apparatus just described. The emulsion vessel in the copper is surrounded by warm water, and the copper itself is jacketed and connected with the hot water pipes, so forming part of the circulating system.

Fig. 7 is a general view of the coating machine recently invented by Mr. Cadett, of the Greville Works, Ashtead, Surrey. The plates warmed in the light room, as already described, are delivered near the end of the coating table, where they are picked off a gridiron-like platform, represented on the right hand side of the cut, and are placed by an assistant one by one upon the parallel gauges shown at the beginning of

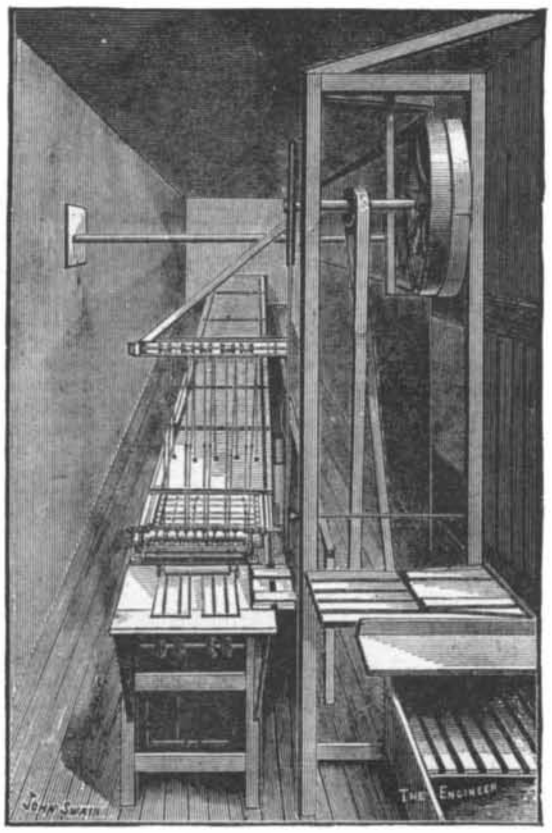


FIG. 7.—GENERAL VIEW OF COATING MACHINE.

the machine proper; they are then carried on endless cords under the coating trough described farther on. After they have been coated they are carried onward upon a series of four broad endless bands of absorbent cotton—Turkish toweling answers well—and this cotton is kept constantly soaked with cold water, which flows over sheets of accurately leveled plate glass below and in contact with the toweling; the backs of the plates being thus kept in contact with fresh cold water, the emulsion upon them is soon cooled down and is firmly set by the time the plates have reached the end of the series of four wet tables. They are then received upon one over which dry toweling travels, which absorbs most of the moisture which may be clinging to the backs of the plates; very little wet comes off the backs, so that during a day's work it is not necessary to adopt special means to redry this last endless band. What are technically known as "whole plates," which are 8½ in. by 6½ in., are placed touching each other end to end as they enter the machine, and they travel through it at the rate of 720 per hour; smaller sizes are coated in proportion, the smaller the plates the larger is the number coated in a given time. The smaller plates pass through the machine in two parallel rows, instead of in a single row, so that quarter plates, 4¼ in. by 3¼ in., are delivered at the end of the machine at the rate of 2,800 per hour, keeping two attendants well employed in picking them up and placing them in racks as quickly as they can do the work. The double row of cords for carrying two lines of small plates through the machine is represented in the engraving. Although the plates touch each other at their edges on entering the machine, they are separated from each other by short intervals after being coated; this is effected by differential gearing. The water flowing over the tables for cooling the plates is caught in receptacles below and carried away by pipes. Between each of the tables is a little roller to enable small plates to travel without tilting over the necessary gap between each pair of bands.

The feeding trough of Cadett's machine is represented in Fig. 8. The plates, cleaned as already described, are carried upon the cords under a brass roller, the weight of which causes sufficient friction to keep the plates from tilting; they next pass under a soft camel's hair brush to remove anything in the shape of dust or grit, and are then coated. They afterward pass over a series of accurately leveled wheels running in a

