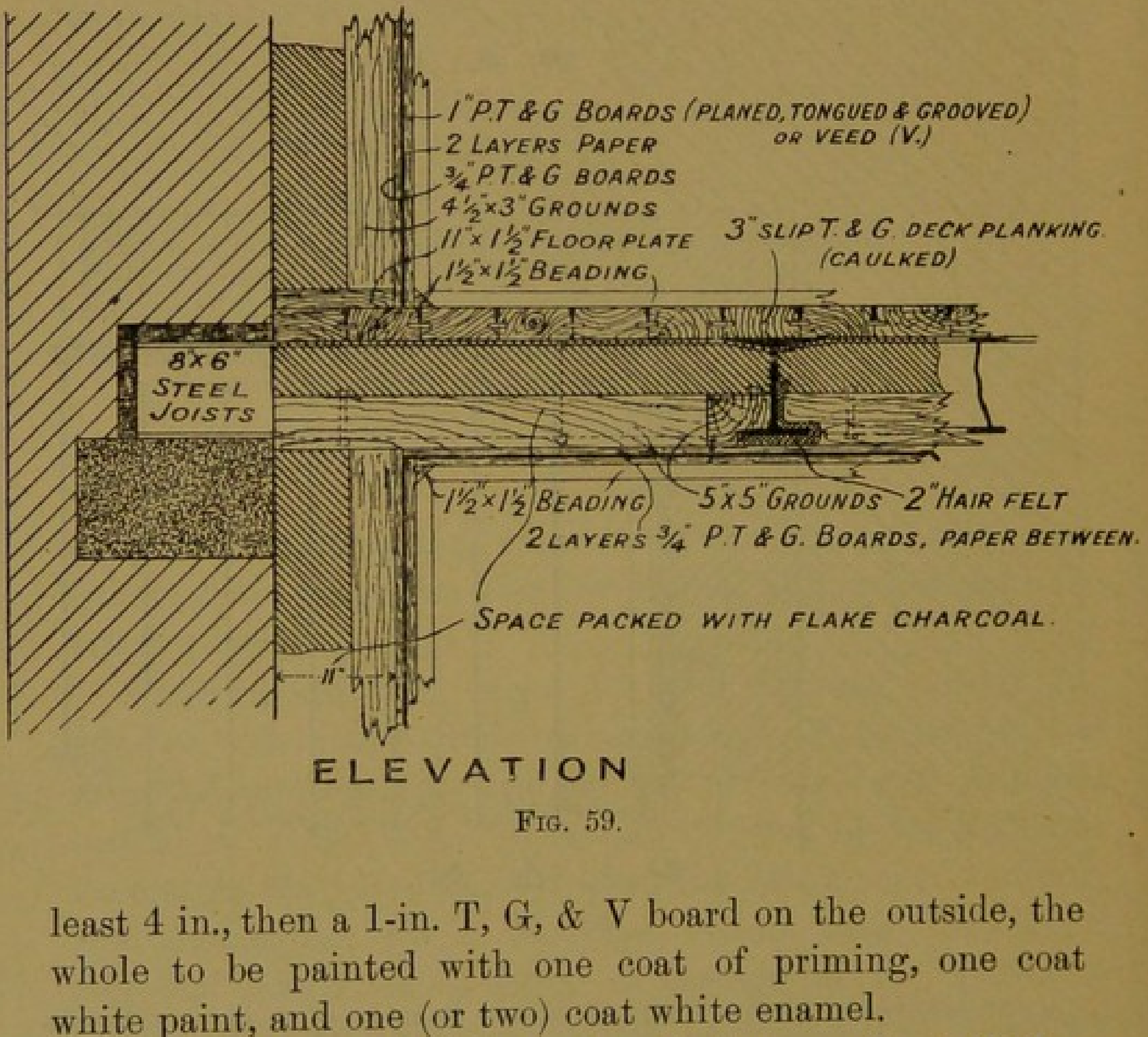
FIG. 58.

A type of insulation recommended by the author in preference to the above is shown in plan in Fig. 58.

The wall, below the ground-level, should be protected from damp by horizontal and vertical damp-proof courses.

Above the ground care should be taken by using good bricks and mortar in ordinary cases, or a vertical cavity filled with damp-proof material in special cases, to ensure the walls being kept dry. The interior face should be covered with two washes of a damp-resisting composition.

The main insulator, say 11 in. of flake charcoal, can be placed right up against the walls and kept in position by a $\frac{3}{4}$-in. T & G board, two layers of insulating paper, lapped at least 4 in., then a 1-in. T, G, & V board on the outside, the whole to be painted with one coat of priming, one coat white paint, and one (or two) coat white enamel.



ELEVATION

Fig. 59.

All right-angled joints—top, bottom, and vertical—should be fitted with a special 1½ in. × 1½ in. vee piece.

Fig. 59 shows the elevation and indicates further details. A 11 in. × 1½ in. floor plate, or sill, is first well bedded down on the floor, and on this and between the ceiling are fixed 4½ in. × 3 in. grounds on which the two layers of boards are nailed, thus the grounds do not go back right to the wall; the charcoal being packed at the back, as shown on the plan.

Floors.—In modern construction steel joists (or re-enforced concrete beams) play an important part in floors, and when used, the ends should rest on ¼ in. compressed tarred felt, and insulated on the sides and top (inside the line of wall) with bitumen, as shown in Figs. 59 and 60. In the chamber itself, the beams should be wrapped for their *whole length* with two layers of 1 in. felt, cased in with two boards with paper between.

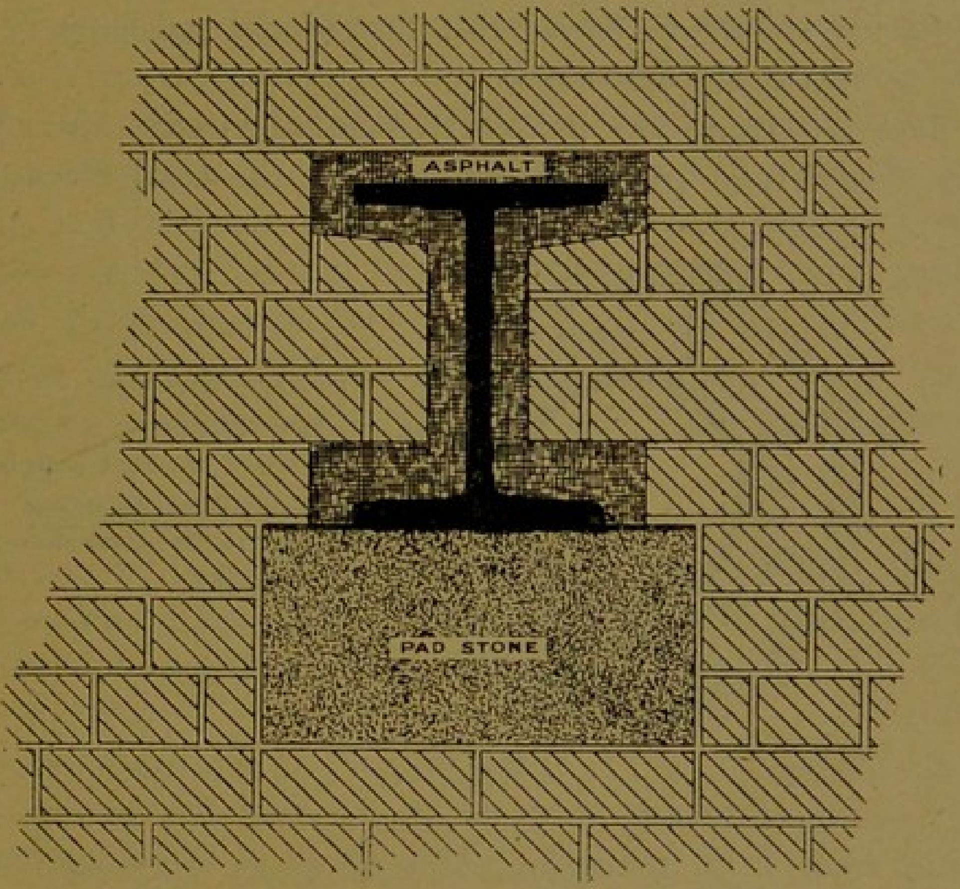


Fig. 60.

The floor itself should be well-seasoned 3 in. pitch-pine deck planking, with slip tongues and grooves, the seams being caulked with oakum and then served with marine pitch. The deck planking rests directly on the steel joists, and instead of casing each separate joist the boards may run directly underneath, being nailed to special wrought pieces (out of 6 in. × 5 in.) fixed to the joists.

This is shown on Fig. 59, and is quite sufficient insulation between one room and the next below, when temperatures below freezing point are carried in each chamber. If, however, it is intended to carry varying temperatures, some above and some below freezing, it is better to fill in the (about) 8 in. space with flake charcoal.

For partitions, such as is shown in Fig. 55, between the cold chamber and the lift way, not less than 11 in. of insulation should be fixed, with boards and paper on *either* side as previously described.

Doors.—Doors are generally insulated with hair felt, with boards and paper on either side, the total thickness being from 7 in. to 9 in. The whole is fitted into very strong pitch-pine framing; the outer edge may be supported on a roller running on a circular-shaped rail. The bottom portion of the outer framework (sill) is made removable, in order that trucks may pass freely in and out.

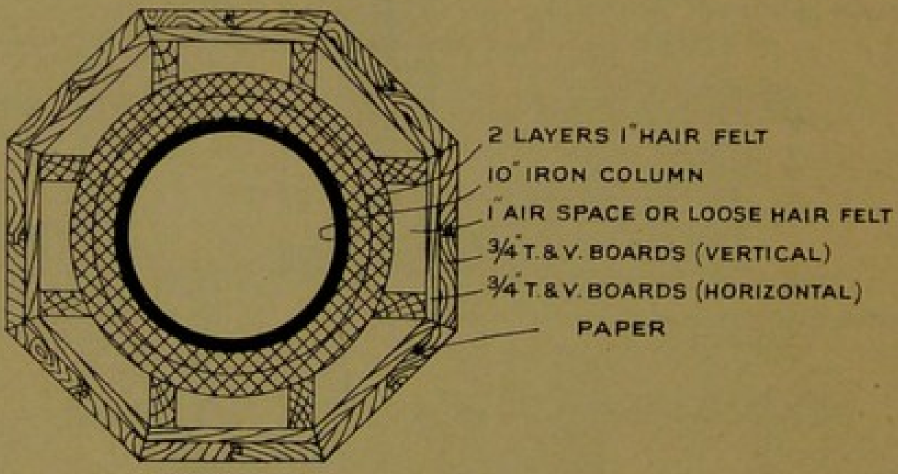


Fig. 61.

A store constructed on the best principle would not, as previously pointed out, have these huge openings (the least being 6 ft. high by 5 ft. wide) in the side, all goods being lowered from the top.

Columns.—Columns should rest on bed stones, which in turn should be insulated by means of bitumen and concrete underneath, and bitumen and ashes at the sides.

In the chambers, the columns should be insulated by two layers of 1 in. felt, then two layers of boards with two layers of paper between.

The boards may be special circular lagging boards, secured by brass or galvanized iron bands at the top and bottom, or the construction may be as shown in Fig. 61.

Basement Floors.—The insulation of the ordinary intermediate floors has already been mentioned; the basement floors call for special treatment.

Supposing ordinary ground (*i.e.* fairly solid and not wet), 6 in. of rubble should be first laid and rammed down, then 6 in. of concrete finished with a cement face, then 1 in. of approved damp course composition, then 4 in. concrete, then 9 in. × 3 in. joists laid on 11 in. × 3 in. creosoted sleeper joists (*i.e.* laid on the flat), the 12 in. space being packed with flake charcoal, then 1 in. P, T, and G boards, two layers of extra thick insulating paper, and finally 1½ in. flooring boards—pitch pine, maple, or other approved wood.

Each basement floor calls for special consideration and treatment; in some cases a much lighter floor than the one above would be possible, while in others extra precaution would be necessary, otherwise ice may form and "lift" the floor.

Windows.—When dealing with Figs. 55 and 56 it was mentioned that only small windows should be allowed in a cold store, and those only in the lift-way.

Fig. 61A shows the treatment of the front of Messrs. Ashton Bros.' Cold Stores, Wigan, in order to meet the requirements "no windows."

Power required for Cold Stores.—The following table may be taken as giving average figures for the power required for driving the compressors of compression machines for refrigerating the given capacities—*space only*. The class and quantities of goods to be stored must be considered separately. The approximate refrigerating capacity in terms of ice melted, of ice made, and thermal units removed per 24 hours are also given.

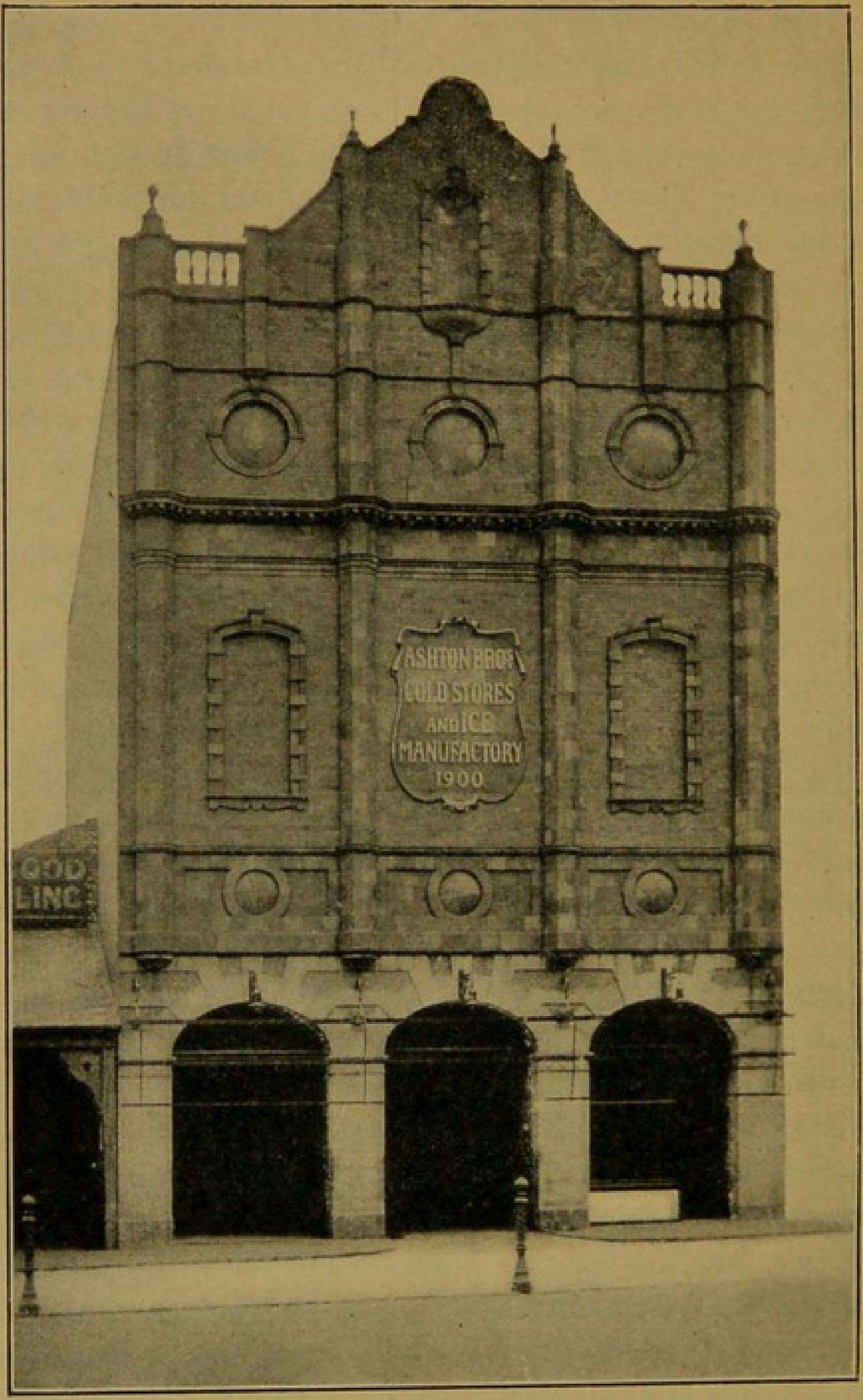


Fig. 61a.

POWER FOR COLD STORES.

Capacity (Space only) in Cubic Feet.	Per Day of 24 Hours.			Horse-power required.
	Ice melted. Tons (Refrigerating Capacity).	Ice made. Tons.	B. Th. U. removed.	
50,000	12	5	3,600,000	17
100,000	20	9	6,000,000	25
300,000	46	23	13,800,000	55
500,000	67	37	20,100,000	80
800,000	88	50	26,400,000	110
1,000,000	100	57	30,000,000	125

Cold Chambers on Shipboard.—The insulation of cold stores on shipboard vary to such an extent that it is impossible to give what may be termed typical examples.

From the ship's side the frames project, and the first lining of boards is generally carried clear outside of these (the insulating material then following), the space being left as an air space, or the space may be filled with charcoal as the prime insulator, or partially filled with sawdust, a superior insulator being placed inside.

In the R.M.S. *Lucania*, the side frames are very deep bulb irons; part of the depth is taken up by sawdust, then boards, paper, boards, hair felt, boards, paper, boards—the whole coming out very nearly level with the separate insulation carried round each bulb—the little space left being taken up by the brine pipes used for cooling purposes.

Fig. 62 shows the roof or ceiling of the chamber, the whole being insulated in a somewhat similar manner to the sides, with the exception that the air space takes the place of the sawdust.

The American steamer *St. Louis* has channels for the side frames, the first sheathing of boards passing clear outside the space being left as an air space; then a layer of ruberoid, then granulated cork, boards, paper, and boards.

Ships' chambers are generally cooled by means of brine circulated in brine pipes placed on the sides and overhead (see Figs. 62 and 83). Stacks of brine pipes, with fans to circulate the air, are also used to a limited extent.

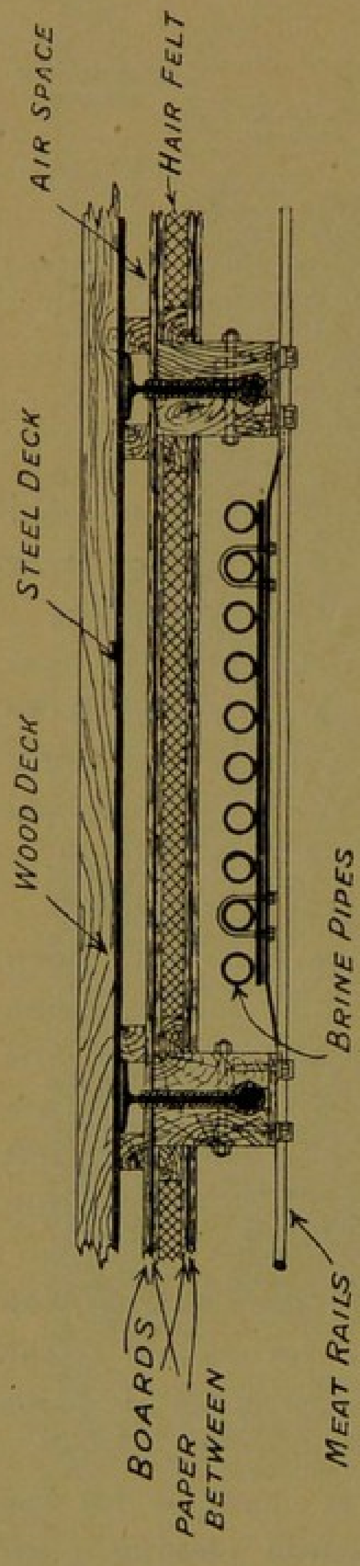


Fig. 62.