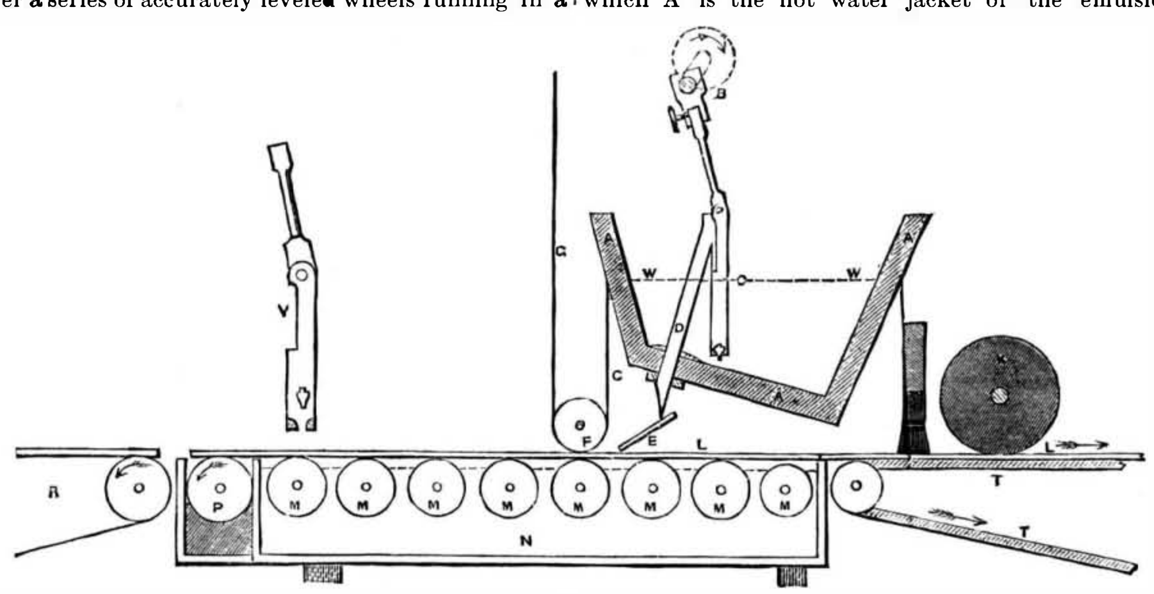


FIG. 9.

tank of water kept exact by an automatic regulator at a temperature of from 80 deg. Fah. to 100 deg. Fah., by means of a small hot water circulating system. The emulsion trough is jacketed with hot water at a constant temperature. This trough is silver plated inside, because most metals in common use would spoil the emulsion by chemical action. The trough is 16 in. long; it somewhat tapers toward the bottom, and contains a series of silver pumps shown in the cut; the whole of this series of pumps is connected with one long adjustable crank when plates of the largest size have to be coated; when coating plates of smaller sizes some of the pumps are detached. A chief object of the machine is to deliver a carefully measured quantity of

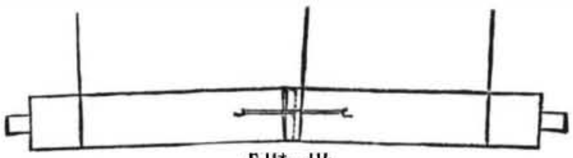


FIG. 10.

emulsion upon each plate, and this is done by means of pumps, in order that the quantity of emulsion delivered shall not be affected by changes in the level of the emulsion in the trough; the quantity delivered is thus independent of variations due to gravity or to the speed of the machine. These pumps draw the emulsion from a sufficient depth in the trough to avoid danger from the presence of air bubbles, and the bottom of the trough is so shaped that should by chance any sedimentary matter be present, it has a tendency to travel downward, away from the bottoms of the pumps. There is a steady flow of emulsion from the pumps to the delivery pipes, then it passes down a guide plate of the exact width of the plate to be coated. Immediately in front of the guide plate is a fixed silver cylinder, kept out of contact with the plate by the thickness of a piece of fine and very hard hempen cord, which can be renewed from time to time. These cords keep the cylinder from scraping the emulsion off the plate, and they help to distribute it in an even layer. There would be two lines upon each plate where it is touched by the cords, were not the emulsion so fluid as to flow over the cut-like lines made and close them up.

The silver cylinder to a certain extent overcomes the effects of irregularities in the glass plates, for the cylinder is jointed somewhat in the cup and ball fashion, and is made in two or more parts, which parts are held together by lengths of India rubber.

The arrangement is shown in section in Fig. 9 in which A is the hot water jacket of the emulsion vessel; B, the crank driving the pumps; C, a pump with piston in position; D, delivery tube of the pump; E, the silver guide plate to conduct the emulsion down to the glass; F, the spreading cylinder; G, the cords regulating the distance of the cylinder from the glass plates; H, soft camel's hair brush; K, friction roller; L L L, three plates passing under the emulsion tank; M, knife edged wheels in the hot water tank, N; the "plucking roller," P, has a hot water tank of its own, and travels at slightly greater speed than the other rollers; R is the beginning of the cooling bands; T, the driving cords; and W, a level of the emulsion in the trough. Y represents one of the bucket pistons of the pumps, detached. The construction of the crank itself is such that, by adjustment of the connecting rods, more or less emulsion may be put upon the plates. Mr. Cowan, however, intends to adjust the pumps once for all, and to regulate the amount of emulsion delivered upon the plates by means of driving wheels of different diameters upon the cranks.

Fig. 10 is a section of the hollow spreading cylinder, made of sheet silver as thin as paper, so that its weight is light. For coating large plates it is divided in the center, so as to adapt itself somewhat to irregularities in the surface of each plate. In this case it is supported by a third and central thread, as represented in the cut. Otherwise the cylinder would touch the center of the plate. Its two halves are held together by a slip of India rubber.—*The Engineer.*

THE USE OF AMMONIA AS A REFRIGERATING AGENT.*

By Mr. T. B. LIGHTFOOT, M.I.C.E.

WITHIN the last few years considerable progress has been made in the application of refrigerating processes to industrial purposes, and the demand for refrigerating apparatus thus created has led to the production of machines employing various substances as the refrigerating agent. In a paper read by the author before the Institution of Mechanical Engineers, in May, 1886, these systems were shortly described, and general comparisons given as to their respective merits, scope of application, and cost of working. In the present paper it is proposed to deal entirely with the use of ammonia as a refrigerating agent, and to deal with it in a more full and comprehensive manner than was possible in a paper devoted to the consideration of a number of different systems and apparatus. In the United States and in Germany, as well as to some extent elsewhere, ammonia has been very generally employed for refrigerating purposes during the last ten years or so. In this country, however, its application has been extremely limited; and even at the present time there are but few ammonia machines successfully at work in Great Britain. No doubt this is, to a large extent, due to the fact that in the United States and in Germany there existed certain stimulating causes, both as regards climate and manufactures, while in this country, on the other hand, these causes were present only in a modified degree, or were absent altogether. The consequence was that up to a comparatively recent date the only machine manufactured on anything like a commercial scale was the original Harrison's ether machine, first produced by Siebe, about the year 1857—a machine which, though answering its purpose as a refrigerator, was both costly to make and costly to work. In 1878 the desirability of supplementing our then existing meat supply by means of the large stocks in our colonies and abroad led to the rapid development of the special class of refrigerating apparatus commonly known as the dry air refrigerator, which, in the first instance, was specially designed for use on board ship, where it was considered undesirable to employ chemical refrigerants. Owing to their simplicity, and perhaps also to their novelty, these cold air machines have very frequently been applied on land, under circumstances in which the same result could have been obtained with much greater

* Paper lately read before the Civil and Mechanical Engineers' Society.