General Remarks on Insulation.—Within reason, too much care cannot be bestowed on insulation of both land and ships' cold chambers; it should be air tight, and as near "heat tight" as possible.

The cold pipes of a machine that are exposed to the atmosphere (not intended for cooling purposes) should also be well insulated. One so often sees pipes thickly coated with "frost" (snow) that must melt as soon as the machine stops, to reform when it is again re-started—a serious loss taking place at all times.

Ice-making tanks and evaporators should also be well insulated, and for this purpose flake charcoal or granulated cork can be recommended, a waterproof insulation being imperative in either case.

In applying insulation to any purpose, the knowledge contained in the opening chapters is essential, particularly Chapter III. This knowledge would prevent such mistakes as insulating the under side of a ship's deck *outside* the chamber (floor) instead of *inside,* and thereby cutting off the great quantities of heat conveyed into the room by means of the beams and stanchions.

CHAPTER XI

MISCELLANEOUS USES OF REFRIGERATION

In the following enumeration of the various uses of refrigeration, an outline is given in a few cases of the reasons for and the methods adopted, to obtain the desired result.

(1) **Cold Storage.**—Cold stores are designed with the object of keeping food and goods in the best possible condition for subsequent consumption, manufacture, or use.

The following table may be taken as indicating the temperatures for storing the various articles named.

Where a range is given, such, for instance—"cigars, tobacco, cider, grapes, potatoes, lemons, onions"—which are given under 34°–40°, it does *not* mean that the temperature may vary at any time between 34° and 40°, but that any temperature between those limits may be selected; once selected, however, *every endeavour must be made to keep that temperature as uniform as possible,* even to one degree variation.

If goods have been stored for some time at, say 22°, and the temperature rises to 30° on account of fresh goods being placed in the chamber, doors opening, etc., it will be found that "damp" will be deposited on the older goods—they act as condensers to the vapour in the higher-temperature air. This "damp" (sweat, as it is sometimes called) may re-evaporate without much harm being done, but mildew and mould often follow, with consequent deterioration.

(2) **Ice Making** for general purposes, also for skating rinks and curling ponds.

STORAGE TEMPERATURES

DEGREES FAHRENHEIT.

10°	15°	20°	24°	26°	28°	30°	32°	34°	36°	38°	40°	45°	50°
Frozen Mutton.		Game (to freeze).	Poultry, Game.		Chilled meat.		Celery, Oysters.	Vegetables, Fresh fruit, Berries, Canned goods, Furs (undressed), Syrup.			Dates, Figs, Dried fruits, Sugar, Wines, Flour.		Clarets.
	Ham and Butter (frozen).												
Fish to freeze 0° to 5°	Furs (long storage).	Frozen meat (general), Rabbits.		Fresh fish, Furs (dressed).			Apples, Eggs, Cheese, Milk.		Bananas, Tomatoes, Peaches.			Oranges.	
				Woollen goods, Carpets.				Cigars, Tobacco, Cider, Grapes, Potatoes, Lemons, Onions.				Ale, Beer, Porter, Wines, etc. (in bottle).	
Frozen eggs.		Margarine.		Hops.		Butter (short period), Lard, Pork, Ham.			Porter, Beer, Ale, etc. (in casks), Nuts.				

The methods of making ice for ordinary commercial purposes have already been described. For skating rinks and curling ponds a water-tight floor is constructed and grids of brine pipes laid thereon; the whole is then flooded and cold brine sent through the pipes, an even surface or floor of ice being the result. Linde has tried, with success, a false floor of steel, on which the water was flooded and cold brine circulated below.

To keep the surface in anything like good condition, it must be swept, re-flooded, and re-frozen daily.

(3) **General Cooling.**—Abattoirs for chilling freshly killed meat; butteries, dairies, and cheese factories: cooling the milk for transport or for future use, cooling cream to increase the yield of butter, cooling water for butter working, storing butter, cheese, cream, and milk; bacon curing; breweries: cooling wort, regulating the fermentation in the tuns, storing malt, hops, yeast, ale, porter, beer, etc.; chemical works: refining; confectionery: rapid setting of creams, chocolates, and general confections; dye works: obtaining certain concentrated colours by low temperatures; india-rubber works: quick setting of india-rubber; hotels: storing provisions, ice making, cooling wines, etc.; laundries: bleaching the linen by freezing; oil works: separating paraffin-wax and stearine from the oils; residences, public buildings: ventilation and cooling (heating in winter); laboratories: keeping constant temperatures; furriers: storing furs both before and after dressing; removal contractors and warehousemen: storing of carpets, blankets, furs, rugs, etc.; railway vans: cooling for food transport; trawlers and collecting boats: cooling the holds for the purpose of keeping the fish fresh, which enables the boats to stay for a longer period on the fishing station.

(4) **Naval and Mercantile Marine.**—(*a*) Keeping ammunition (such as cordite) in a fit and proper condition.

Cordite, to be kept in good condition for any length of time, should not be stored in a temperature exceeding 70° F. This is hardly possible in a warship without refrigeration.

Great care must be exercised in the construction and arrangements for cooling magazines, as deposition of moisture (sweating) would be fatal.

(*b*) Storing a supply of fresh provisions for the crew, or passengers and crew.

A constant supply of fresh, seasonable food is now one of the features of ocean travel.

(*c*) Transport of perishable produce.

The last twenty years has seen a very great advance in the amount of over-sea perishable produce imported into Great Britain. Rabbits from Australia, mutton and lamb from New Zealand, and chilled beef from the United States of America, together form the bulk of the trade, but poultry, butter, cheese, and fruit are being carried by all the larger steamers; Canada, in particular, exporting increasing quantities.

(5) **Central Stations.**—Supplying liquid refrigerant from a central station for use in private refrigerators and drawing back the vapour for re-condensing.

Supplying cold brine and circulating it direct in the pipes fitted in private stores and re-cooling same.

(6) **Horticulture.** — Checking the growth of plants, shrubs, etc.; keeping unripe fruit to ripen according to the market; regulating the hatching of silkworm eggs.

(7) **Infirmaries and Hospitals.**—For general cooling and ice making. Cooling mortuaries.

Use of low-pressure refrigerants, such as *ethyl chloride* (C_2H_5Cl) for numbing (by freezing) local parts in minor surgical operations.

(8) **Production of Low Temperatures.**—For physical and chemical investigation. Production of liquid air, liquid oxygen, liquid hydrogen, liquid nitrogen, etc.

(9) **General Engineering.**—(*a*) For excavations in loose soil, mining operations, tunnelling in mud or sand by first hardening (freezing) the ground by artificial refrigeration; sheet piles—hollow pipes driven close together and brine circulated through them, the opening between the pipes or piles being closed by ice and a water-tight wall formed.

(*b*) Drying the air supply to blast furnaces, increasing the production per furnace and per ton of fuel; regulating the kind of pig iron produced.

Shaft sinking and drying the air for blast furnaces call for further description and comment.

Shaft Sinking.—The system of shaft sinking by freezing was first suggested by Poetsch, in 1883, for sinking through boggy land and water-bearing rock.

It has since been used with success both in this country and on the continent, and would seem to be a method that could be employed when the ordinary systems would fail.

The general principle is to form a cylinder of ice, through which the shaft is sunk—the ice keeping back the water. This is effected by sinking vertical tubes (forming a circle) to the required depth, and circulating cold brine down them by means of an inner pipe.

The best results are obtained when the ice cylinder is hollow, as the actual sinking can then be carried out with a minimum of trouble and expense; great care being taken that the ice cylinder is taken well down into the solid strata, so as to prevent the water coming up through the centre.

If a solid cylinder should be formed, it can be quite well understood that the shaft would take extra time and trouble to sink.

The process, for convenience of description, may be divided into six sections—

(1) formation of a fore shaft.

This is, virtually, a convenient working circular chamber, formed round the centre of the proposed shaft, from which the bore holes may be sunk, and in which the brine-pipe connections may be made, and the temperatures of the outgoing and returning brine noted and regulated.

The fore shaft should be lined and about 34 to 36 ft. in diameter, 8 to 10 ft. deep.

(2) sinking the bore holes to receive the brine pipes.

The sinking of bore holes, although an ordinary operation in most cases, requires the very greatest care for this work, as the holes must be perpendicular, guide-tubes being erected in the foreshaft to help this purpose.

The size of the holes varies with the depth required, and may be 8 in. to 10 in. at the top to 6½ in. to 7½ in. at the bottom. The holes should be lined with lining tubes, in order that each bore may be kept clean.

The number of holes depend on the size of shaft and nature of the soil to be frozen.

The diameter of the circle round which the holes are placed is about 28 to 30 ft., and there is, approximately, one hole to each foot of diameter, *i.e.* the holes would be about 3 ft. apart.

(3) fixing the brine pipes.

The external brine pipes may be 2½ in. to 5 in. diameter, and are closed at the bottom; the internal pipes are 1 in. to 1½ in. diameter and open at the bottom.

The outer pipes are connected by internal couplings and the inner pipes by external couplings.

At the Dowden Colliery[1] the lining tubes were 6½ in. diameter, these being withdrawn after inserting special 5 in. tubes to within 32 ft. of the bottom (484 ft.); the outer brine pipe was 2½ in. and the internal 1¼ in.

The air space thus formed was left to prevent direct connection with the strata and to protect the tubing from severe frost.

(4) forming and maintaining the ice wall.

Brine (magnesium chloride solution 26 to 28 per cent., see p. 128) is sent down at the outset at about 8° to 10° F.; returning about 18° to 25° F.

When the ice wall is nearing completion, which takes 4 to 10 months, the outgoing brine will be about 0° and the return 3° to 8° F.

Many conjectures have been made as to the shape of the ice wall. The coldest brine is sent to the bottom, so that probably the frozen soil for the most part takes the form of a truncated cone, the greatest diameter being at the bottom. This cone would, however, be chamfered off at the bottom, owing to the influence of the brine pipes falling off,

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[1] E. Seymour Wood, M.Inst.C.E. *Transactions of the Institution of Mining Engineers.*

this chamfer forming a second truncated cone, inverted and very short.

On an average, the ice may be taken as forming to a radius of 2 ft. beyond the freezing pipes (with a cold zone 5 or 6 ft. beyond this) and 3 or 4 ft. inside the pipes.

The time the ice wall has to be maintained depends on the depth of the shaft and the nature of the strata through which it passes, say 6 to 15 months.

(5) sinking the shaft and inserting the tubing,
(6) extracting the tubes.

After the shaft has been finished, the refrigerating machine is stopped and the brine heated.

This has the effect of thawing off all pipes within the ice wall and the tubes can be withdrawn. If the brine is to be saved it has to be "bailed" out, otherwise it is best to displace it by pumping water down until the whole system is clear of brine.

The holes left by the pipes should be filled with concrete.

The chief difficulties experienced with this process are (*a*) the pipes not being perpendicular, resulting in the distance between two consecutive pipes at the bottom being too great to freeze across, or the pipe projecting into the shaft itself; (*b*) leaky brine pipes—brine leaking into the strata in any quantities will prevent the ice wall forming; (*c*) water breaking through the ice wall, owing to malformation, or getting under the ice wall and forcing itself up through the centre.

Regulating the Moisture in the Air Supply to Blast Furnaces.—Mr. James Gayley, in a paper read before the New York meeting of the Iron and Steel Institute, October 26, 1904, and reported in the *Iron Trade Review*, October 27, termed, "The Application of Dry-air Blast to the Manufacture of Iron," showed that a very great saving could be effected by drying the air by refrigeration before sending it to the blowing engines. His contentions were, that not only was the air very humid, but that the constant variation from hour to hour, day to day, and month to month prevented anything like an effective and efficient regulation of the "burden" to the blast furnace and the production of a constant grade of iron.

The following tables are taken from the paper, the first being the quantity of moisture in the air given by the U.S. Weather Bureau, Pittsburg.

It will be noted that the grains of water per cubic foot multiplied by 40 will give the gallons of water entering an ordinary blast furnace per hour.

MONTH.	AVERAGE TEMPERATURE.	GRAINS OF WATER PER CUBIC FOOT OF AIR.	GALLONS OF WATER ENTERING PER HOUR INTO A FURNACE USING 40,000 CUBIC FEET OF AIR PER MINUTE.
January . .	37·0	2·18	87·2
February . .	31·7	1·83	73·2
March . . .	47·0	3·4	136·0
April . . .	51·0	3·0	120·0
May . . .	61·6	4·8	192·0
June . . .	71·6	5·94	237·6
July . . .	76·2	5·6	224·0
August . .	73·6	5·16	206·4
September . .	70·4	5·68	227·2
October . .	56·4	4·0	160·0
November . .	40·4	2·35	94·0
December . .	36·6	2·25	90·0

The next table shows how the amount of water varies from day to day, and at various times in the day.

DAY OF THE MONTH.	GRAINS OF WATER PER CUBIC FOOT OF AIR.			
	JANUARY.		JULY.	
	8 A.M.	8 P.M.	8 A.M.	8 P.M.
1	1·96	3·06	7·24	7·48
2	2·55	3·66	8·23	7·98
3	2·46	3·80	8·50	7·48
4	2·07	2·27	8·50	7·48
5	1·81	1·12	8·46	7·72
6	0·99	1·12	6·50	8·24
7	1·16	1·67	8·78	7·47
8	1·49	1·88	7·98	7·24
9	1·96	2·19	6·78	5·94
10	1·81	1·88	7·48	6·35
11	1·74	1·55	7·98	7·48
12	1·55	1·07	6·73	6·35
13	0·99	1·55	5·94	4·84
14	1·61	1·81	5·55	5·74

Details are given of a test carried out on a blast furnace at the Carnegie Steel Co. at Etna, Pa., first, with ordinary blast, and then with the air dried by means of a refrigerating plant with a brine air cooler. The following table gives a summary of the average results :—

Type of Blast.	Grains of Moisture per Cubic Foot of Air.	Output per Day. Tons.	Coke Consumption per Ton of Pig Iron. Lb.	H.P. for Blowing Engines.	H.P. for Refrigerating Machine.	H.P. Total.
Normal .	5·66	358	2147	2700	—	2700
Dried .	1·75	447	1726	2013	535	2548

Thus, there was a reduction in the coke consumption of 20 per cent., an increased output of about 25 per cent., and a net saving of 152 horse-power.

The necessary refrigerating machinery was installed by the York Manufacturing Co., York, Pa., and was of the ammonia compression type. The compressors, two in number, were each 22½ in. diameter and 36 in. stroke, their refrigerating capacity being 225 tons each, *i.e.* both together would be equal to making about 250 tons of ice per 24 hours. One compressor was held in reserve.

The average amount of water caught per 24 hours in the tank under the cooler, taken over four days, was 2588 gallons. This represents about 69 lb. of water per ton of iron produced.

At the meeting of the Iron and Steel Institute in May, 1905, Mr. Gayley gave working records of the furnaces working with normal and also with the dry air blast, taken over extended periods, the results substantiating to a remarkable degree those obtained by the earlier tests.

The arrangement adopted by Mr. Gayley—excellent in every way, particularly for a first installation—seems to offer plenty of scope for further economy and improvement from a *refrigerating point of view.* From a general point of view, these economies must sink into insignificance compared to those already effected by Mr. Gayley.

The following record of two days' work shows the effect of cooling on the amount of moisture in the air.

Time.	Temperature of the Air.		Grains of Water per Cubic Foot of Air.		Temperature of the Air.		Grains of Water per Cubic Foot of Air.	
	Inlet.	Outlet.	Inlet.	Outlet.	Inlet.	Outlet.	Inlet.	Outlet.
6 A.M.	70	22	6·35	1·70	77	22	3·94	1·48
7 "	71	22	6·78	1·77	—	—	4·08	1·29
8 "	69	22	6·67	1·62	—	—	4·22	1·42
9 "	73	22	6·78	1·70	71	25	4·85	1·36
10 "	74	22	6·78	1·70	—	—	5·02	1·48
11 "	77	23	6·67	1·70	—	—	5·19	1·55
12 M.	81	23	6·56	1·62	81	28	5·37	1·70
1 P.M.	78	24	6·56	1·70	—	—	4·85	1·62
2 "	82	25	6·56	1·90	—	—	4·85	1·62
3 "	81	24	6·19	1·74	84	29	5·02	1·70
4 "	81	24	6·19	1·42	—	—	4·68	1·48
5 "	80	24	6·14	1·48	—	—	4·85	1·60
6 "	75	24	5·56	1·55	78	29	5·37	1·77
7 "	72	24	5·94	1·70	—	—	5·37	1·62
8 "	70	23	5·19	1·62	—	—	5·56	1·70
9 "	69	22	5·19	1·42	72	29	5·74	1·70
10 "	68	21	5·19	1·55	—	—	5·74	1·77
11 "	66	20	3·94	1·77	—	—	5·74	1·62
12 night	62	20	3·54	1·62	66	28	5·56	1·70
1 A.M.	59	18	3·41	1·42	—	—	4·85	1·70
2 "	57	17	3·54	1·13	—	—	5·37	1·70
3 "	56	16	3·18	1·13	64	27	5·19	1·48
4 "	56	16	3·18	0·99	—	—	5·19	1·36
5 "	53	14	2·85	1·06	—	—	4·85	1·48

The daily record above indicates that the amount of moisture in the dried air was by no means constant, and various suggestions have already been made for keeping the amount of moisture entering with the air at a *predetermined figure*, enabling a certain grade of iron to be produced with regularity. It is evident that altering the burden according to the moisture in the air is useless, seeing that the one is introduced at the top of the furnace and the other at the bottom.

Economies may also be effected—particularly in summer—by having two air coolers, in the first of which the refrigerant could be carried at a higher pressure and temperature than in the second, and the greater quantity of moisture eliminated under conditions that would enable the machine to work with great efficiency.

It is further possible that the cooled air (without the two mixing) could be made to partially cool and dry the incoming air (regenerative principle), but experiments would be necessary to determine whether the gain on the refrigerating side would be greater than the loss to the blowing engines.

CHAPTER XII

MISCELLANEOUS ARRANGEMENTS—MOTIVE POWER FOR REFRIGERATING MACHINES — CARE OF MACHINES

In this chapter a few actual arrangements of refrigerating plants for various purposes are discussed, together with one or two machines and appliances of special manufacture, the whole to be regarded as **typical** examples only. A few words are added respecting the care of, and motive power for, machines.

BREWING.—The necessary materials for brewing beer are *water*, *malt*, and *hops*.

Water.—The first named, water, is more important than would appear at the outset, because it should be particularly free from organic matter, yet at the same time certain mineral salts are essential for the production of good beers. This is one of the reasons why certain districts are noted for their breweries.