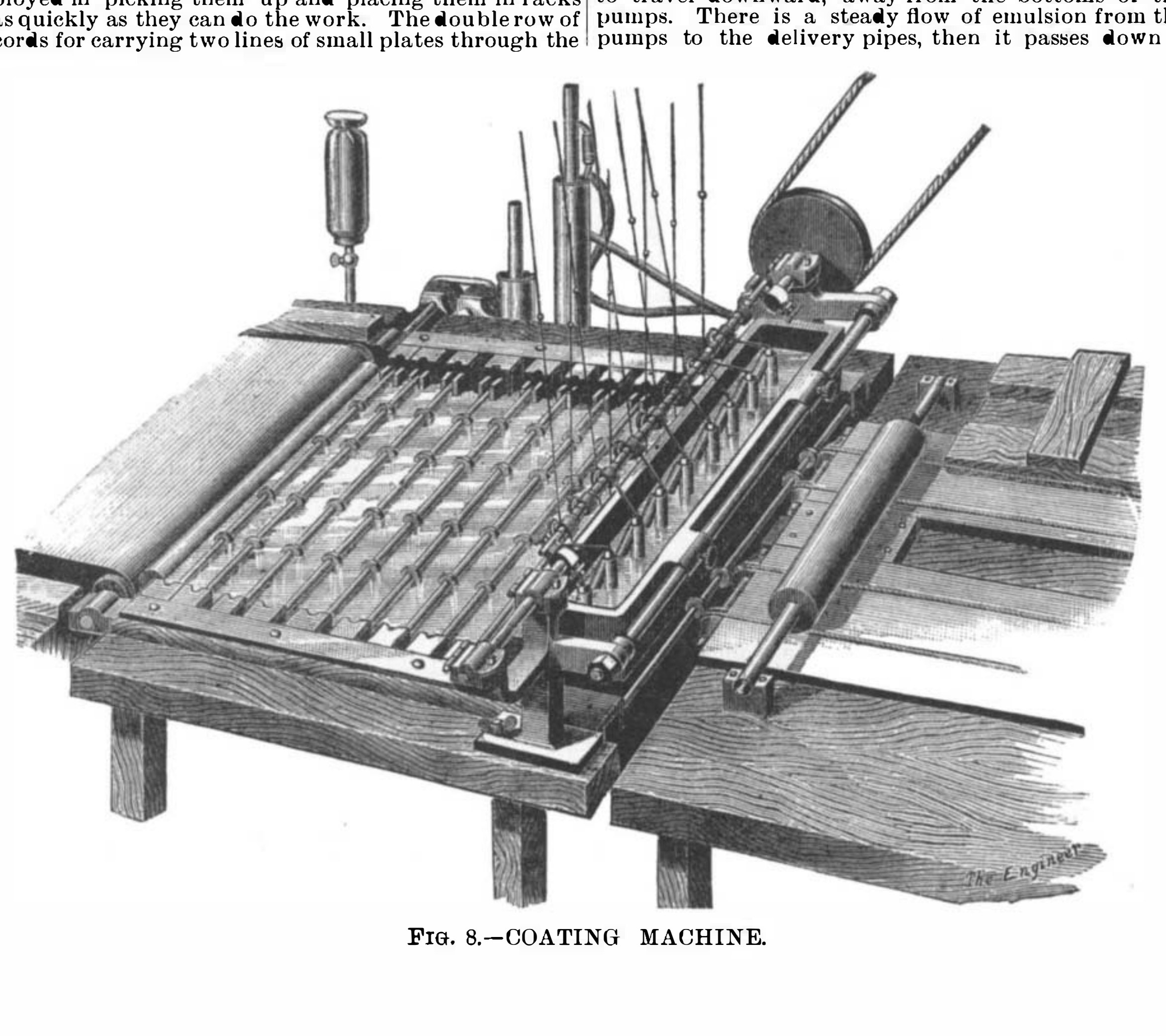


FIG. 8.—COATING MACHINE.

economy by the use of ammonia or some other chemical agent. Recently, however more attention has been directed to the question of economy, and consideration is now being given to the applicability of certain machines to certain special purposes, with the result that ammonia—which is the agent that, in our present state of knowledge, gives as a rule the best results for large installations, while on land at any rate its application for all refrigerating purposes presents no unusual difficulties—promises to become largely adopted. It is hoped, therefore, that the following paper respecting its use will be of interest.