Malt.—Malt is produced from grain, generally barley, by first steeping in water and then spreading on floors, where the grain partially germinates. This partly germinated grain forms the *malt*, which is dried and stored for further use.

Diastase.—During the conversion of the grain into malt, a substance, "diastase," is formed, which converts the insoluble starch of the grain into fermentable sugar.

The malt, when required, is taken from the store, crushed between rollers, and placed, together with hot water, into the *mash-tuns,* and both kept agitated by mechanical means.

Wort.—The resulting liquor, wort, is then boiled in "coppers," hops being added to give preserving qualities and taste. The whole is then run into shallow tanks (where a very great portion of the heat is given off), and afterwards it passes over special "coolers."

These coolers are either vertical stacks of flattened pipes or corrugated plates, so placed together that the cooling medium may circulate between.

"Fore-coolers" are often used, the cooling being performed by the well water, which can afterwards be used for other purposes. Further cooling is done by the aid of refrigerating machines, either by circulating a refrigerant direct through the cooler, or by brine, but more generally by "cooled water," known as "iced liquor," the last term being a survival of the time when ice was actually used instead of direct refrigeration.

Fermentation.—The cooled wort is then run into the fermenting vats, when the soluble and fermentable sugar (formed from the starch by the diastase) is acted on by yeast and converted into alcohol and CO_2.

This process requires the greatest possible care and attention from the brewer, the temperature and consequently the fermentation having to be very carefully regulated. The tendency is for the beer to become too warm, and so "cooling" has to be effected.

After fermentation has proceeded sufficiently far, the liquor is "cleansed" (the yeast being removed) and run into casks or otherwise stored.

Cold Filtration.—When beer is to be bottled, it has been found that if the beer is cooled slightly below 32° F. and then filtered, secondary fermentation in the bottle does not take place, and hence deposit is prevented.

Brewery Refrigeration.—Fig. 63 shows an arrangement of a brewery by Messrs. Haslam.

The refrigerating machine is placed in the main engine room, the condenser being of the atmospheric evaporative type, placed on the roof of the copper house.

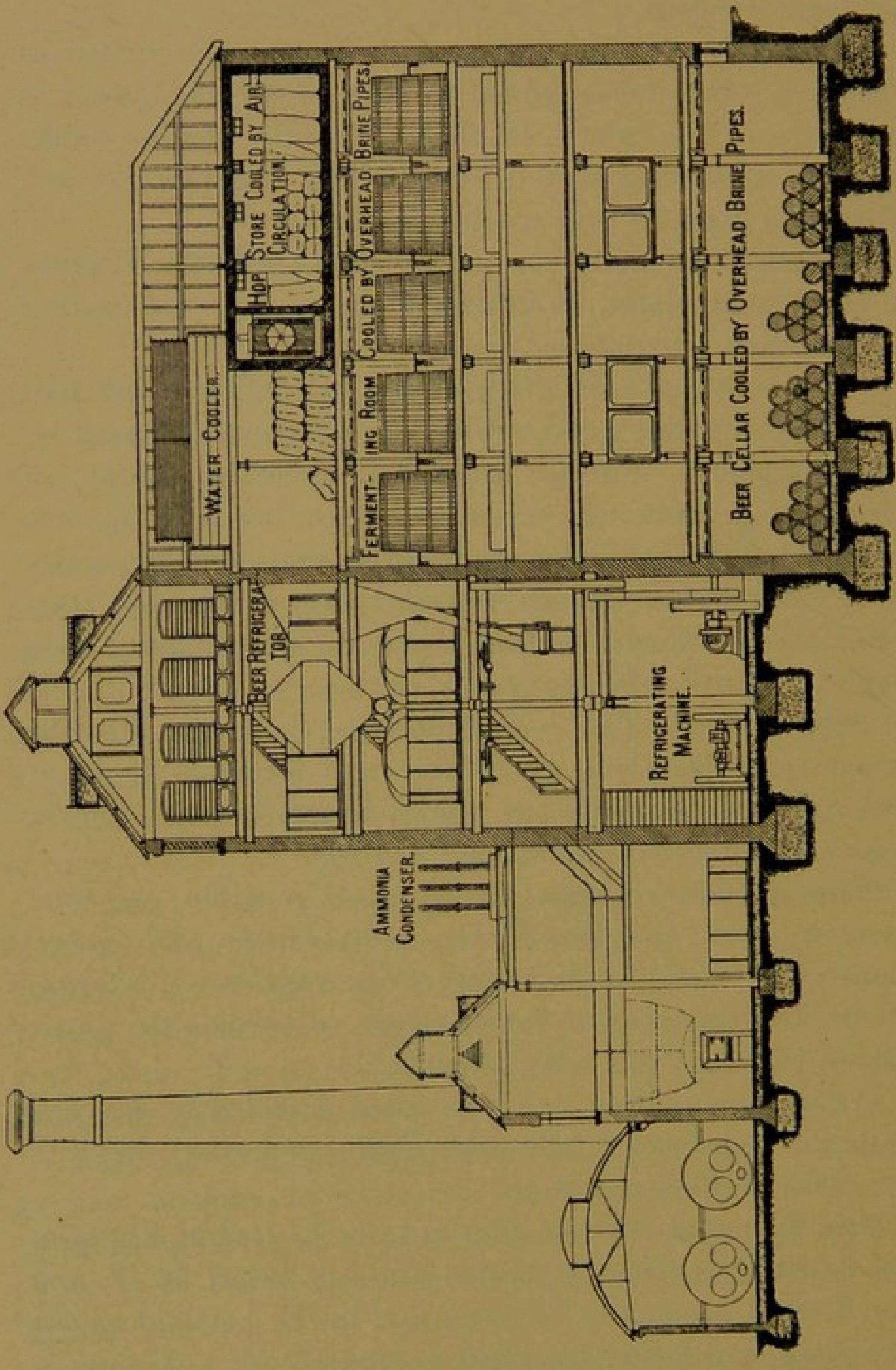


Fig. 63.

The water cooler consists of vertical grids of direct expansion, or brine pipes placed over a water-storage tank in the roof. The water supply trickles over these pipes, and is cooled before reaching the storage tank.

The cooled water, or "iced liquor," runs *through* the beer refrigerators or coolers, which are shown just below the wort cooling floor (top left-hand corner), the beer passing *over* the outside.

The cooled water is further used in the "attemperators" (coils of pipe) placed in the fermenting vats and used for regulating the fermentation.

The rooms in which these vats are placed are, in many cases, also cooled by brine pipes.

On the top right-hand corner will be noticed the hop store, which is insulated and kept cool by means of a fan, which circulates the air through a Haslam air cooler. This method is preferred to brine pipes, it being important that the hops should be free from the slightest suspicion of damp.

The beer cellars are also cooled by overhead brine pipes.

The general arrangement of the brewery itself should command attention. The grain (malt) and hops are hoisted to the top floor. The malt is then conducted by a shoot to the malt mill, where it is ground, and the "grist" so formed elevated to a large hopper or grist case; this is directly above, and connected to, the mashing machine — a cylinder having revolving rakes, where the grist and hot water are thoroughly intermingled.

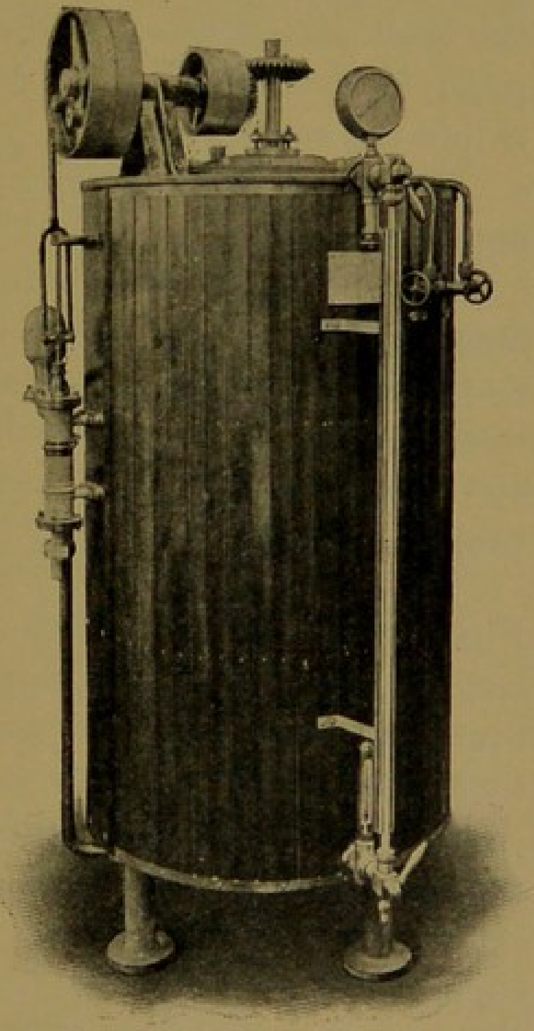


FIG. 64.

The "mash" is discharged into the mash tuns, and the liquid strained off and led to the coppers, the "wort" being pumped to the "cooler" on the top floor, and gradually passes, by the process previously described, to the cellar.

Fig. 64 shows a combined beer chiller and carbonator by the same firm. It consists of a copper cylinder to contain the beer, surrounded by a brine jacket, in which are placed the cooling coils for NH_3 or CO_2.

The centre drum is provided with a rotary agitator for aërating the beer, the gear for which is seen at the top of the figure. There are two further CO_2 connections, one for aëration purposes and the other to put on "top pressure" for forcing the beer through the filter. A safety valve, pressure gauge, thermometer, and gauge glass for showing the level of the beer, are also provided. On the side is a pump for drawing the beer from the casks and discharging it into the cooler.

The whole forms a very complete, compact, and efficient apparatus.

Fig. 65 shows H. Pontifex & Sons' general arrangement of their "Rapid" beer-chilling plant. A is a vertical ammonia compressor, which may be driven in any approved manner; B an ammonia condenser of the evaporative type; and C a horizontal beer chiller, which is, in reality, the evaporator.

The construction of the chiller is best understood from Fig. 66. It consists of a wrought-iron tank with gun-metal end plates, into which copper tubes are securely fixed, every two adjoining tubes being connected outside the tank by hollow gun-metal caps in such a manner as to form a continuous coil, the beer thus passing through all the tubes before leaving the chiller.

The ammonia pipes are placed immediately over the copper tubes, and both sets of pipes are covered by brine, the heat from the beer thus passing first to the brine and then to the ammonia in the ordinary way.

The chilled beer is then taken to the carbonator D, then to filter E, and from there to the bottling machine.

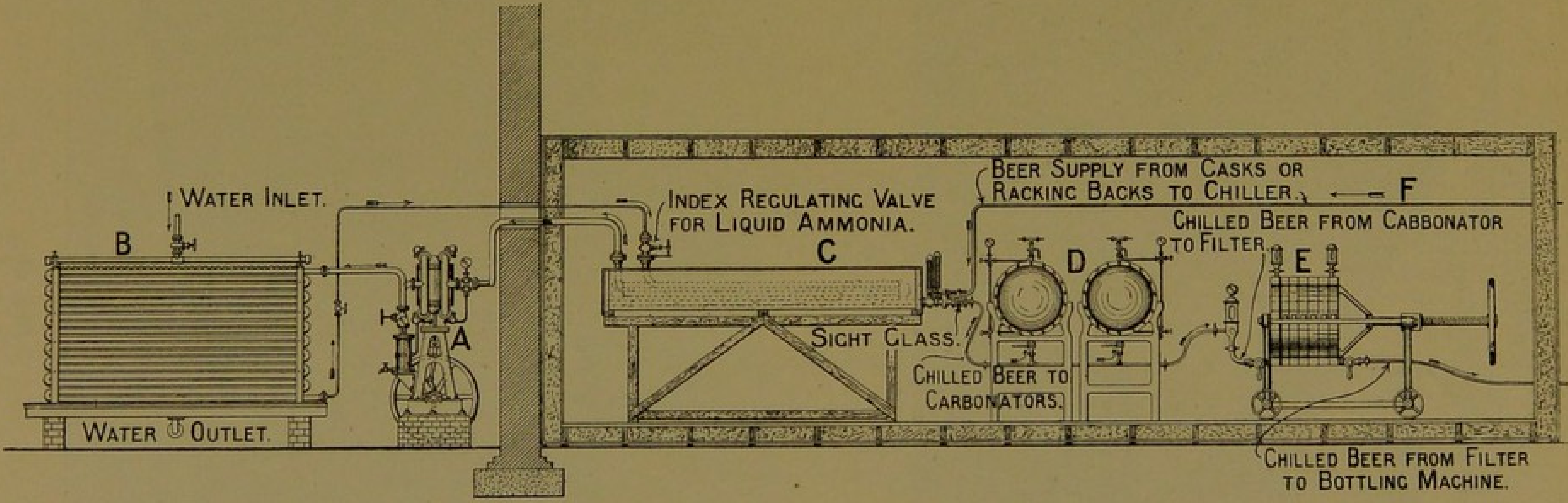

Water Inlet.
B
Water
Outlet.
A
Index Regulating Valve for Liquid Ammonia.
C
Sight Glass.
Beer Supply from Casks or Racking Backs to Chiller.
F
Chilled Beer from Cabbonator to Filter.
D
E
Chilled Beer to Carbonators.
Chilled Beer from Filter to Bottling Machine.

Fig. 65.

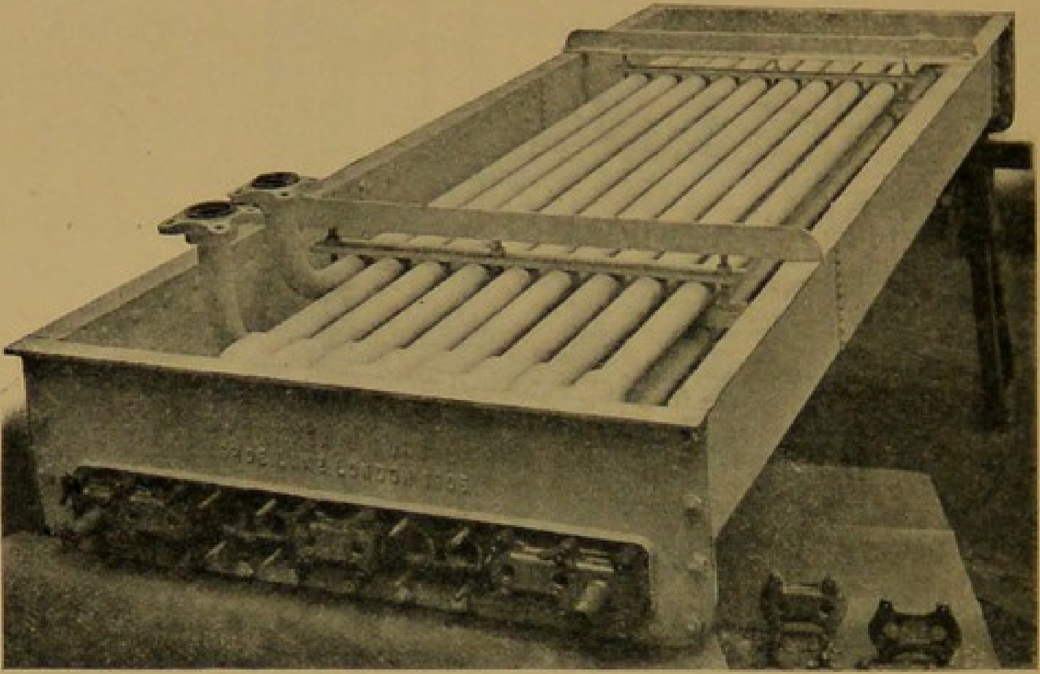


FIG. 66.

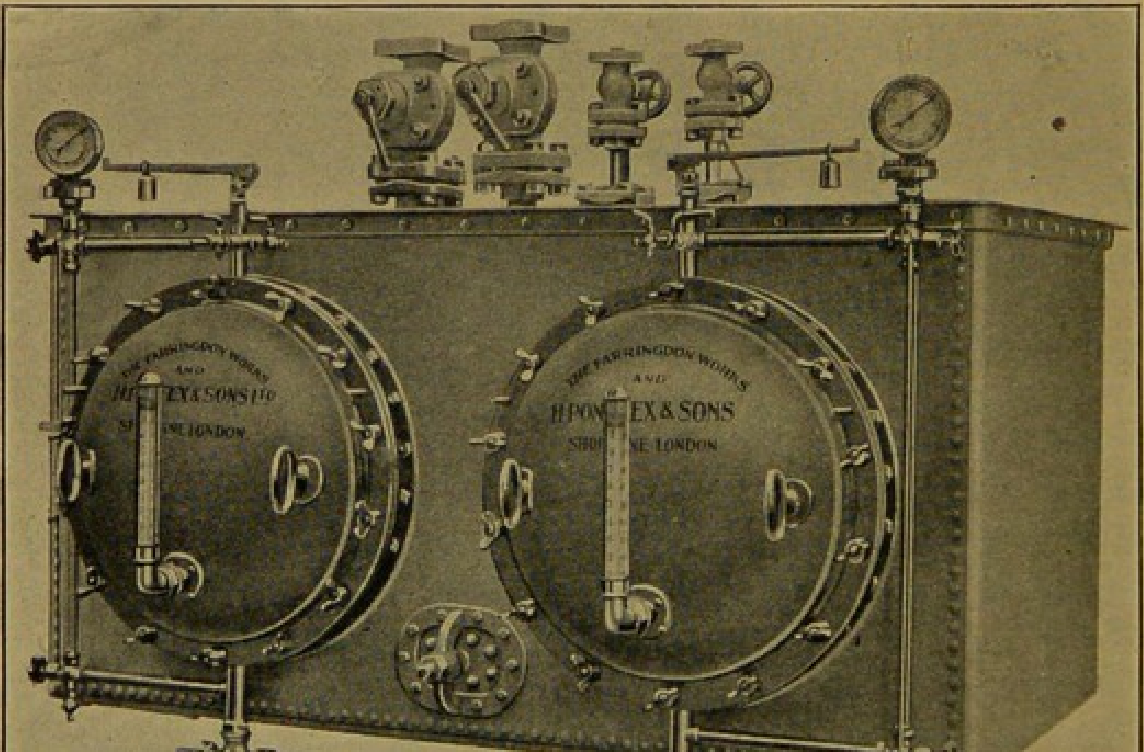


FIG. 66A.