In all cases where a liquid is employed, the refrigerating action is produced by the change in physical state from the liquid to the vaporous form. It is, of course, well known that such a change can only be brought about by the acquirement of heat; and for the purpose of refrigeration (by which must be understood the abstraction of heat at temperatures below the normal) it is obvious that, other things being equal, that liquid is the best which has the highest heat of vaporization, because with it the least quantity has to be dealt with in order to produce a given result. In fact, however, liquids vary, not only in the amount of heat required to vaporize them (this amount also varying according to the temperature or pressure at which vaporization occurs), but also in the conditions under which such change can be effected. For instance, water has an extremely high latent heat, but as its boiling point at atmospheric pressure is also high, evaporation at such temperatures as would enable it to be used for refrigerating purposes can only be effected under an almost perfect vacuum. The boiling point of anhydrous ammonia, on the other hand, is 37½° below zero F. at atmospheric pressure, and therefore for all ordinary cooling purposes its evaporation can take place at pressures considerably above that of our atmosphere. Some other agents used for refrigerating purposes are methylic ether, Pictet's liquid, sulphur dioxide, and ether. In this connection it should be stated that Pictet's liquid is a compound of carbon dioxide and sulphur dioxide, and is said to possess the property of having vapor tensions not only much below those of pure carbon dioxide at equal temperatures, but even below those of pure sulphur dioxide at temperatures above 78° F. The considerations, therefore, which chiefly influence the selection of a liquid refrigerating agent are:

1. The amount of heat required to effect the change from the liquid to the vaporous state, commonly called the latent heat of vaporization.

2. The temperatures and pressures at which such change can be effected.

This latter attribute is of twofold importance; for, in order to avoid the renewal of the agent, it is necessary to deprive it of the heat acquired during vaporization, under such conditions as will cause it to assume the liquid form, and thus become again available for refrigeration. As this rejection of heat can only take place if the temperature of the vapor is somewhat above that of the cooling body which receives the heat, and which, for obvious reasons, is in all cases water, the liquefying pressure at the temperature of the cooling water, and the facility with which this pressure can be reached and maintained, is of great importance in the practical working of any refrigerating apparatus. Ammonia in its anhydrous form, the use of which is specially dealt with in this paper, is a liquid having at atmospheric pressure a latent heat of vaporization of 900, and a boiling point at the same pressure of 37½° below zero F. Water being unity, the specific gravity of the liquid at a temperature of 40° F. is 0·76, and the specific gravity of its vapor is 0·59, air being unity. In the use of ammonia, two distinct systems are employed. So far, however, as the mere evaporating or refrigerating part of the process is concerned, it is the same in both. The object is to evaporate the liquid anhydrous ammonia at such tension and in such quantity as will produce the required cooling effect. The actual tension under which this evaporation should be effected in any particular case depends entirely upon the temperature at which the acquirement of heat is to take place, or, in other words, on the temperature of the material to be cooled. The higher the temperature, the higher may be the evaporating pressure, and therefore the higher is the density of the vapor, the greater the weight of liquid evaporated in a given time, and the greater the amount of heat abstracted. On the other hand, it must be remembered that, as in the case of water, the lower the temperature of the evaporating liquid, the higher is the heat of vaporization. It is in the method of securing the rejection of heat during condensation of the vapor that the two systems diverge, and it will be convenient to consider each of these separately.

The Absorption Process.—The principle employed in this process is physical rather than mechanical. Ordinary ammonia liquor of commerce of 0·880 specific gravity, which contains about 38 per cent. by weight of pure ammonia and 62 per cent. of water, is introduced into a vessel named the generator. This vessel is heated by means of steam circulating through coils of iron piping, and a mixed vapor of ammonia and water is driven off. This mixed vapor is then passed into a second vessel, in order to be subjected to the cooling action of water. And here, owing to the difference between the boiling points of water and ammonia, fractional condensation takes place, the bulk of the water, which condenses first, being caught and run back to the generator, while the ammonia in a nearly anhydrous state is condensed and collected in the lower part of the vessel.

This process of fractional condensation is due to Rees Reece, and forms an important feature in the modern absorption machine. Prior to the introduction of this invention, the water evaporated in the generator was condensed with the ammonia, and interfered very seriously with the efficiency of the process by reducing the power of the refrigerating agent by raising its boiling point. In the improved form of apparatus, ammonia is obtained in a nearly anhydrous condition, and in this state passes on to the refrigerator. In this vessel, which is in communication with another vessel called the absorber, containing cold water or very weak ammonia liquor, evaporation takes place, owing to the readiness with which cold water or weak liquor absorbs the ammonia, water at 59° Fahr. absorbing 727 times its volume of ammonia vapor. The heat necessary to effect this vaporization is abstracted from brine or other liquid, which is circulated through the refrigerator by means of a pump. Owing to the absorption of ammonia, the weak liquor in the absorber becomes strengthened, and it is then pumped back into the generating vessel to be again dealt with as above described.

The absorption apparatus, as applied for cooling purposes, consists of a generator, which is a vessel of cast iron containing coils of iron piping to which steam at any convenient pressure is supplied; an analyzer, in which a portion of the water vapor is condensed, and from which it flows back immediately into the generator; a rectifier and condenser, in the upper portion of which a further condensation of water vapor and a little ammonia takes place, the liquid thus formed passing back by a pipe to the analyzer and thence to the generator, while in the lower portion the ammonia vapor is condensed and collected; and a refrigerator or cooler, into which the nearly anhydrous liquid obtained in the condenser is admitted by a pipe and regulating valve, and allowed to evaporate, the upper portion being in communication with the absorber.