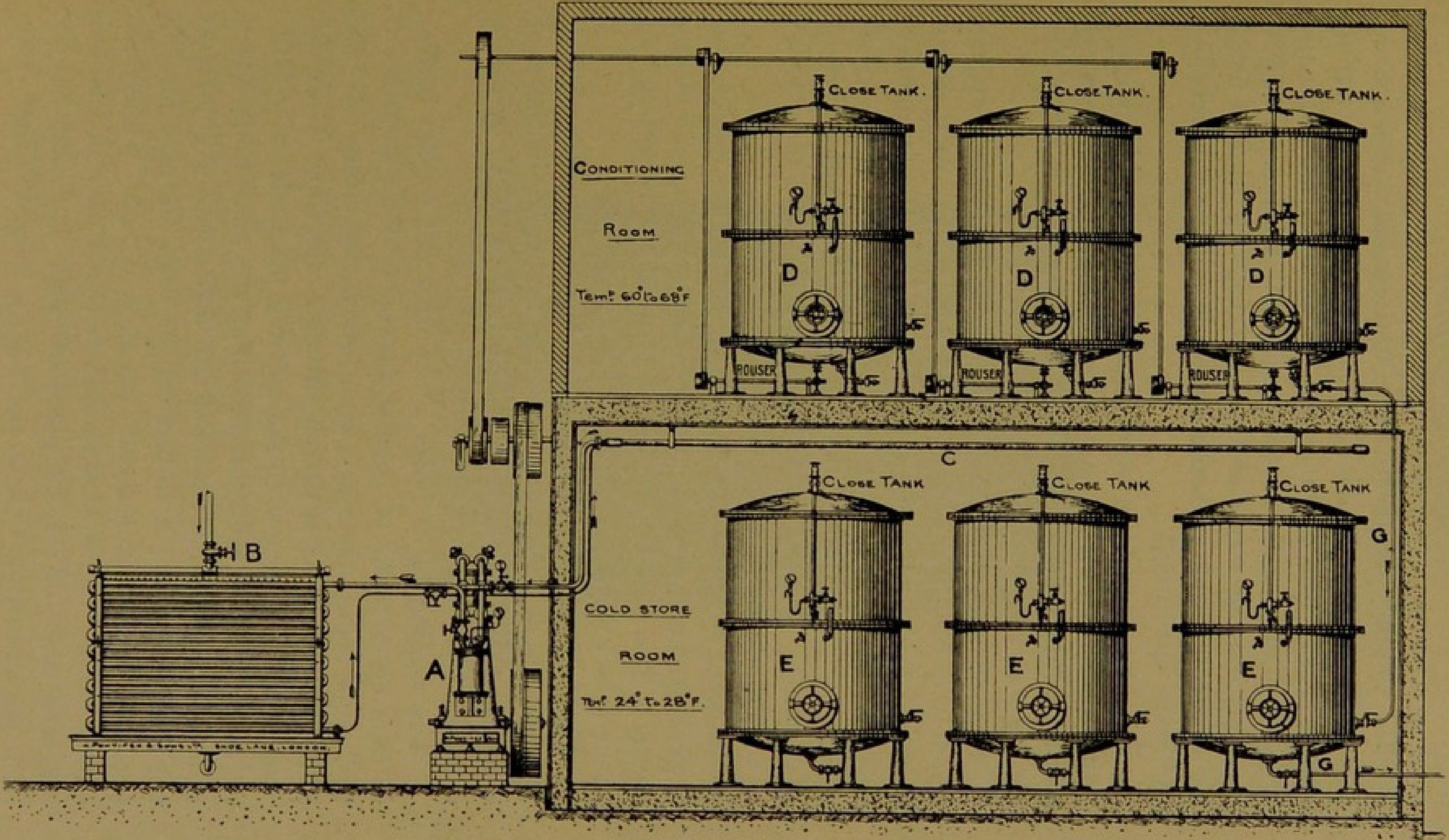

CLOSE TANK.
CLOSE TANK.
CLOSE TANK.
CONDITIONING
ROOM
TEMP. 60° to 68° F
D
D
D
ROUSER
ROUSER
ROUSER
C
CLOSE TANK
CLOSE TANK
CLOSE TANK
G
B
A
COLD STORE
ROOM
TEMP. 24° to 28° F.
E
E
E
G

Fig. 67.

For smaller plants Messrs. Pontifex make a combined beer chiller and carbonator, in which the usual carbonating vessel is surrounded by a coil of wrought-iron ammonia pipes and immersed in a tank containing brine. In addition to the usual cocks and gauges, etc., a stirrer is fitted for agitating the beer, and a screw propeller for circulating the brine in the tank.

Fig. 66A shows the usual form of this combined apparatus. It consists of a pair of copper tin-lined carbonators of the ordinary type, the brine tank forming a jacket for the sides and back ends of the carbonators.

Fig. 67 shows another system by the same firm, in which the beer is "conditioned" and chilled very slowly in metal tanks. The beer is brought from the fermenting vats to "close tanks" D in the conditioning room, which should be kept at 60° to 68° F. A small propeller (known as a *rouser*) is worked in the tank from time to time, so as to thoroughly mix the beer.

As the "conditioning" proceeds, a large amount of CO_2 is generated and collects under a pressure, due to its evaporation. The beer is brought to a suitable "condition" in about 5 to 7 days.

The beer is then, still under the same pressure of 1 to $1\frac{1}{2}$ atmospheres, passed to similar tanks, E, in the cold store room below, which is kept at 29° to 30° F. by direct expansion pipes.

The cooling of so large a quantity (20 to 100 barrels in each close tank) of beer is naturally slow; a further 5 to 7 days being necessary, after which, by means of "top pressure," the beer is driven through the pipe G to the filter, and from thence to the bottling machine.

Fig. 68 shows the construction of the close tank, which is of copper, heavily tin-lined and fitted with a gun-metal tin-lined manhole; a tinned copper draw-off pipe (at the bottom) with a gun-metal union cock and branch for admission of CO_2; a cock in side of vessel near the bottom for beer draw off; a sample cock with lock and key; a cock for admitting CO_2 at the top; a loaded safety valve and pressure gauge, and the necessary gear for driving the rouser.

ICE-MAKING PLANTS.—Fig. 69 shows an arrangement of a 60-ton cell ice plant by Messrs. Haslam, and consists of two horizontal double acting compressors driven by a vertical triple-expansion condensing steam engine, the compressors being driven from the high and low pressure steam cranks.

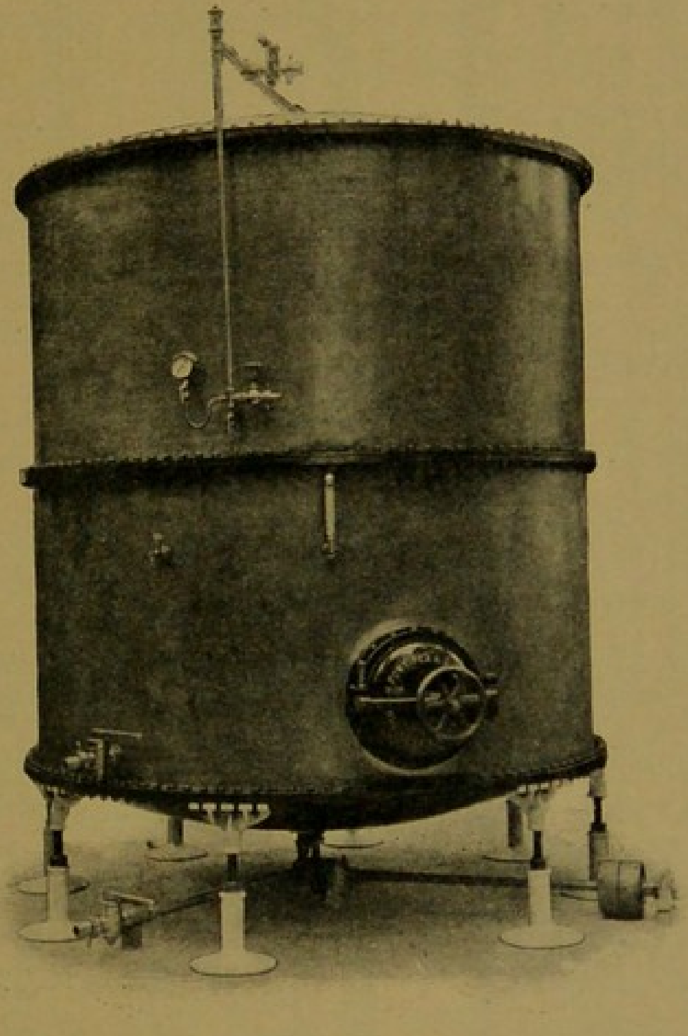


FIG. 68.

The ammonia, after leaving the compressor, passes into a separator (which will catch any oil that may pass over), and then on to the condenser, which is of the exact type described on p. 105.

The liquid ammonia then passes to a receiver placed in the insulated chamber which surrounds the coolers and cold brine tank.

This is an excellent arrangement; the further cooling

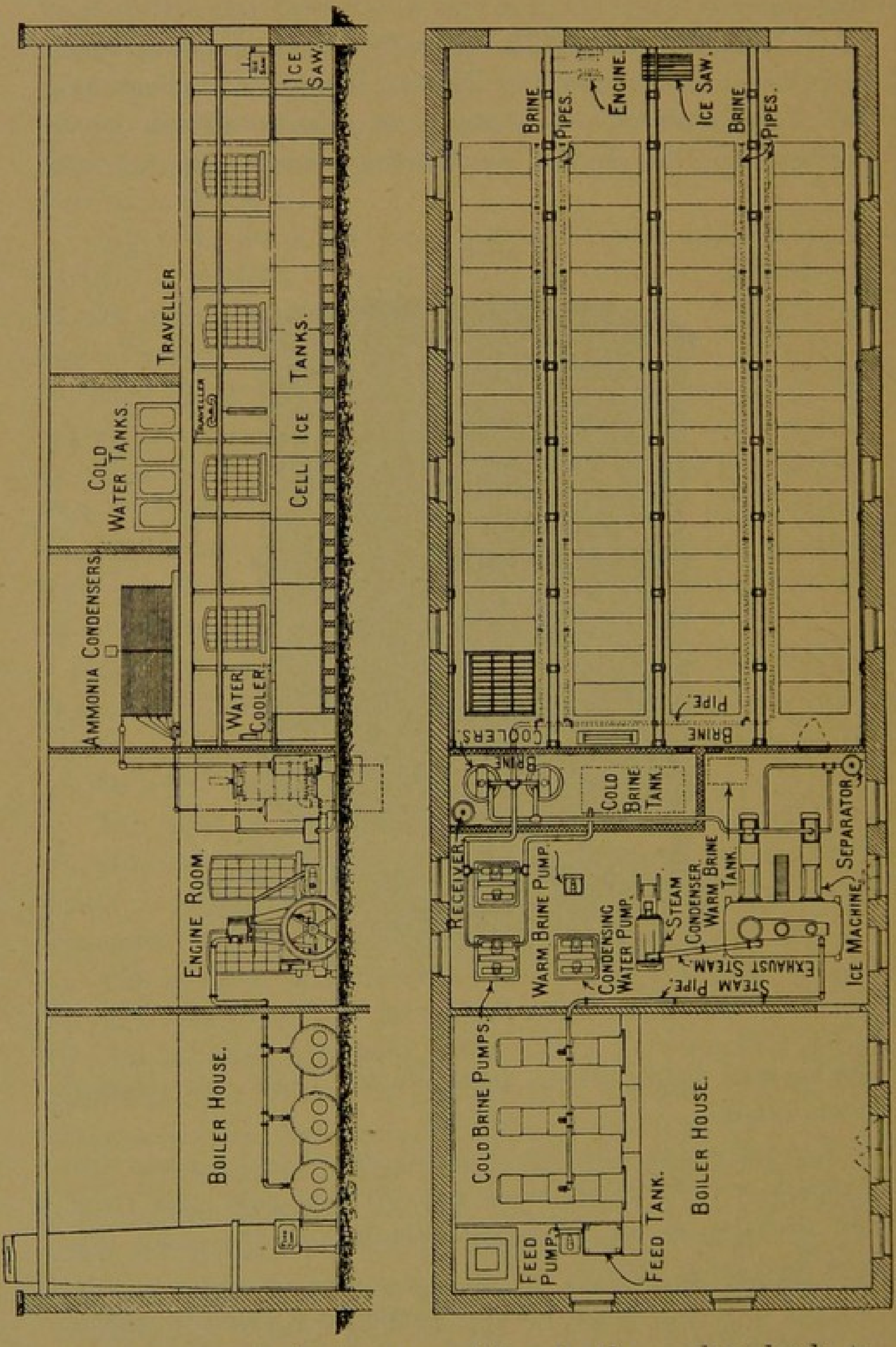


Fig. 69.

of the ammonia before vaporizing in the coolers leads to a greater economy than would be at first expected. The ammonia, after leaving the coolers, is once more pumped into the condensers by the compressors.

The ice tanks are, of course, in a separate section of the building—the ice being made by the Siddeley cell system, described on p. 146. The cold and warm brine pumps will be noticed on the plan.

The travellers deliver the ice from the cells direct to the platform, from whence it can be delivered direct into the ice waggons, or placed in an ice store above, below, or at the side of the factory, exactly as local requirements would demand.

An ice saw or crusher, or both, would be provided, and would be driven by suitable motive power.

Further points in the general arrangement can be gathered from an inspection of the figure.

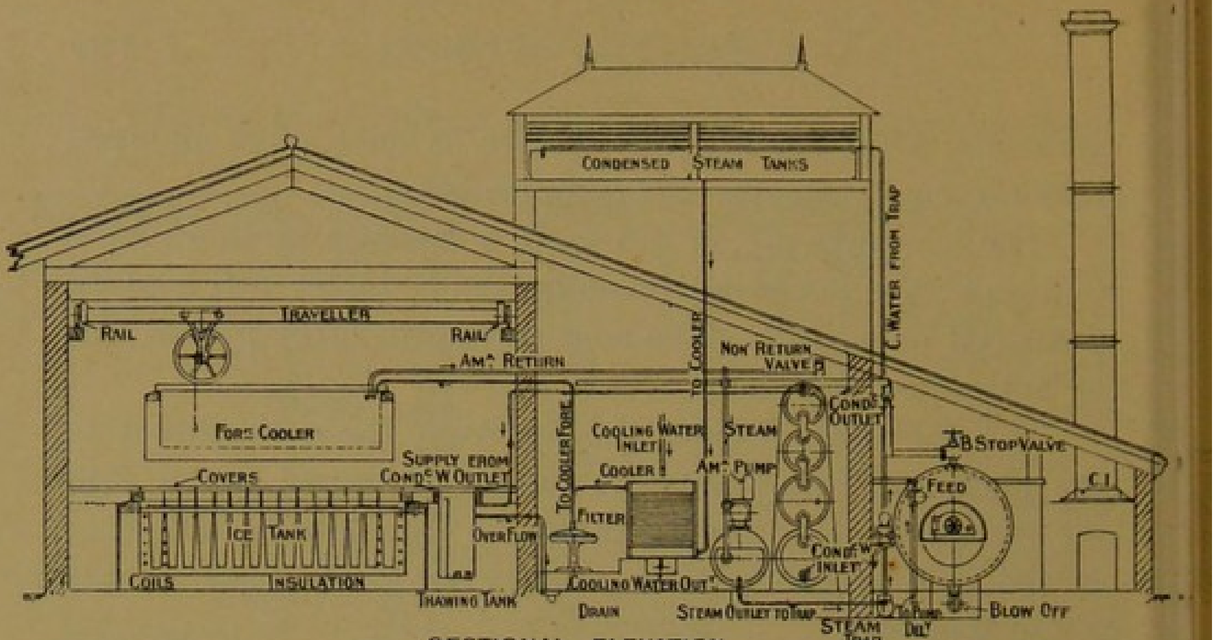
While Fig. 69 shows a typical ammonia (or CO_2) compression plant, Fig. 70 indicates an arrangement for ice making by the ammonia absorption system.

It shows a factory designed and erected by Ransomes & Rapier, for use abroad, the ice being made from distilled water.

The general principle of an absorption machine being understood (see p. 113), it may be said that the bulk of the distilled water required is taken from the condensed steam used in the generator, supplemented by steam taken direct from the boiler. As this steam is not brought into contact with any moving parts requiring the use of lubricating oils, no special apparatus is required for dealing with it; further, as the steam is condensed under pressure, it does not require re-boiling.

Where, however, the water used for feeding the boiler is of a hard nature, it is advisable to install a water-softener.

Where it is important to economize fuel as much as possible, the exhaust steam from the circulating pumps—or, where power is used for other work, from the engine also—can be utilized in the generator, but in this case a "de-oiling apparatus" would be required.



SECTIONAL ELEVATION

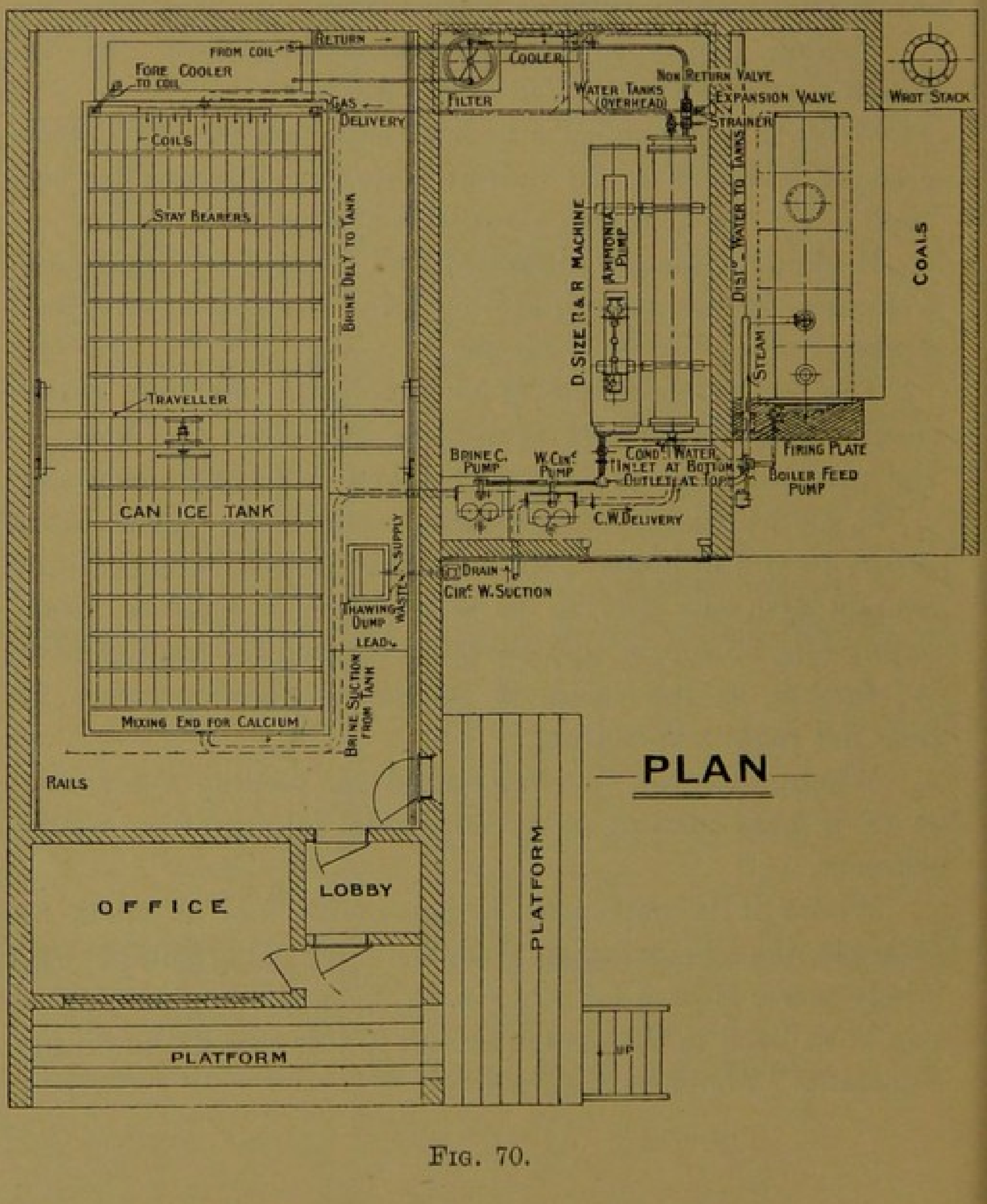


FIG. 70.