Through this vessel weak liquor, which has been deprived of its ammonia in the generator, is continually circulated, after being first cooled in an economizer by an opposite current of strong cold liquor passing from the absorber to the generator, while, in addition, the liquor in the absorber, which would become heated by the liberation of heat due to the absorption and consequent liquefaction of the ammonia vapor, is still further cooled by the circulation of cold water. As the pressure in the absorber is much lower than that in the generator, the strong liquor has to be pumped into the latter vessel, and for this purpose pumps are provided. Though of necessity the various operations have been described separately, the process is a continuous one, strong liquor from the absorber being constantly pumped into the generator through the heater or economizer, while nearly anhydrous liquid ammonia is being continually formed in the condenser, then evaporated in the refrigerator and absorbed by the cool weak liquor passing through the absorber.

Putting aside the effect of losses from radiation, etc., all the heat expended in the generator will be taken up by the water passing through the condenser, less that portion due to the condensation of the water vapor in the analyzer, and plus the amount due to the difference between the temperature of the liquid as it enters the generator and the temperature at which it leaves the condenser. In the refrigerator the liquid ammonia, in becoming vaporized, will take up the precise quantity of heat that was given off during its cooling and liquefaction in the condenser, plus the amount due to the difference in heat of vaporization, owing to the lower pressure at which the change of state takes place in the refrigerator, and less the small amount due to the difference in temperature between the vapor entering the condenser and that leaving the refrigerator, less also the amount necessary to cool the liquid ammonia to the refrigerator temperature. When the vapor enters into solution with the weak liquor in the absorber, the heat taken up in the refrigerator is imparted to the cooling water, subject also to corrections for differences of pressure and temperature. The sources of loss in such an apparatus are:

a. Radiation and conduction of heat from all vessels and pipes above normal temperature, which can, to a large extent, be prevented by lagging.

b. Conduction of heat from without into all vessels and pipes that are below normal temperature, which can also to a large extent be prevented by lagging.

c. Inefficiency of economizer, by reason of which heat obtained by the expenditure of steam in the generator is passed on to the absorber and there uselessly imparted to the cooling water.

d. The entrance of water into the refrigerator, due to the liquid being not perfectly anhydrous.

e. The useless evaporation of water in the generator.

With regard to the amount of heat used, it will have been seen that the whole of that required to vaporize the ammonia, and whatever water vapor passes off from the generator, has to be supplied from without. Owing to the fact that the heating takes place by means of coils, the steam passed through may be condensed, and thus each pound can be made to give up some 950 units of heat. With the absorption process worked by an efficient boiler, it may be taken that 200,000 thermal units per hour may be eliminated by the consumption of about 100 lb. of coal per hour, with a brine temperature in the refrigerator of about 20° Fahr.

Compression Process.—In this process ammonia is used in its anhydrous form. So far as the action of the refrigerator is concerned, it is precisely the same as it is in the case of the absorption apparatus, but instead of the vapor being liquefied by absorption by water, it is drawn from the refrigerator by a pump, by means of which it is compressed and delivered into the condenser at such pressure as to cause its liquefaction at the temperature of the cooling water. It must be borne in mind, however, that allowance must be made for the rise of temperature of the water passing through the condenser, and also for the difference in temperature necessary in order to permit the transfer of heat from one side of the cooling surface to the other. In a compression machine the work applied to the pump may be accounted for as follows:

a. Friction.

b. Heat rejected during compression and discharge.

c. Heat acquired by the ammonia in passing through the pump.

d. Work expended in discharging the compressed vapor from the pump.

But against this must be set the useful mechanical work performed by the vapor entering the pump. The heat rejected in the condenser is the heat of vaporization taken up in the refrigerator, less the amount due to the higher pressure at which the change in physical state occurs, plus the heat acquired in the pump, and less the amount due to the difference between the temperature at which the vapor is liquefied in the condenser and that at which it entered the pump. An ammonia compression machine, as applied to ice making, contains ice-making tanks, in which is circulated a brine mixture, uncongealable at any temperature likely to be reached during the process. This brine also circulates around coils of wrought iron pipes, in which the liquid ammonia passing from the condenser is vaporized, the heat required for this vaporization being obtained from the brine. A pump draws off the ammonia vapor from the refrigerator coils, and compresses it into the condenser, where, by means of the combined action of pressure and cooling by water, it assumes a liquid form, and is ready to be again passed on to the refrigerator for evaporation. The ammonia compression process is more economical than the absorption process, and with a good boiler and engine about 240,000 thermal units per hour can be eliminated by the expenditure of 100 lb. of coal per hour, with a brine temperature in the refrigerator of about 20° Fahr.

GENERAL CONSIDERATIONS.

From what has been said, it will have been seen that, so far as the mere application is concerned, there is no difference whatever between the absorption and compression processes. The following considerations, therefore, which chiefly relate to the application of refrigerating apparatus, will be dealt with quite independent of either system. The application of refrigerating apparatus may roughly be divided into the following heads:

a. Ice making.
b. The cooling of liquids.
c. The cooling of stores and rooms.

Ice Making.—For this purpose two methods are employed, known as the can and cell systems respectively. In the former, moulds of tinned sheet copper or galvanized steel of the desired size are filled with the water to be frozen, and suspended in a tank through which brine cooled to a low temperature in the refrigerator is circulated. As soon as the water is completely frozen, the moulds are removed, and dipped for a long time into warm water, which loosens the blocks of ice and enables them to be turned out. The thickness of the blocks exercises an important influence upon the number of moulds required for a given output, as a block 9 in. thick will take four or five times as long to freeze solid as one of only 3 in. In the cell system a series of cellular walls of wrought or cast iron are placed in a tank, the distance between each pair of walls being from 12 to 16 in., according to the thickness of the block required. This space is filled with the water to be frozen. Cold brine circulates through the cells, and the ice forms on the outer surfaces, gradually increasing in thickness until the two opposite layers meet and join together. If thinner blocks are required, the freezing process may be stopped at any time and the ice removed. In order to detach the ice it is customary to cut off the supply of cold brine and circulate brine at a higher temperature through the cells. Ice frozen by either of the above described methods from ordinary water is more or less opaque, owing to the air liberated during the freezing process, little bubbles of which are caught in the ice as it forms, and in order to produce transparent ice it is necessary that the water should be agitated during the freezing process in such a way as to permit the air bubbles to escape. With the can system this is generally accomplished by means of arms having a vertical or horizontal movement. These arms are either withdrawn as the ice forms, leaving the block solid, or they are made to work backward and forward in the center of the moulds, dividing the block vertically into two pieces. With the cell system agitation is generally effected by making a communication between the bottom of each water space and a chamber below, in which a paddle or wood piston is caused to reciprocate. The movement thus given to the water in the chamber is communicated to that in the process of being frozen, and the small bubbles of air are in this way detached and set free. The ice which first forms on the sides of the moulds or cells is, as a rule, sufficiently transparent even without agitation. The opacity increases toward the center, where the opposing layers join, and it is, therefore, more necessary to agitate toward the end of the freezing process than at the commencement. As the capacity for holding air in solution decreases if the temperature of the water is raised, less agitation is needed in hot than in temperate climates. Experiments have been made from time to time with the view of producing transparent ice from distilled water, and so dispensing with agitation. In this case the cost of distilling the water will have to be added to the ordinary working expenses.

Cooling of Liquids.—In breweries, distilleries, butter factories, and other places where it is desired to have a supply of water or brine for cooling and other purposes at a comparatively low temperature, refrigerating machines may be advantageously applied. In this case the liquid is passed through the refrigerator and then utilized in any convenient manner.

Cooling of Rooms.—For this purpose the usual plan is to employ a circulation of cold brine through rows of iron piping, placed either on the ceiling or on the walls of the rooms to be cooled. In this, as in the other cases where brine is used, it is employed merely as a medium for taking up heat at one place and transferring it to the ammonia in the refrigerator, the ammonia in turn completing the operation by giving up the heat to the cooling water during liquefaction in the condenser. The brine pipes cool the adjacent air, which, in consequence of its greater specific gravity, descends, being replaced by warmer air, which in turn becomes cold, and so the process goes on. Assuming the air to be sufficiently saturated, which is generally the case, some of the moisture in it is condensed and frozen on the surface of the pipes; and if the air is renewed in whole or in part from the outside, or if the contents of the chamber are wet, the deposit of ice in the pipes will in time become so thick as to necessitate its being thawed off. This is accomplished by turning a current of warm brine through the pipes. Another method has been proposed, in which the brine pipes are placed in a separate compartment, air being circulated through this compartment to the rooms, and back again to the cooling pipes in a closed cycle by means of a fan. This plan was tried on a large scale by Mr. Chambers at the Victoria Docks, but for some reason or other was abandoned. One difficulty is the collection of ice from the moisture deposited from the air, which clogs up the spaces between the pipes, besides diminishing their cooling power. This, in some cases, can be partially obviated by using the same air over again, but in most instances special means would have to be provided for frequent thawing off, the pipes having, on account of economy of space and convenience, to be placed so close together, and to be so confined in surface, that they are much more liable to have their action interfered with than when placed on the roof or walls of the room.

In addition to the foregoing there are, of course, many other applications of ammonia refrigerating machines of a more or less special nature, of which time will not permit even a passing reference. Many of these are embraced in the second class, cold water or brine being used for the cooling of candles, the separation of paraffin, the crystallization of salts, and for many other purposes. In the same way cold brine has been used with great success for freezing quicksand in the sinking of shafts, the excavation being carried out and the watertight tubing or lining put in while the material is in a solid state. In a paper such as this it would be quite impracticable to enter into details of construction, and the author has therefore confined himself chiefly to principles of working. In conclusion, however, it may be added that in ammonia machines, whether on the absorption or compression systems, no copper or alloy of copper can be used in parts subjected to the action of the ammonia. Cast or wrought iron and steel may, however, be used, provided the quality is good, but special care must be taken in the construction of those parts of absorption machines which are subjected to a high temperature. In both classes of apparatus first-class materials and workmanship are most absolute essentials.

[Continued from SUPPLEMENT, No. 646, p. 10319.]