In the plant under consideration (Fig. 70) the condensed steam from the generator passes up to a tank outside the

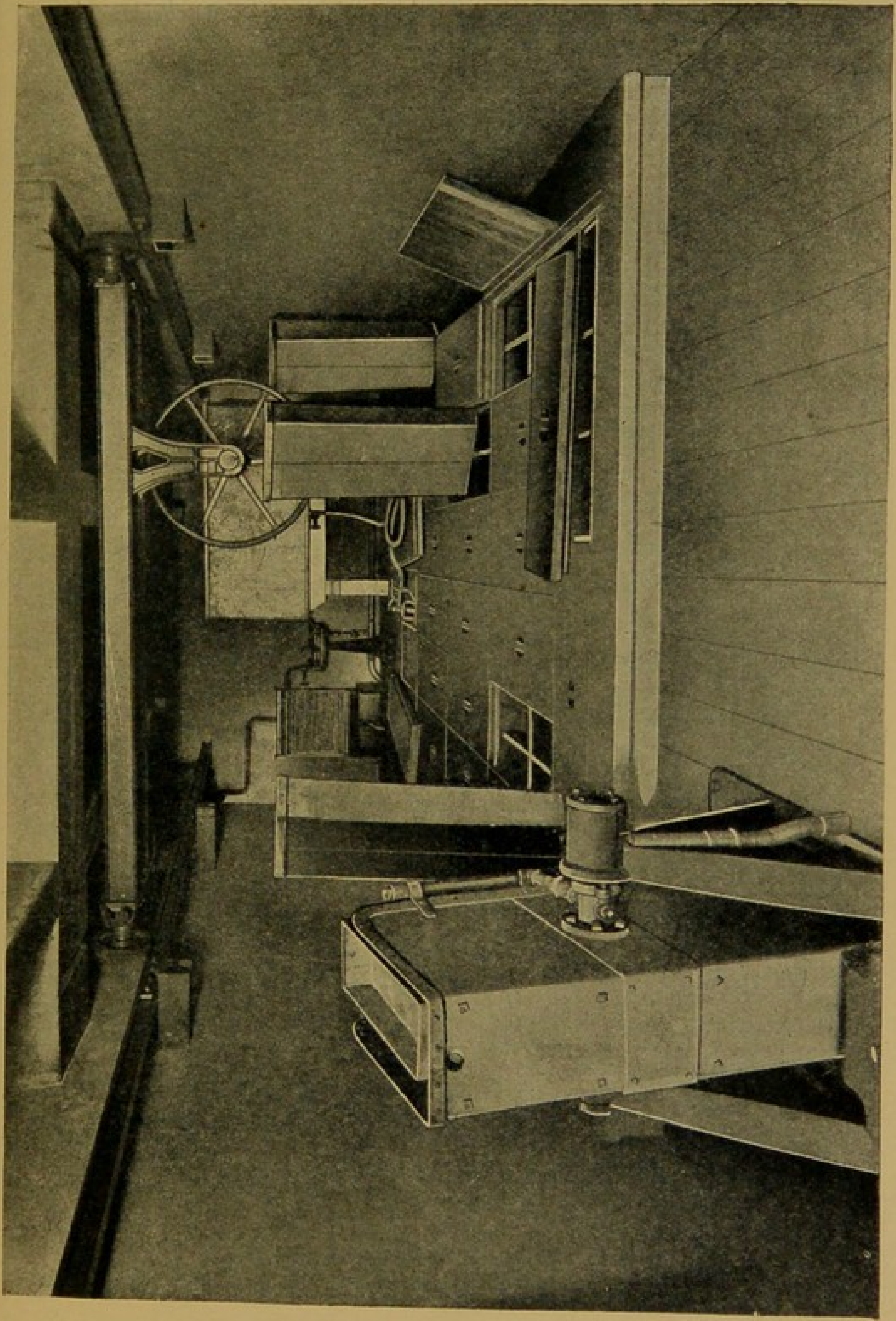


Fig. 71.

building. The water then runs *through* a cooler (cooled by water passing *over* the outside); it is then filtered and, before entering the ice moulds, is further cooled in a "fore-cooler" by the ammonia gas returning to the machine from the evaporator coils in the ice tank.

As distilled water requires no agitation to produce good, clear, hard ice, the ice cans, on being filled, are simply dropped into the brine, which in turn is cooled by the ammonia in the coils, placed between the cans, as indicated.

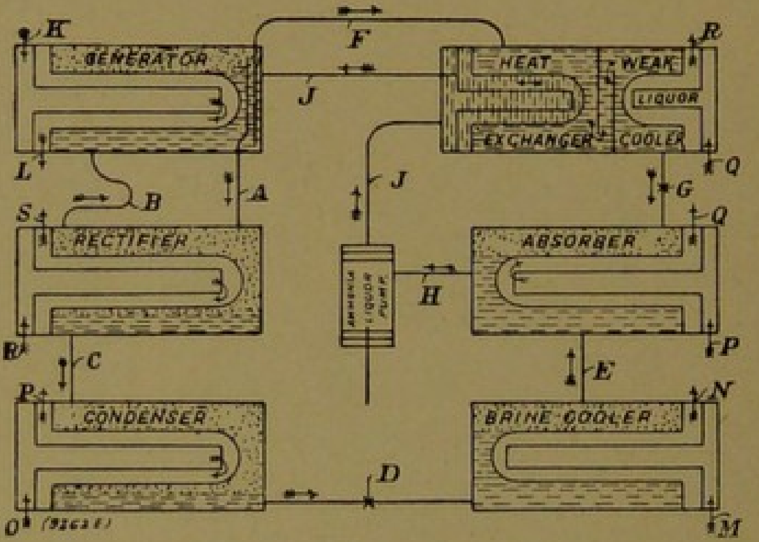


FIG. 72.

A, ammonia vapour from generator; *B*, drain from rectifier; *C*, anhydrous ammonia to condenser; *D*, regulating or expansion valve; *E*, ammonia vapour to absorber; *F*, weak liquor from generator to exchanger; *G*, weak liquor regulating valve; *H*, strong liquor to pump; *J*, strong liquor through exchanger to generator; *K*, steam supply; *L*, to steam trap; *M*, brine inlet; *N*, brine outlet; *O*, *P*, *Q*, *R*, *S*, cooling water circuit.

The brine is kept in constant circulation by a pump, which distributes it evenly by means of distributing and collecting pipes.

After the ice is made up, the can is taken to the "thawing dump" where the ice is loosened by means of the waste condensing water and is then automatically delivered.

This figure, also, will repay further study.

Fig. 71 shows a similar plant at the Ritz Hotel, London, where all the parts mentioned can be clearly followed, together with the method of filling each can from the

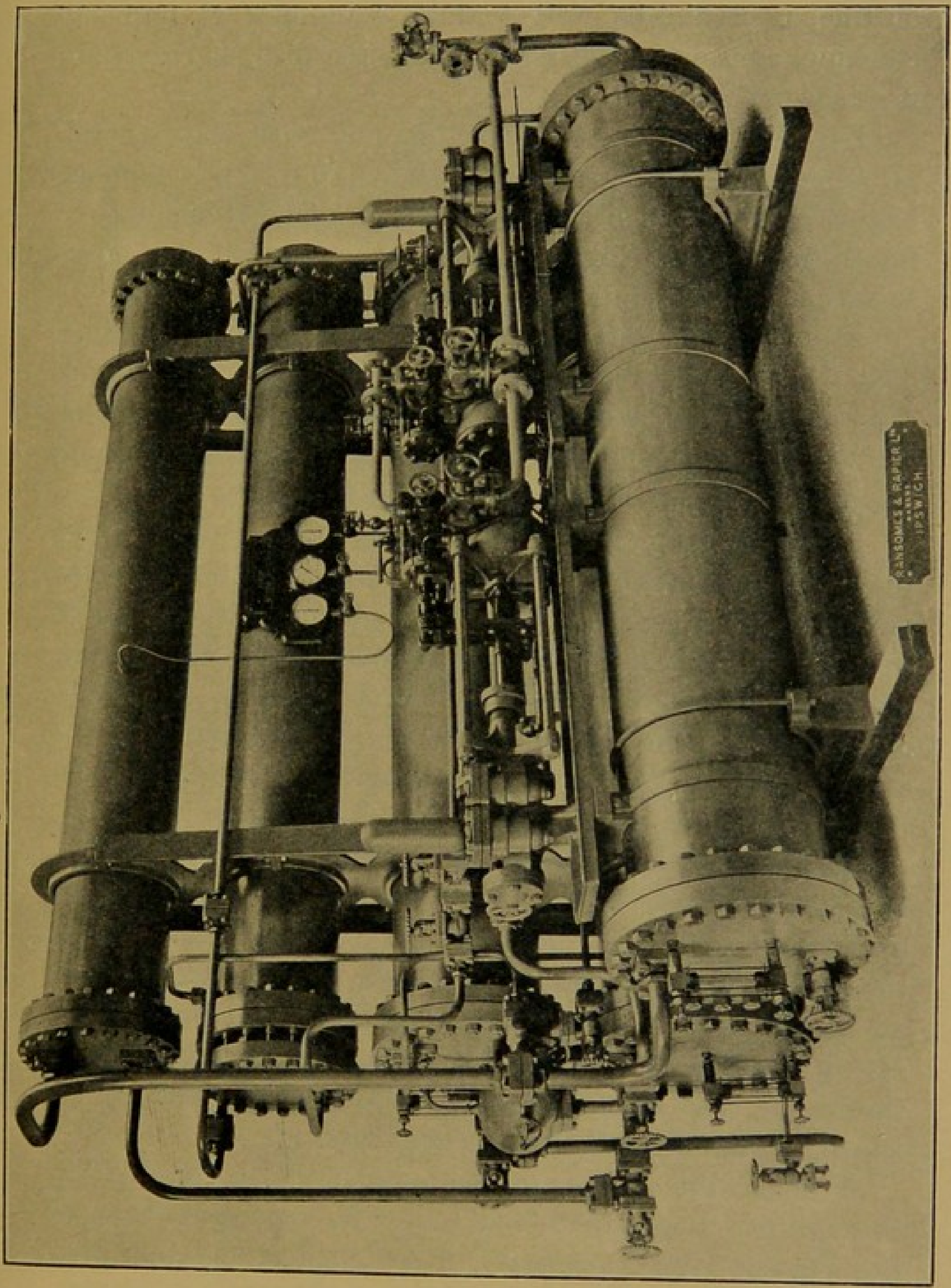


FIG. 73.

fore-cooler, an automatic filler (*i.e.* an arrangement which will shut off the water when the desired height is reached in the can) being employed at the end of the hose pipe.

As the absorption machine has only been explained in outline, it would be well to take Ransomes & Rapier's machine, as used in the plants just described, and explain it somewhat in detail.

Fig. 72, when taken in conjunction with the general principle given on p. 113, to which a previous reference has been made, requires no further explanation, but is interesting as showing, in outline, the system of double tubes employed in this actual machine.

Fig. 73 shows the general appearance of the machine. The front cylinder is the generator on which is mounted the ammonia pumps (in duplicate), the one at the back is the condenser, then, above, the absorber, exchanger, and rectifier (the latter being the uppermost).

Generator.—Fig. 74 shows the generator. Steam enters the outer portion of the casting shown in the bottom left-hand portion of the section, and passes through a series of small tubes to the end of the generator and returns, by means of an annular space (left by these tubes and larger ones), to the inner portion of the end casting, connected to a steam trap, through which the condensed steam escapes, but prevents any escape of uncondensed steam.

The strong liquor from the exchanger enters the top, and is distributed by means of an internal manifold, through a series of pipes and down screens of wire gauze. Thus, the strong liquor, in the form of thin films, meets the hot ammonia gas on its way from the generator to the rectifier (see perforated pipe at the top, which is the outlet) with the result that ammonia is driven off, while some of the vapour in the ascending gas is condensed.

Further, the drain from the rectifier also enters the top through two large tubes, and helps the wire gauze to take the place of the "analyzer," fitted with other absorption machines.

Exchanger.—Fig. 75 shows the heat exchanger.

Here the weak, but very hot, liquor from the generator on its way to the absorber, first passes *outside* a series of annular tubes, *through* which the strong, but fairly cool, liquor from the absorber to the generator circulates. By

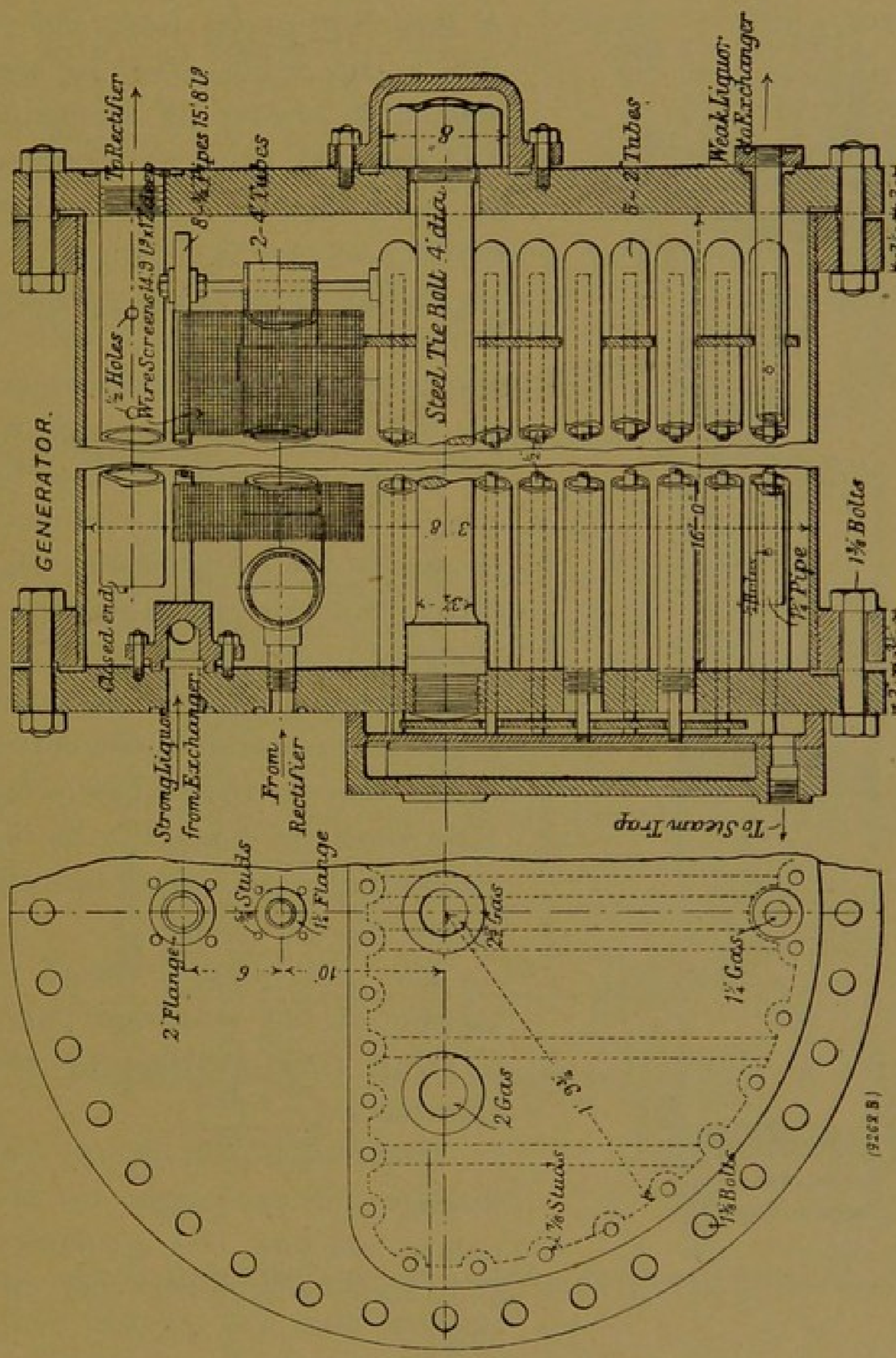


FIG. 74.

means of the hollow diaphragm, the weak liquor flows to the other end of the exchanger, where it is further cooled by water circulating inside the tubes.

Absorber.—The absorber, which is similar in construction to the generator, consists of a cylinder of welded steel, having flanges screwed on each end, to which the rolled steel plate covers are attached. A stay bolt passes from end to end, a cap being fitted to prevent any escape of ammonia. The external tubes are screwed and also expanded into the end covers.

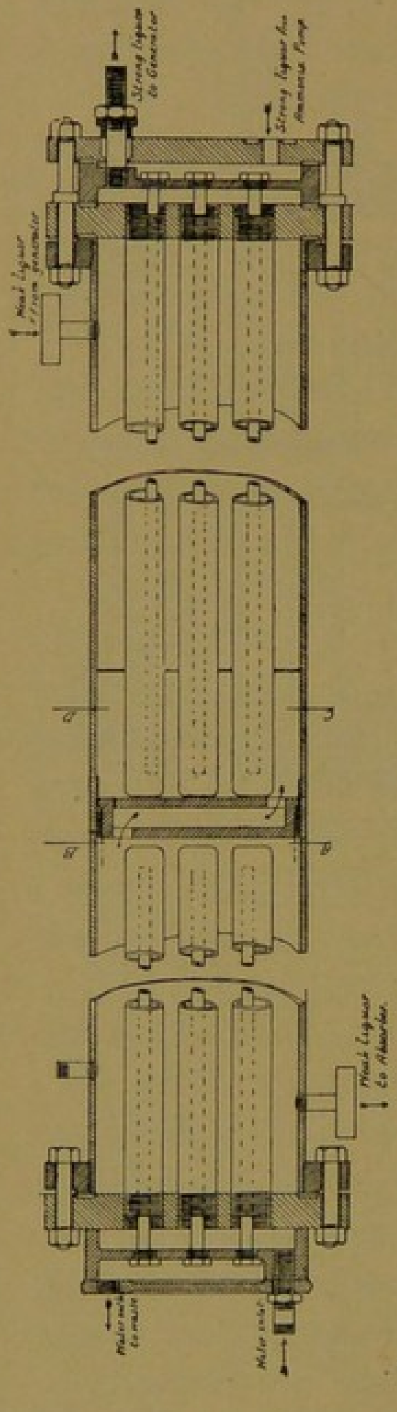


FIG. 75.

In Fig. 76, which is a section through the absorber, it will be seen, that the weak liquor enters the top (the flow is regulated by an automatic valve worked by a lever float) and is distributed, by means of a tray, over annular tubes, through which water is circulated.

The ammonia gas from the evaporator or brine cooler, enters at the bottom, and in ascending will come in contact with the descending weak liquor, and will be absorbed.

The rich liquor outlet or suction to the ammonia pump is about three-quarters up the absorber.

The rich liquor, being sent through the exchanger by this pump, reaches the generator, and thus completes the circuit.

Working Pressures.—The makers give the following pressures for the due working of their machine. The table should be compared with those given with Fig. 42.

Temperature of Condensing Water.		Pressure lb. sq. inch.		
Inlet.	Outlet.	Steam.	Generator.	Absorber.
50° F.	95° F.	40	135	The same pressure as the temperature (in degrees F.) of the brine.
60° F.	100° F.	45	150	
70° F.	105° F.	50	165	
80° F.	110° F.	55	180	
90° F.	115° F.	60	200	

This type of machine, although only described here in connection with an ice-making plant, can, of course, be used for any refrigerating purpose, and is particularly economical when used for low temperatures.

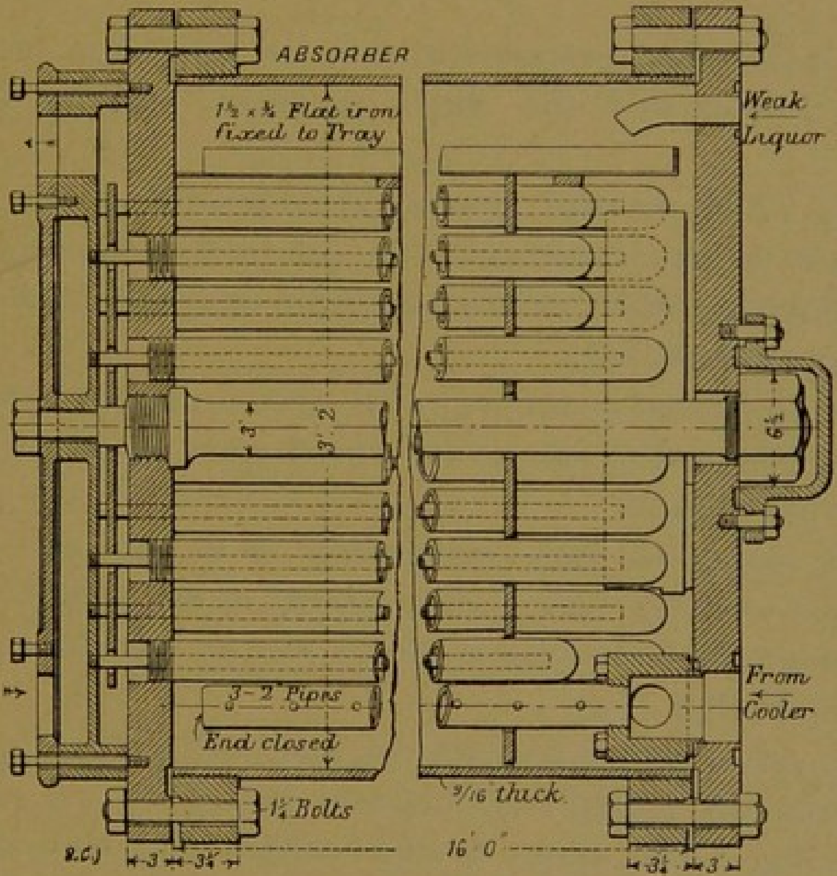


Fig. 76.

Ransomes & Rapier also design machines for using steam as low as 5 lb. sq. in. for working in conjunction with the exhaust steam of an existing engine. A combination of this type of plant and a compression system (driven by steam) can be so arranged as to give most satisfactory results. Fig. 85 shows this machine as used on shipboard.

MARINE REFRIGERATION.—Through the courtesy of the Liverpool Refrigeration Co., we are enabled to illustrate the latest marine practice in refrigeration as fitted on the Q. T. *SS. Lusitania* and *Mauretania*, the T. *SS. Carmania*, of the Cunard Line, and *SS. Tropic* and *Cufic*, of the White Star Line.

The installations on the *Lusitania* and *Mauretania* comprise machines for both cargo and ship's provisions, which, although differing in themselves, are very similar in each ship.

It is, therefore, proposed to describe the cargo machine of the former and the ship's provision machine of the latter.

Fig. 77 shows the general arrangement of the cargo machines on the *Lusitania*. It comprises two complete, but interchangeable, plants—carbonic anhydride being the refrigerant employed.

The horizontal compressors are driven direct by electromotors, designed to run at any speed from 40 to 110 revolutions per minute.

The casing of each compressor is of soft cast steel, while the working bore is of a special close-grained metal, so fitted to the body that it can be readily withdrawn from either end (Fig. 77A).

The valves, which are vertical, and work without springs, are carried in forged-steel headers bolted to the ends of the casing. The front header carries the stuffing-box, which is fitted with metallic packing, and the back-header, a plain plug cover.

The pistons, which in most CO_2 machines are packed with cup-leathers, are, in these compressors, fitted with special metallic packing-rings, secured in position by means of a patent split junk-ring head, so constructed that, while it is perfectly secure in working position, it may be said to fall asunder when withdrawn—the construction is so simple.

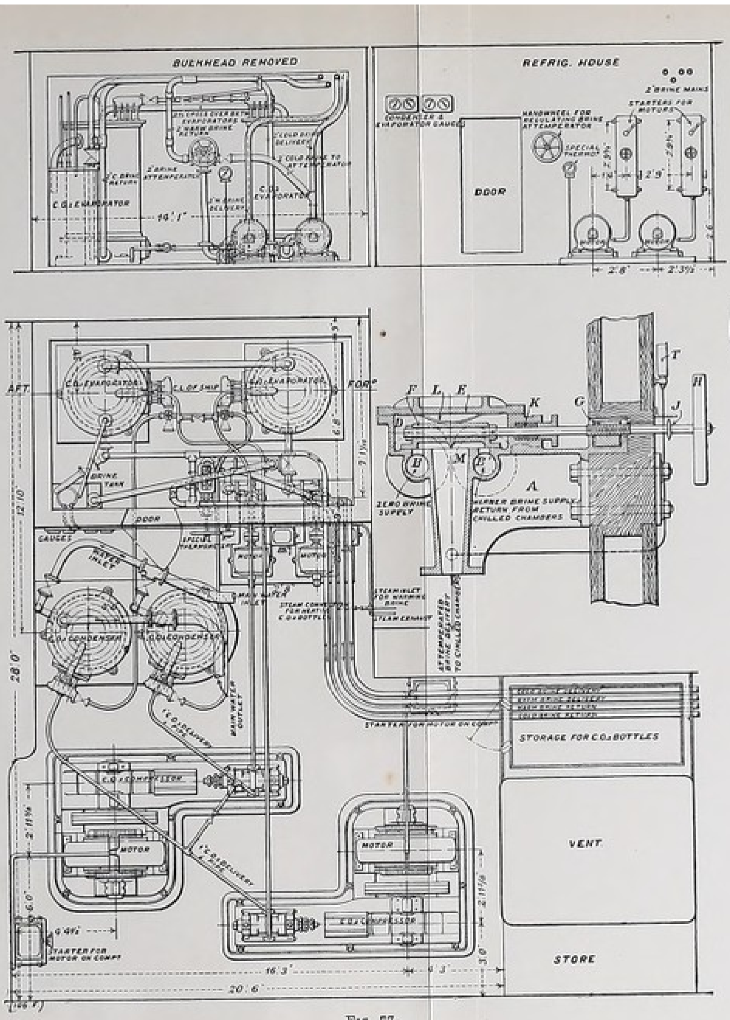


Fig. 77.

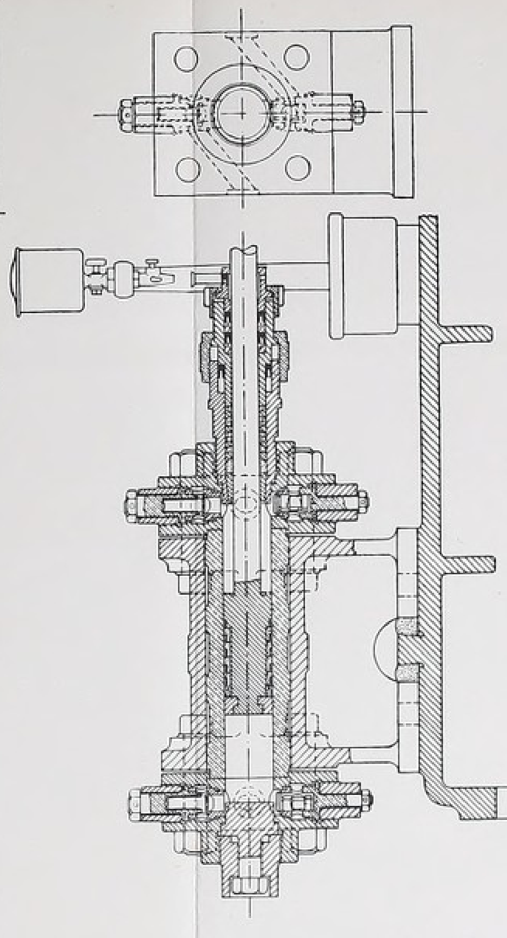


Fig. 77a.

[To face p. 206.

Fig. 77A shows a section through the compressor (Webb and others' patent); the principal features of construction, some of which have been mentioned, can be easily followed.

Fig. 78 indicates the general construction of the compressor and motor.

The compressor is bolted, by means of two large feet, to a substantial box-bed, which also carries the guide and crank-shaft bearings.

A flywheel (also used for barring purposes) is carried between the crank and motor, to ensure easy running during the heavy compression part of the stroke.

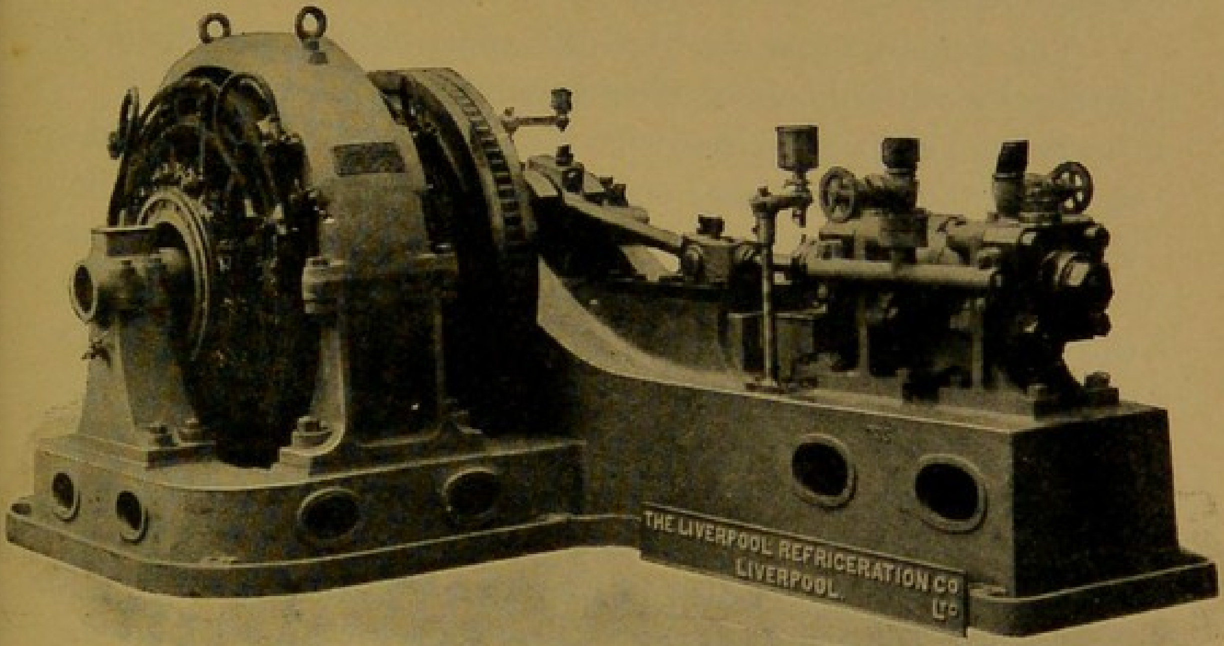


Fig. 78.

The motor is carried on a bed which forms part of the same casting as the compressor bed, and thus secures steady and even running—the whole, it will be noticed, being so arranged as to afford every facility for overhauling.

Each compressor (Fig. 77) delivers into a separate condenser, but a cross connection enables either compressor to deliver into either or both condensers.

The condensers consist of vertical galvanized wrought-steel shells, containing coils of galvanized lap-welded wrought-iron pipes.

The coils are connected at the top and bottom by manifolds, the gas entering at the top, and the liquid leaving at the bottom.

The circulating water (which is circulated by the ship's pumps), on the other hand, enters at the bottom and discharges at the top.

The evaporators are similar in construction to the condensers, the liquid CO_2 from the condenser entering at the bottom manifold, and after evaporation passing on to the compressors.

The brine pumps are high-lift centrifugals by Gwynne, driven by variable-speed electro-motors.

These pumps (together with the evaporators) are enclosed in an insulated chamber; only the spindles passing through the walls to the motors.

Fig. 77 contains a great deal of detail, particularly of the pipe connections, that will repay a close study; but one further and important fitting must be described—the *brine attemperator* (Webb and others' patent).

A steamer's cold chambers have frequently to be arranged to carry a variety of refrigerated goods, some hard frozen, others more or less chilled, each class requiring to be kept accurately at a suitable temperature and without influencing or being affected by goods stored in adjoining compartments, all of which must be under proper control. Further, any proportion or all of the compartments or chambers should be available for either frozen or chilled goods as may be necessary.

The usual method of dealing with this problem is to fit all the chambers with sufficient brine piping to meet the *lowest* temperature demanded (a good practice), and to regulate the temperatures by the *quantity* of cold brine circulated.

When higher temperatures are required, a *small quantity of very cold brine* is circulated, which will be raised through *many* degrees during circulation and before returning to the machine.

The aim of the attemperator about to be described is to circulate a relatively *large quantity of brine at a suitable temperature*, which will only be raised through a *few* degrees—this being the only efficient method (with brine circulation) of keeping *even* temperatures.

The attemperator is shown in section in Fig. 77, and consists of a spindle provided with a screw and nut at G, and a handle H at the end outside the insulated chamber surrounding the evaporators. The other end is connected to a slide-valve F working over three ports B, B′, and M. The valve is kept tight on its face by the spring L, while K is the valve spindle packing.

The cold brine pump draws the brine from the evaporators and sends a portion of the brine through the attemperator (connection B), and the remainder to a special distributing insulated box close to the cold chambers.

A second brine pump takes its "suction" from the attemperator by the connection M, and also sends it to the distributing box, which contains for each hold a distributing-header, so arranged with valves that either the cold or the attemperated brine may be circulated.

Thus, if cold brine is being used in a chamber, then, after circulation, it returns direct to the evaporator to be cooled. If the attemperated brine is in circulation, it returns to the attemperator, a quantity (equal to the cold brine supply to the attemperator) overflowing back to the evaporators.

The action is very positive. If the special thermometer T shows the attemperated brine is too high in temperature, then H is turned in such a manner that the opening at B is increased and B′ decreased, and *vice versâ*.

The chamfered disc J serves as an indication of the position of the slide valve F.

It will be noticed that the two delivery (cold and attemperated) and two return brine pipes pass through a small insulated chamber for storing the CO_2 bottles carried as reserve.

Arrangements are made for heating the brine with the object of thawing off the frost on the brine pipes and drying out the cold chambers after the discharge of the *chilled* cargo, thus preparing the holds for *ordinary* cargo on the return voyage.

The machines are placed on the shelter deck just abaft the forward funnel, the centre line of the ship passing through the centre of the evaporators.

The cold chambers are on the orlop deck, and have a total capacity of about 30,000 cub. ft.

The machine for the ship's provisions is situated (in both vessels) on the main deck, just forward of the port engine hatch.

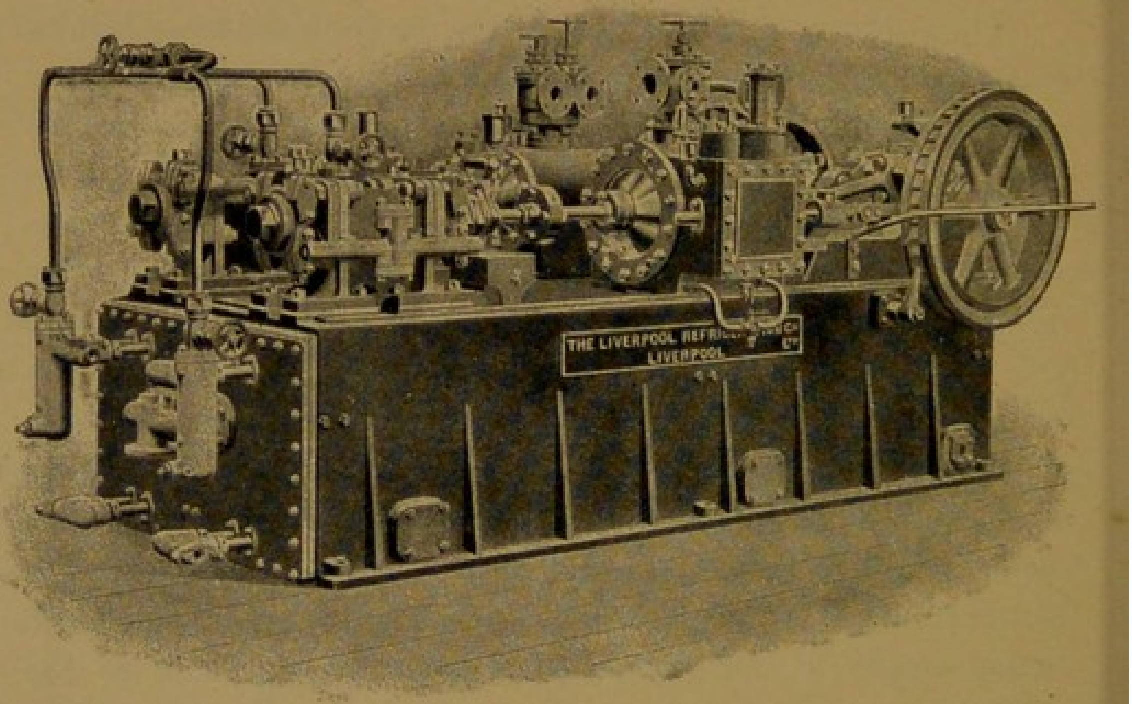


Fig. 79.

The refrigerant employed is CO_2, and the general arrangement of the horizontal double-acting compressors is shown in Fig. 79.

Their construction is similar to those in the cargo machines, but in this case they are driven off the tail rods of a compound engine; each cylinder, however, has its steam and exhaust connections so arranged that either may work independent of the other, if necessary.