ELEMENTS OF ARCHITECTURAL DESIGN.*

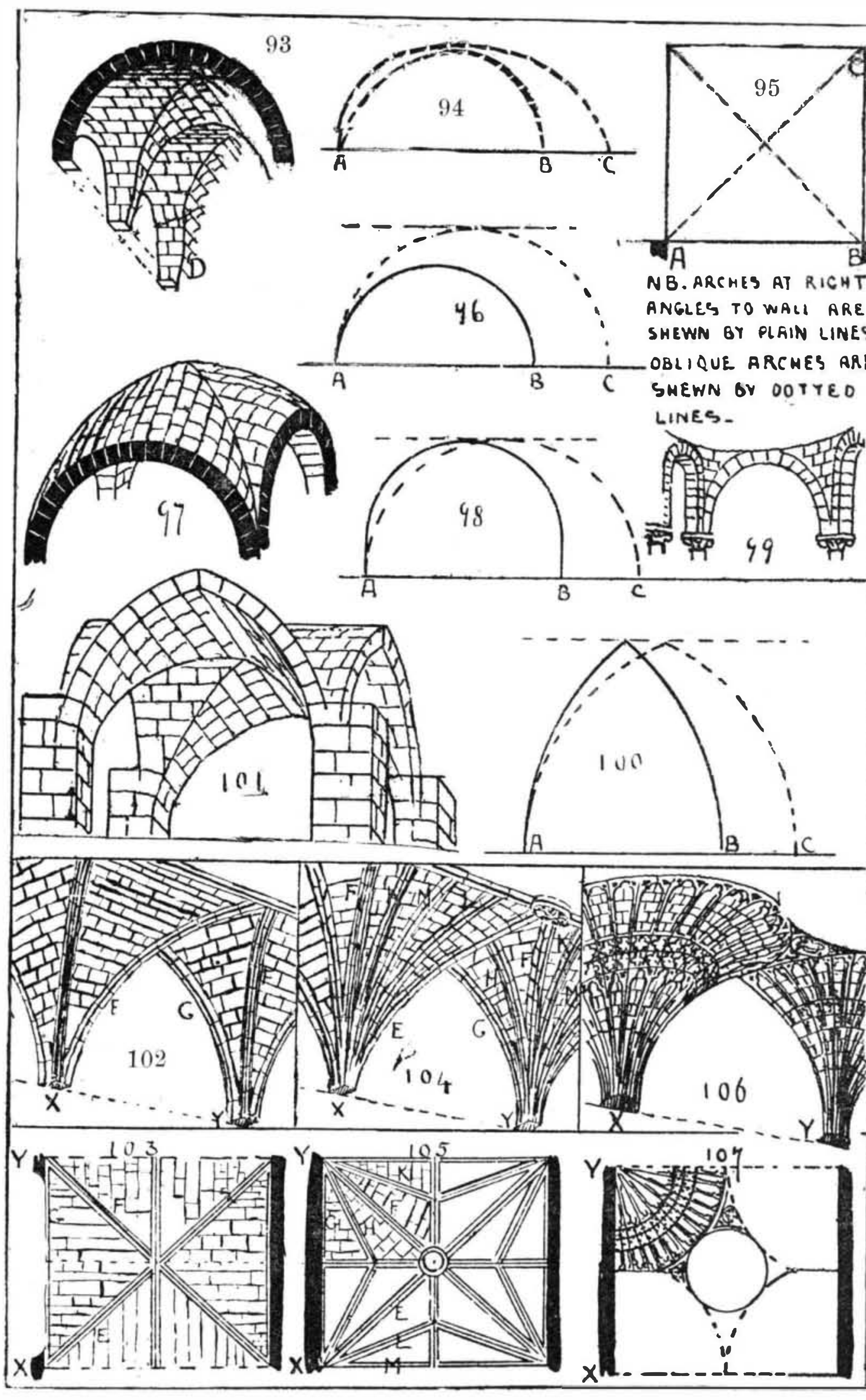
By H. H. STATHAM.

III.—CONTINUED.

THE Romans, in their arched constructions, habitually strengthened the point against which the vault thrust by adding columnar features to the walls, as shown in Fig. 108; thus again making a false use of the column in a way in which it was never contemplated by those who originally developed its form. In Romanesque architecture the column was no longer used for this purpose; its place was taken by a flat pilaster-like projection of the wall (plan and section, Fig. 109), which gave sufficient strength for the not very ambitious vaulted roofs of this period, where often in fact only the aisles were vaulted, and the center compartment covered with a wooden roof. At first this pilaster-like form bore a reminiscence of a classic capital as its termination; a moulded capping under the eaves of the building. Next this capping was almost insensibly dropped, and the buttress became a mere flat strip of wall. As the vaulting became bolder and more ambitious, the buttress had to be made more massive and of greater projection, to afford sufficient abutment to the vault, more especially toward the lower part, where the thrust of the roof is carried to the ground. Hence arose the tendency to increase the projection of the buttress gradually downward, and this was done by successive slopes or "set-offs," as they are termed, which assisted (whether intentionally or not in the first instance) in further aiding the correct architectural expression of the buttress. Then the vaulting of the center aisle was carried so high and treated in so bold a manner, with a progressive diminution of the wall piers (as the taste for large traceried windows developed more and more), that a flying buttress (see section, Fig. 110) was necessary to take the thrust across to the exterior buttresses, and these again, under this additional stress, were further increased in projection, and were at the same time made narrower (to allow for all the window space that was wanted between them), until the result was that the masses of wall, which in the Romanesque building were placed longitudinally and parallel to the axis of the building, have all turned about (Fig. 110, plan) and placed themselves with their edges to the building to resist the thrust of the roofing. The same amount of wall is there as in the Romanesque building, but it is arranged in quite a new manner, in order to meet the new constructive conditions of the complete Gothic building.