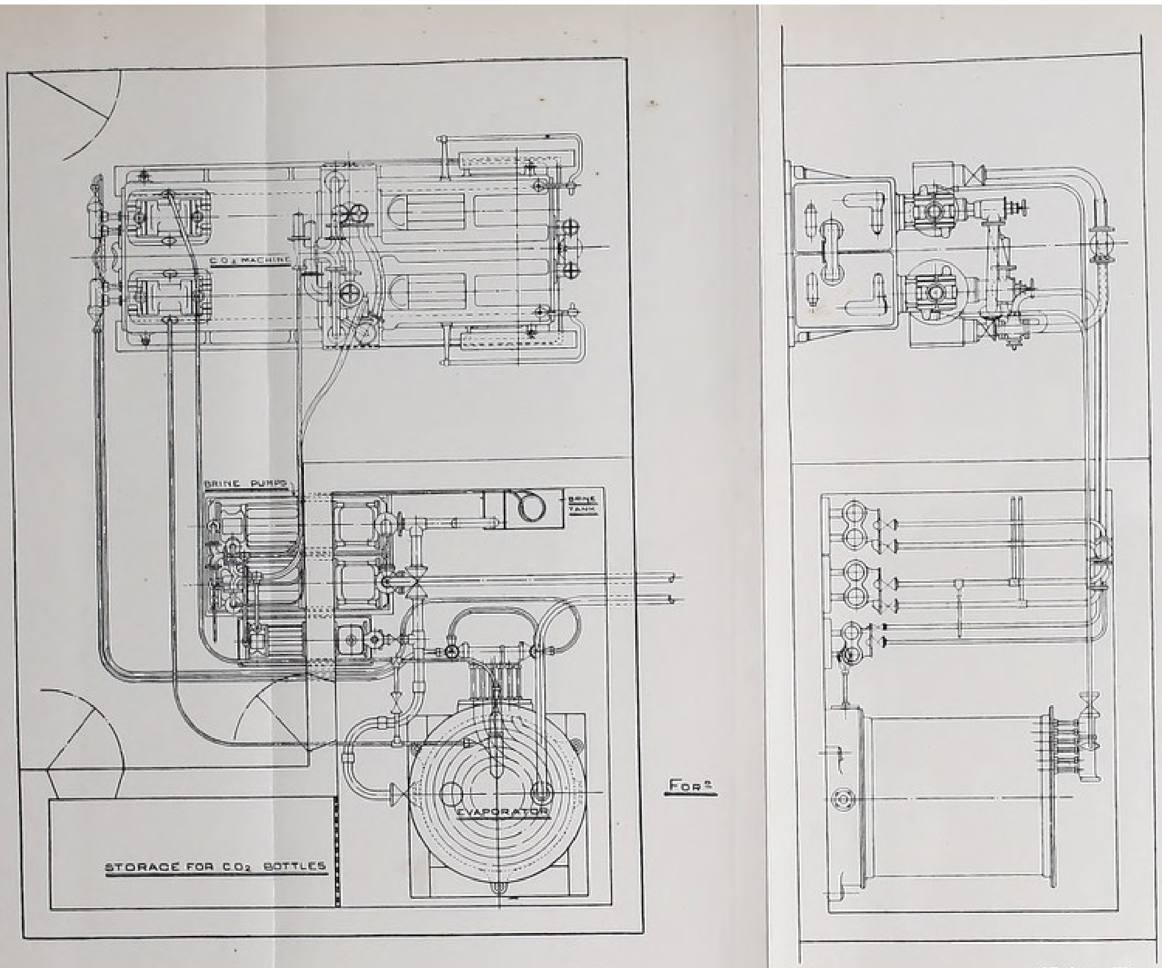


Fig. 80.

[*To face p.* 211.

A crank shaft is fitted, which carries the necessary fly-wheels, and is, of course, also used for working the steam valve gears.

The box bed is divided by a longitudinal partition into two separate compartments, each forming a CO_2 condenser. A cross connection—clearly indicated—enables either compressor to deliver into either condenser, the whole machine being thus in duplicate.

Fig. 80 shows the general arrangement of the machine as fitted on the *Mauretania*.

The liquid CO_2 passes from the condensers to the evaporator, which is vertical, the galvanized wrought-steel shell containing five coils of lap-welded wrought-iron tubes. It is contained in an insulated box, which also covers the actual cold ends of the horizontal duplex steam brine pumps; a space is also reserved for CO_2 bottles.

In both the cargo and ship's provision machines the brine is kept in a closed circuit, a small tank being used for mixing purposes.

A vent is carried from each evaporator by means of a pipe, well up and out into the open, to allow any gas to escape, a collection being thus impossible (see p. 218).

The cooled brine is sent into pipes, through the bulkhead and down to the lower deck (*i.e.* one deck below), where, on the port side, there are special rooms for (*a*) beef, (*b*) mutton and poultry, (*c*) bacon, (*d*) ice, (*e*) fruit and vegetables, (*f*) milk; while on the starboard side there are rooms for (*g*) beer, (*h*) wines, (*k*) spirits and table waters. There are also arrangements for cooling drinking water and liquors in other parts of the ship.

The whole capacity is almost 13,000 cub. ft., and suitable temperatures are carried in each room to suit the particular materials stored.

White deal boards, special waterproof paper, and granulated cork are used for the insulation.

The rooms on the starboard side (wines, etc.) carry a lighter insulation than those on the port side.

The refrigeration installation must of necessity be differently arranged in different classes of steamers, and chiefly for purposes of comparison the general arrangement on the T. *SS. Carmania* is given in Fig. 81.

Here one provision and three cargo ammonia compression machines are fitted, the former being just forward of the mast, the compressor being worked off a crank shaft, driven by a single cylinder. The condenser is in the box bed, and the evaporator in a *separate* insulated chamber, because the cargo machines (say on the outward voyage) may not be running.

The three cargo machines are duplex throughout, each consisting of two compressors driven by a compound engine (either cylinder of each may be worked independently of the other) placed on a box bed, containing two distinct condensers. Each machine has two vertical evaporators and two brine pumps, the cold parts all being enclosed in an insulated box.

In the *Carmania* each principal shipper of beef is provided with a separate machine, a system which, with the rapid increase of refrigerated cargo, is hardly likely to be maintained, and in Fig. 82 we have shown what may be termed the normal practice of the Liverpool Refrigeration Co., and indicates the arrangement fitted on the SS. *Tropic* and *Cufic,* and suitable for about 150,000 cub. ft. of insulated space.

It consists essentially of two large horizontal ammonia compressors driven direct from the tail rods of a compound engine, the ammonia condensers being separate and of the vertical type.

It is interesting to note two points: (1) That a separate steam condenser is used, the circulating water for which passes through the ammonia condenser; (2) that a brine-distributing header is placed in the box, and is for the hold below, close to the machine, while a second header (and return) is placed in a special insulated distributing house for the forward cargo space.

It may be again mentioned that usually the cargo space

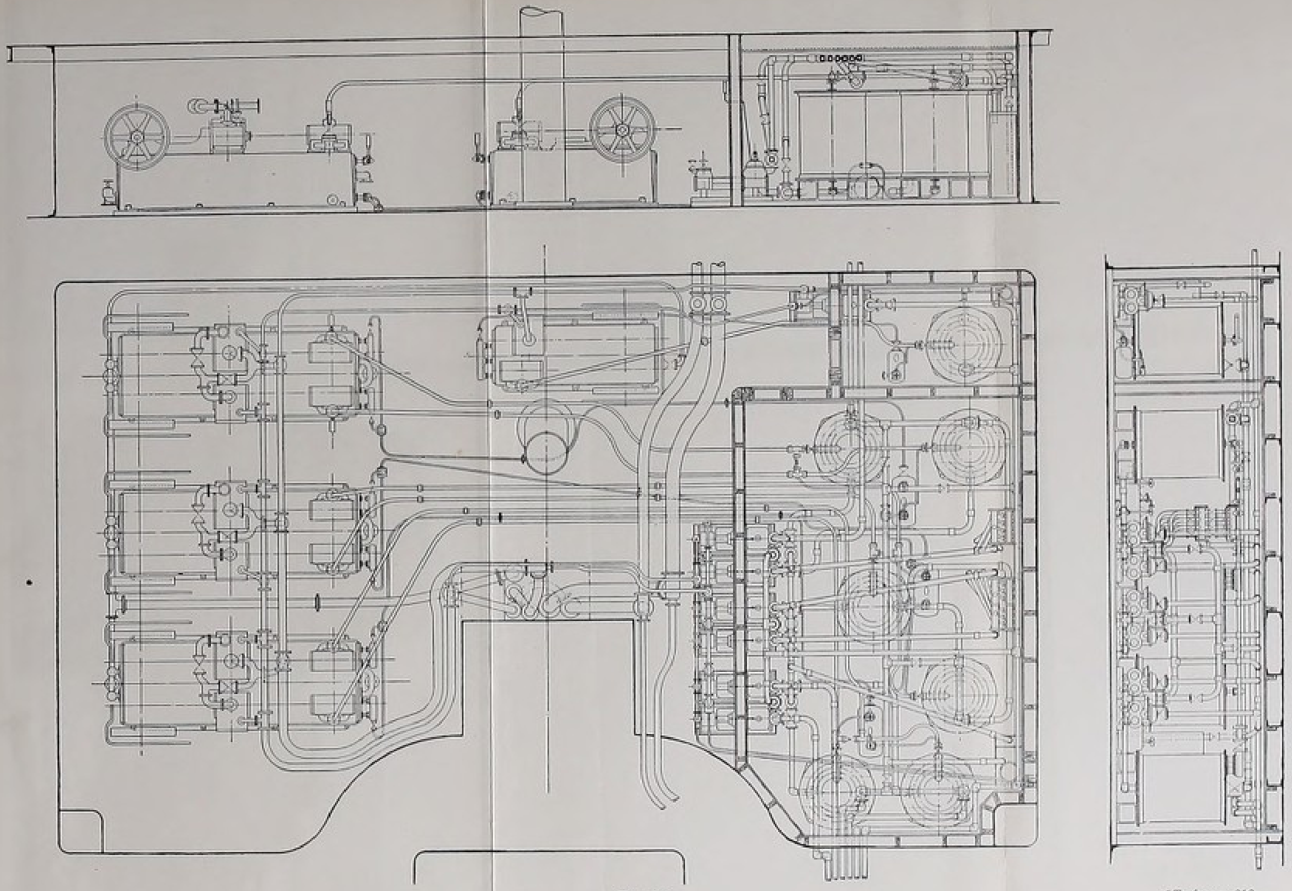


Fig. 81.

[*To face p.* 212.

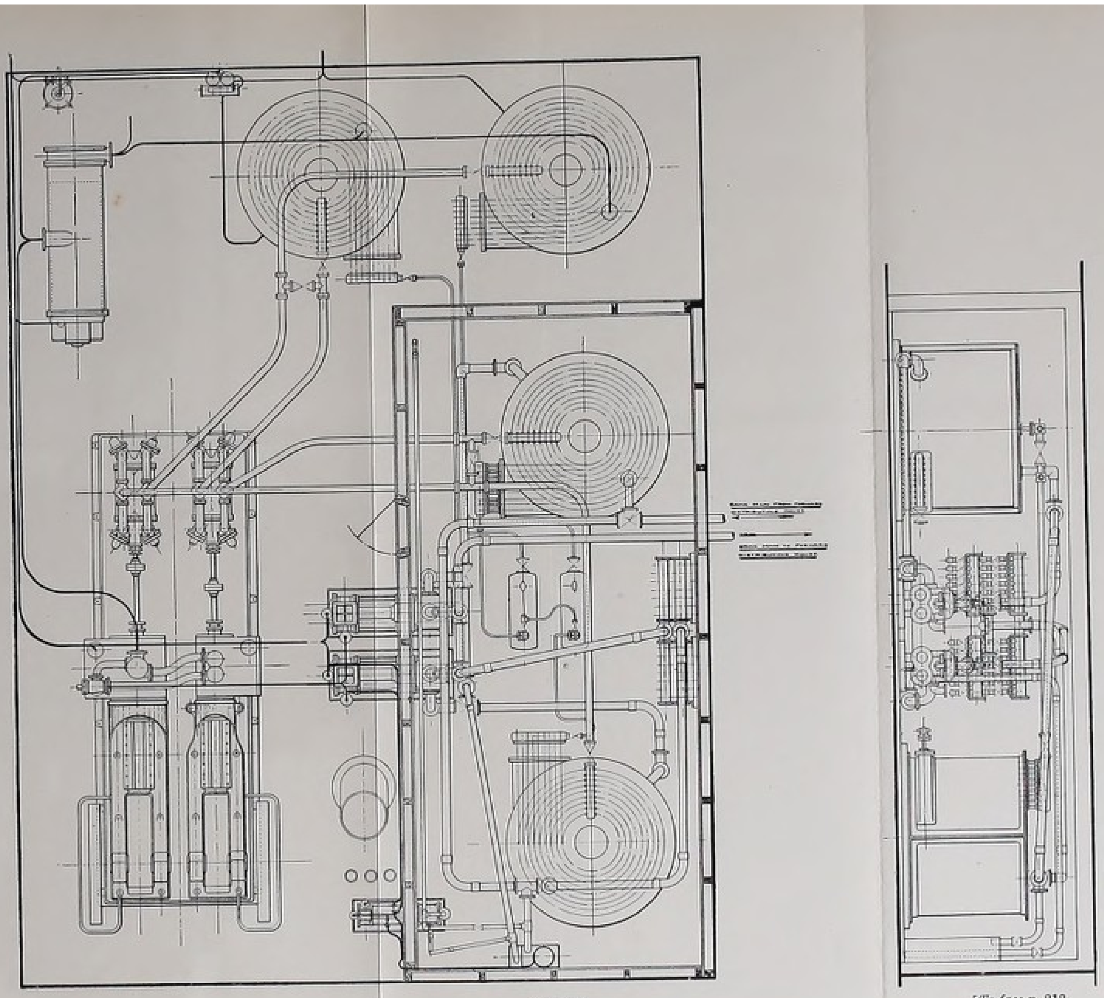


Fig. 82.

[*To face p.* 212.

is cooled by means of galvanized pipes, divided (in each hold) into a number of separate circuits, which not only prevents too long a run for the brine, but also ensures more even temperatures.

The pipes are carried overhead or on the sides, or both, the meat rails running between the overhead pipes, as shown in Fig. 83, or they may be arranged as in the *Lucania*, shown in Fig. 62, p. 174.

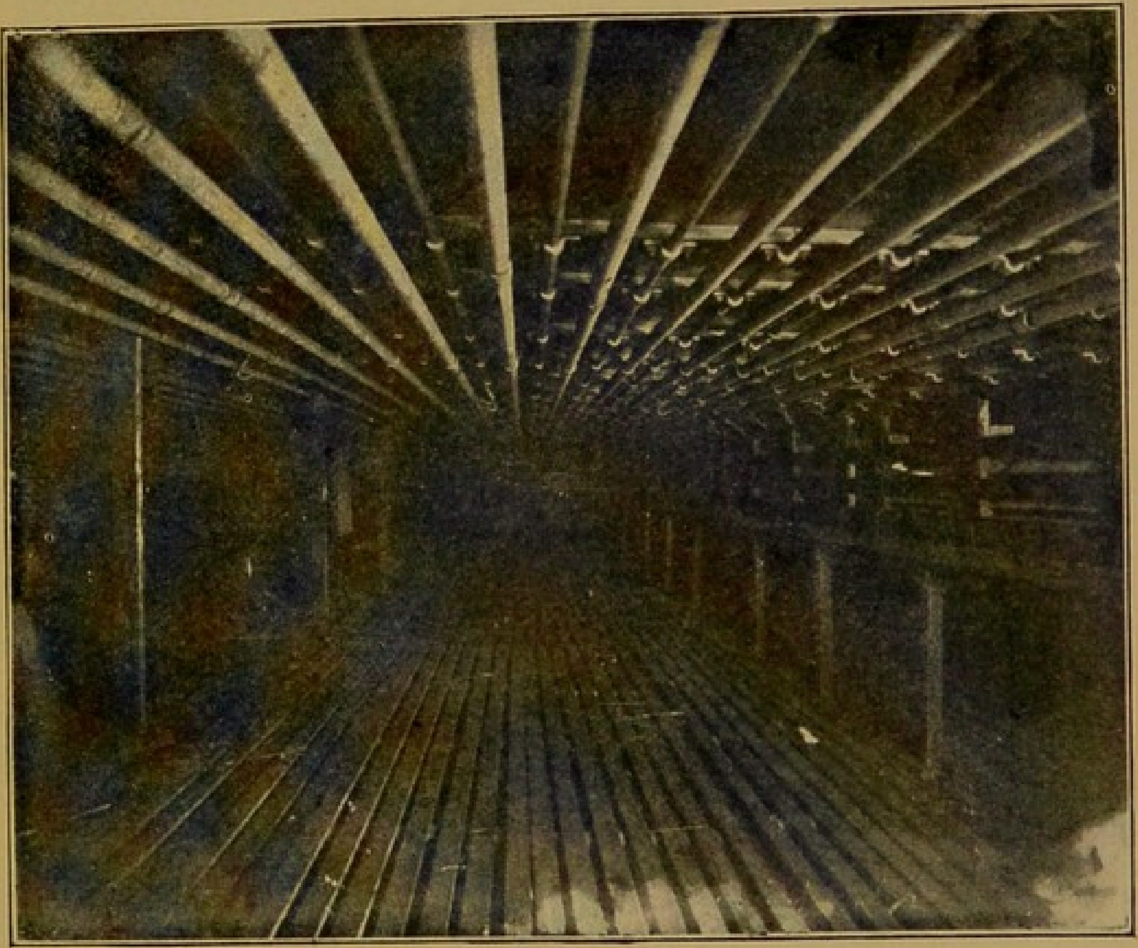


FIG. 83.

Fig. 84 is an arrangement where the cold-air circulating system is used as well as brine-pipe cooling. Here a steam-driven duplex CO_2 machine, by Messrs. Haslam, is so fitted that air is blown, by means of a steam-driven fan, through a stack of pipes (top left hand), through which the cooled brine is circulated. The cooled air is conveyed by ducts to the deck below. On the right hand is seen the ship's provision store, cooled by brine pipes, the same method being adopted for the hold.