It will be seen thus how completely this important and characteristic feature of Gothic architecture, the buttress, is the outcome of practical conditions of construction. It is treated decoratively, but it is itself a necessary engineering expedient in the construction. The application of the same principle, and its effect upon architectural expression, may be seen in some other examples besides that of the buttress in its usual shape and position. The whole arrangement and disposition of an arched building is affected by the necessity of providing counterforts to resist the thrust of arches. The position of the central tower, for instance, in so many cathedrals and churches, at the intersection of the nave and transepts, is not only the result of a feeling for architectural effect and the centralizing of the composition, it is the position in which also the tower has the cross walls of nave and transepts abutting against it in all four directions: if the tower is to be placed over the central roof at all, it could only be over this point of the plan. In the Norman buildings, which in some respects were finer constructions than those of later Gothic, the desire to provide a firm abutment for the arches carrying the tower had a most marked effect on the architectural expression of the interior. At Tewkesbury, for instance, while the lower piers are designed in the usual way toward the north and south sides (viz., as portions of a pier of nearly square proportion standing under the angle of the tower), in the east and west direction the tower piers run out into great solid masses of wall, in order to insure a sufficient abutment for the tower arches. On the north and south sides the solid transept walls were available immediately on the other side of the low arch of the side aisle, but on the east and west sides there were only the nave and choir arcades to take the thrust of the north and south tower arches, and so the Normans took care to interpose a massive piece of wall between, in order that the thrust of the tower arches might be neutralized before it could operate against the less solid arcaded portions of the walls. This expedient, this great mass of wall introduced solely for constructive reasons, adds greatly to the grandeur of the interior architectural effect. The true constructive and architectural perception of the Normans in this treatment of the lower piers is illustrated by the curious contrast presented at Salisbury. There the tower piers are rather small, the style is later, and the massive building of the Normans had given way to a more graceful but less monumental manner of building. Still the abutment of the tower arches was probably sufficient for the weight of the tower as at first built; but when the lofty spire was put on the top of this, its vertical weight, pressing upon the tower arches and increasing their horizontal thrust, actually thrust the nave and choir arcades out of the perpendicular toward the west and east respectively, and there they are leaning at a very perceptible angle away from the center of the church—the architectural expression, in a very significant form, of the neglect of balance of mass in construction.

But while the buttress in Gothic architecture has been in process of development, what has the vault been doing? We left it (Fig. 92) in the condition of a round wagon vault, intersected by another similar vault at right angles. By that method of treatment we got rid of the continuous thrust on the walls. But there were many difficulties to be faced in the construction of vaulting after this first step had been taken, difficulties which arose chiefly from the rigid and unmanageable proportions of the circular arch, and which could not be even partially solved till the introduction of the pointed arch. The pointed arch is the other most marked and characteristic feature of Gothic architecture, and, like the buttress, it will be seen that it arose entirely out of constructive difficulties.



These difficulties were of two kinds; the first arose from the tendency of the round arch, when on a large scale and heavily weighted, to sink at the crown if there is even any very slight settlement of the abutments. If we turn again to diagram 77, and observe the nearly vertical line formed there by the joints of the keystone, and if we suppose the scale of that arch very much increased without increasing the width of each voussoir, and suppose it built in two or three rings one over the other (which is really the constructive method of a Gothic arch), we shall see that these joints in the uppermost portion of the arch must in that case become still more nearly vertical; in other words, the voussoirs almost lose the wedge shape which is necessary to keep them in their places, and a very slight movement or settlement of the abutments is sufficient to make the arch stones lose some of their grip on each other and sink more or less, leaving the arch flat at the crown. There can be no doubt that it was the observance of this partial failure of the round arch (partly owing probably to their own careless way of preparing the foundations for their piers—for the mediæval builders were very bad engineers in that respect) which induced the builders of the early transitional abbeys, such as Furness and Fountains and Kirkstall, to build the large arches of the nave pointed, though they still retain the circular-headed form for the smaller arches in the same buildings, which were not so constructively important. This is one of the constructive reasons which led to the adoption of the pointed arch in mediæval architecture, and one which is easily stated and easily understood. The other influence is one arising out of the lengthened conflict with the practical difficulties of vaulting, and is a rather more complicated matter, which we must now endeavor to follow out.

Looking at Fig. 92, it will be seen that in addition to the perspective sketch of the intersecting arches, there is drawn under it a plan, which represents the four points of the abutment of the arches (identified in plan and perspective sketch as A, B, C, D), and the lines which are taken by the various arches shown by dotted lines. Looking at the perspective sketch, it will be apparent that the intersection of the two cross vaults produces two intersecting arches, the upper line of which is shown in the perspective sketch (marked *e* and *f*); underneath, this intersection of the two arches, which forms a furrow in the upper side of the construction, forms an edge which traverses the space occupied by the plan of the vaulting as two oblique arches, running from A to C and from B to D on the plan. Although these are only lines formed by the intersection of two cross arches, still they make decided arches to the eye, and form prominent lines in the system of vaulting; and in a later period of vaulting they were treated as prominent lines and strongly emphasized by mouldings; but in the Roman and early Romanesque vaults they were simply left as edges, the eye being directed rather to the vaulting surfaces than to the edges. The importance of this distinction between the vaulting surfaces and their meeting edges or *groins** will be seen just now. The edges, nevertheless, as was observed, do form arches, and we have therefore a system of cross arches (A B and C D† Fig. 95), two wall arches (A, D and B C), and two oblique arches (A C and B D), which divide the space into four equal triangular portions; this kind of vaulting being hence called *quadripartite* vaulting. In this and the other diagrams of arches on this page, the cross arches are all shown in positive lines, and the oblique arches in dotted lines.

* Delivered before the Society of Arts, London, December 12, 1887. From the *Journal* of the Society.

* A *groin* is the edge line formed by the meeting and intersection of any two arched surfaces. When this edge line is covered and emphasized by a band of moulded stones forming an arch, as it were, on this edge, this is called a *groin rib*.

† The "D" seems to have been accidentally omitted in this diagram; it is of course the fourth angle of the plan.