While CO_2 and NH_3 compression machines are most commonly adopted for marine work, ammonia absorption

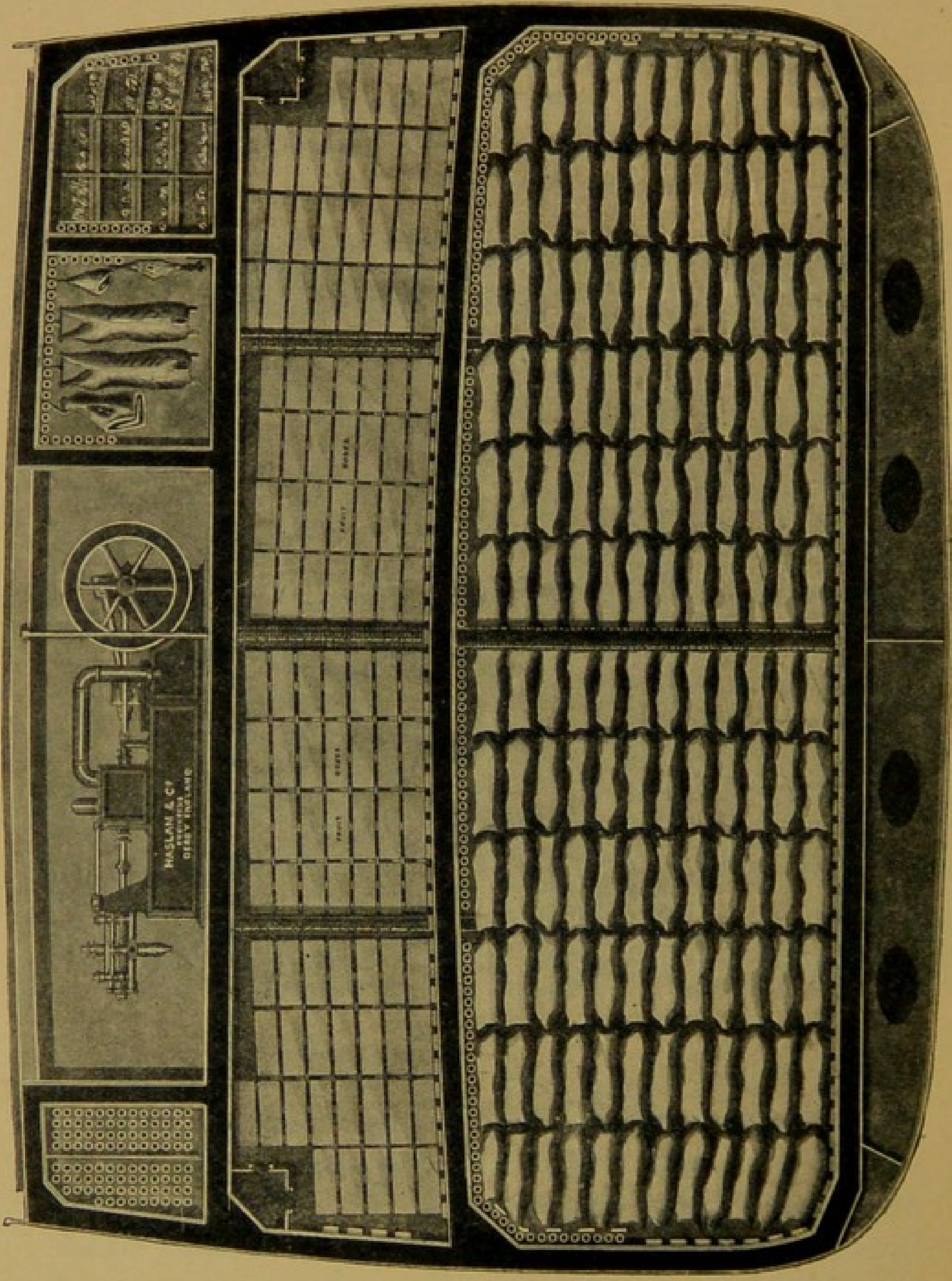


Fig. 84.

machines are also employed. Fig. 85 is an arrangement of such a machine supplied by Messrs. Ransomes & Rapier to the Holland Steamship Co. for their steamers *Ijstroom* and *Maastroom.* A description of a similar machine is given on p. 202.

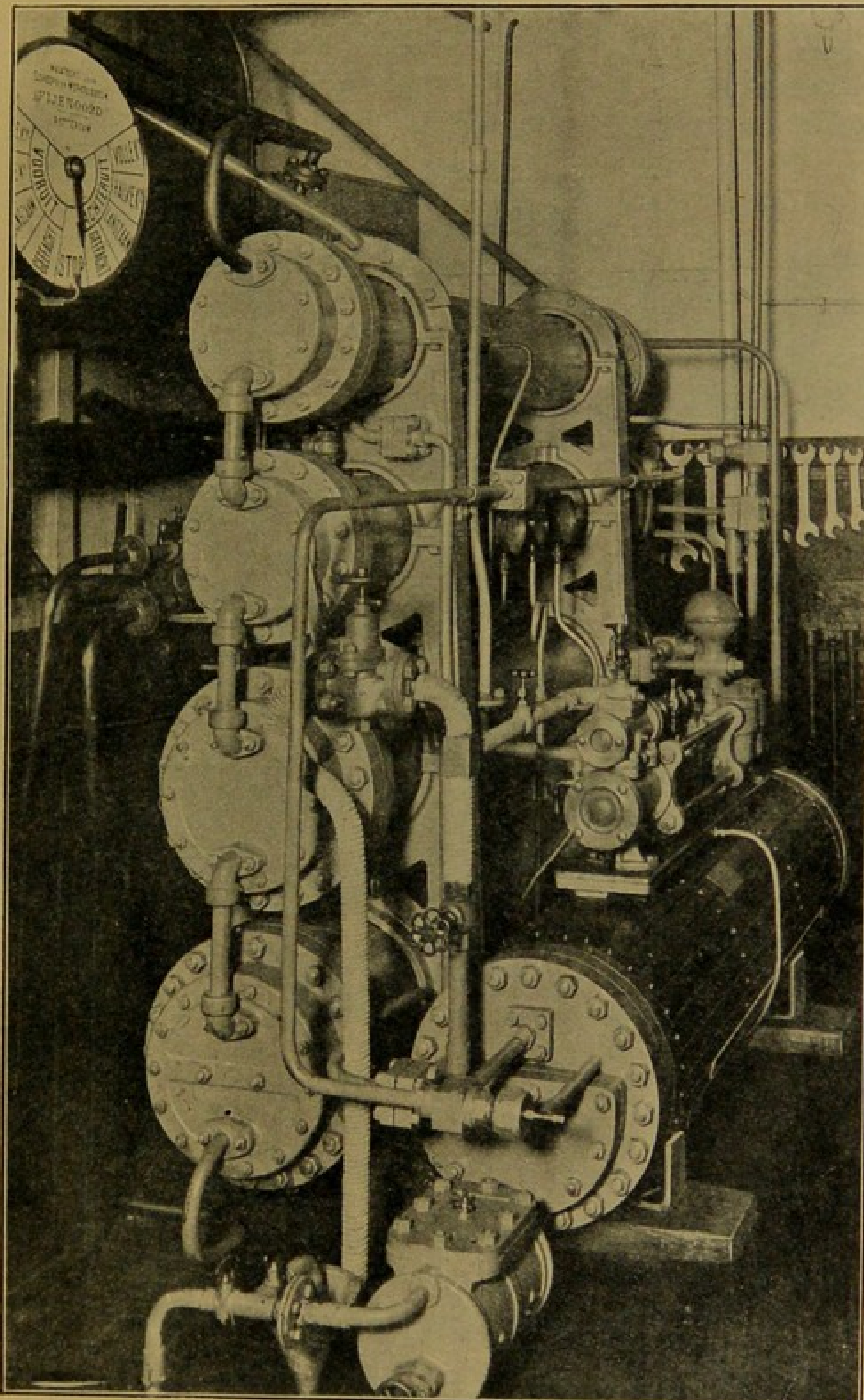


FIG. 85.

In concluding this section (marine refrigeration), it must be pointed out that the machines are used on the

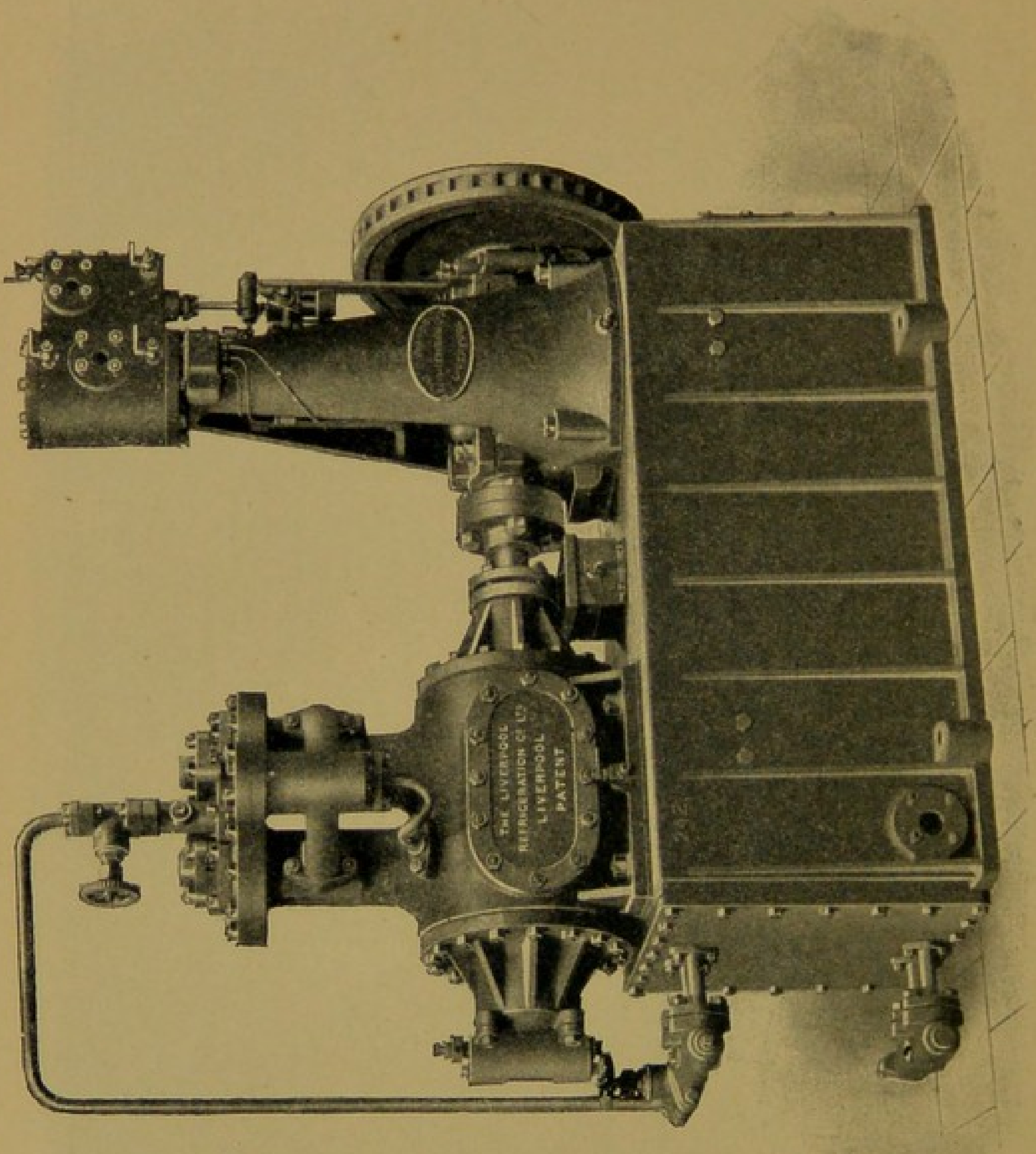


Fig. 86.

smallest trawlers and steam yachts, up to the largest Atlantic liners.

Fig. 86 is a combined vertical steam engine and ammonia compressor by the Liverpool Refrigeration Co., for use on a trawler, the ammonia condenser being placed in the box bed; the over-all dimensions are only 7 ft. long × 6 ft. 7 in. high × 3 ft. wide.

Motive Power for Refrigerating Machines.—The student will have gathered that *any* motive power may be employed for driving refrigerating machines. Steam, however, is most generally adopted, and many illustrations have been given of machines so driven.

In Messrs. Ruddins' Central Cold Stores (erected some ten years ago) two gas engines and one electro motor are used for driving the compressors by means of belts; a noteworthy feature of the plant being that no loose pulleys are fitted. When a compressor is to be started, a bye-pass is opened, connecting one end of the compressor to the other end; the gas-engine (or motor) can then be easily started, no load, or very little, being imposed on it at the outset. When the engine is fairly under weigh, the discharge, and then the suction-valves are opened, and the bye-pass closed, the compressor being now in full working order.

Electric power has much to recommend it. In the winter, when the greatest number of units are required by the ordinary consumer, the refrigerating machine requires but little, and could easily be stopped during the hours of greatest demand. In summer the call for electricity is small in most districts—refrigeration then requires the most. In a small town, then, an improved day-load could be established by running a refrigerating plant in conjunction with an electric generating station.

Local circumstances, however, will always determine the motive power to be employed for all types of machines, and it is interesting at this point to refer back to the case—even on board ship—where, in the *Lusitania* and *Mauretania*, the ship's provision machines are steam driven, while the cargo machines are electrically driven.

Care of Refrigerating Machinery.—The proper care of refrigerating machinery can, of course, only follow ripe, practical experience.

The "essential points" alone are very numerous, but a few must be enumerated.

Clean Surfaces.—The temperature differences being at all times small, it is of the utmost importance that the surfaces should be kept in a high state of efficiency.

Sediment and slime must be cleaned from the exterior of the condenser, while the interior of the tubes must be (in a compression machine) kept clear of oil or other sealing material used in the compressor. The exterior should be coated regularly with a high-class paint to preserve the surface.

In like manner the coils of the evaporator require attention from time to time; the interior of the tubes may accumulate the sealing material of the compressor that has passed through the condenser.

Brine.—The brine in a cold air evaporator or refrigerator should be changed from time to time, as it is apt to become very foul from the material blown into it by the fan.

The brine, if used in a closed circuit, may generate gases, which, if unrelieved in the circuit, may cause trouble by "air" pockets, therefore a vent is desirable. After the machine has been working a few months, little or no trouble should be experienced from this cause.

Air in Machine.—After overhauling a portion of the plant (say the compressor), where the refrigerant generally circulates, a vacuum must be pumped before opening up the connections to the refrigerant again. Air and foreign gases lead to uncertain working, and the pressure in the condenser should always be compared to the temperatures of the condensing water, the cause of an abnormal increase being removed.

Clearance in Compressor.—The clearance in a compressor should always be as small as possible, while the packing rings and rod packing must be kept in a high state of efficiency. Inefficiency in the compressor is more common than generally supposed; leaks through the stuffing-box and from one side of the piston to the other are particularly costly.

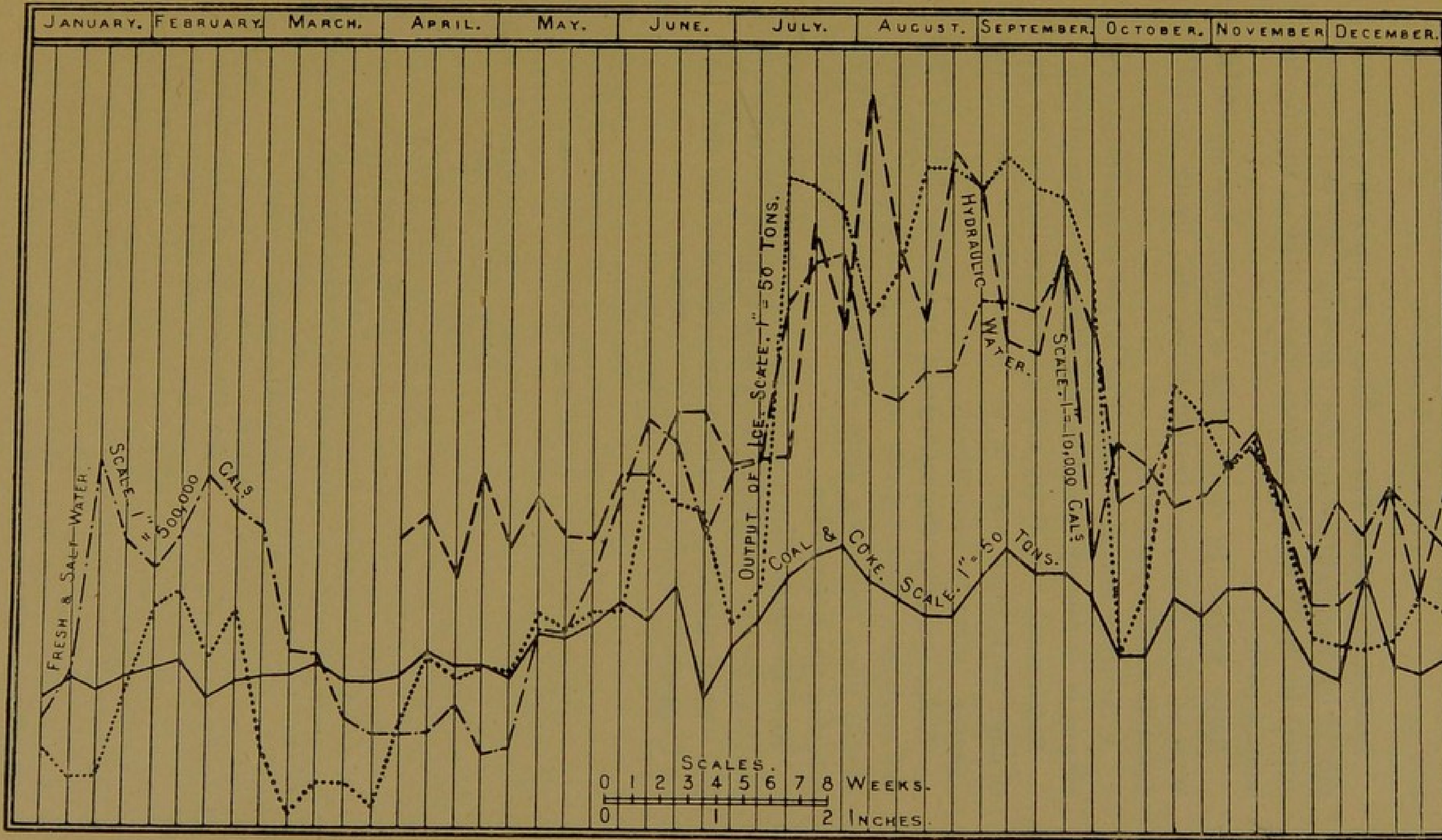

January.
February.
March.
April.
May.
June.
July.
August.
September.
October.
November
December.
Fresh & Salt Water.
Scale. 1" = 500,000 Gals.
Output of Ice. Scale. 1" = 50 Tons.
Hydraulic Water.
Scale. 1" = 10,000 Gals.
Coal & Coke. Scale. 1" = 50 Tons.
Scales.
0 1 2 3 4 5 6 7 8 Weeks.
0 1 2 Inches.

Fig. 87.

Insulation of Cold Pipes.—The cold pipes of a machine should be thoroughly insulated ; an appalling waste is permitted in many machines from the neglect of this fundamental point.

Daily Work.—In daily work a proper log should be kept, all the pressures, temperatures, etc., being carefully noted at regular intervals.

A monthly graphical log (Fig. 87) of consumptions and output is extremely useful for the purposes of comparison.

Refrigerant.—A cheap and inferior quality of the particular refrigerant used is to be avoided. The proper "charge" must be maintained.

When stopping, the refrigerant should be pumped into the condenser, keeping the evaporator as free as possible, so that when restarting there will be little chance of liquid entering the compressor.

New Machines.—In new machines scale in the pipes and connections are common. It is wise to place a "cage" on the suction near the compressor, in order that the scale may be trapped.

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FIRMS WHO HAVE SUPPLIED DRAWINGS, DATA, ETC., WITH REFERENCES TO THE TEXT.

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