COMPRESSION DISTILLATION

by

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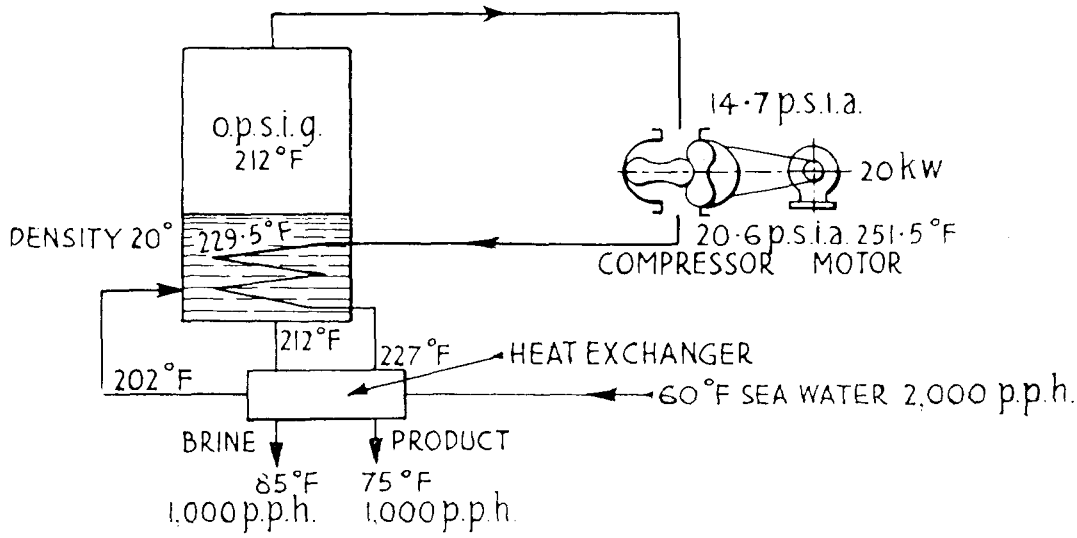

FIG. 1. DIAGRAMMATIC ARRANGEMENT OF VAPOUR COMPRESSION STILL

Now that it has become recognised that the modern sailor requires considerably more water than his forebears to keep him healthy and efficient, larger evaporating and distilling plants are being fitted in warships. The increase in capacity of these plants has brought about a considerable increase in fuel consumption and a corresponding decrease in a ship's endurance. On her recent Royal Tour, H.M.S. *Vanguard* distilled approximately 4,260 tons during the fifteen days of the outward passage ; of this amount nearly 3,400 tons was used for domestic purposes. Thus, about 470 tons of fuel were accounted for by the distilling plants alone,—at a total cost of £1,880, taking fuel at the Rate Book figure of £4 a ton.

In order to reduce this drain on the fuel stocks, attention is being given at the Admiralty, and elsewhere, to the development of more economical plants than those at present fitted. Amongst possible types is the vapour compression distilling plant.

This plant embodies no new principle ; attempts to produce such a design go back nearly a hundred years. During the 1939-45 war, the idea was revived by Dr. (then serving as Commodore) Kleinschmidt in the United States and a large number of small mobile plants were manufactured in conjunction with Messrs. E. B. Badger & Sons of Boston. Small units, originally copied from a captured German plant, have also been in operation in H.M. submarines for some time.

General Principle

This type of plant (shown diagrammatically in Fig. 1) consists essentially of an evaporator fitted with heating coils or tubes in the brine space, and a compressor. By means of the compressor, mechanical energy is transformed into heat which is added to that in the vapour drawn by it from the separation space above the brine. The heated vapour then passes to the heating coils where it gives up the greater proportion of its total heat to the brine, and is condensed. In order to retain as much heat within the system as possible, a heat exchanger is added to raise the temperature of the feed by utilising the otherwise waste heat in the brine discharge and the coil drain (or product). A small combined pump is also required for shipboard use or where the plant is operated under vacuum conditions.

To bring the evaporator into operation a period of heating by external means is necessary in order to raise the temperature of the plant and its contents to the boiling point corresponding to the operating pressure. As soon as the separation space is full of steam the compressor may be started for continuous distillation. The feed enters the brine space *via* the heat exchanger and circulates (as a rule, naturally) over the heating surface, and is further heated to its boiling point by the compressed vapour passing through the tubes or coils. The vapour which is condensed in the coils represents the product or output of the plant.

Practically the whole of the latent heat of the vapour is used in heating and evaporating the brine. No circulating water is required and the plant virtually "eats its own tail."

Effect of Scale Formation

As in the conventional evaporator, scale formation has an adverse effect on the performance of the compression type. The lower heat transfer co-efficient (k), resulting from a layer of scale, necessitates a higher temperature difference between the brine and the heating steam, if the output is to be maintained ; thus, an increase in the temperature (and, consequently, pressure) of the vapour leaving the compressor is required. This means more heat entering the system in this way and more heat leaving it in the coil drain or product, since the heat extracted by the brine is constant for a given output. Here again, scaling in the heat exchanger results in further losses due to the lower efficiency brought about by the decreased "k."

With electrically driven plant these changes in the heat balance may be compensated by adjustment of the immersion heaters which, however, are also affected by scale.

In the I.C.E.-driven plant, most of the waste heat from the exhaust and cooling water is retained in the system by pre-heating the feed. As scale is formed the engine load increases and, consequently, the available waste heat also increases and becomes surplus to requirements. Thus, the tendency is for fuel consumption to increase with scale formation whilst the output is maintained at a reasonably constant figure.

Compressors

Development of compression distilling plant is gravely hampered by the lack of suitable compressors. In spite of the enormous strides in design associated with gas turbines, no suitable equipment is yet available for this service. Axial-flow compressors are "touchy" and the presence of water, or any deposits which will inevitably form on the blades, seriously reduces efficiency. Furthermore, as high blade speeds are necessary, the relatively small quantities of vapour to be dealt with would require inordinately short blades, with proportionally higher losses due to tip clearance. Whilst the adiabatic efficiency of the compressor in electrically-driven machines is unimportant, it is essential that it be accurately known, as the design of the plant is based on this figure and any change in conditions may lead to instability, or excessive drop in output or economy. Moreover, the required rise in pressure associated with scale formation conflicts with the characteristics of both axial-flow and centrifugal compressors.

For the smaller plants displacement blowers of the Root's type are the most suitable and one of these is now running trials before being fitted to an experimental evaporator. This plant is to be of $12\frac{1}{2}$-tons/day capacity working at about 20 in. Hg vacuum. The compressor would also be suitable for a 35-tons/day plant working at atmospheric pressure.

The necessity for excluding lubricating oil from the vapour circuit entails the use of elaborate sealing arrangements and precludes the normal reciprocating compressor ; indeed, the size would, in any case, be prohibitive.

The Lysholm compressor appears to offer considerable advantages over the Root's type for the larger plants as it is capable of handling greater volumes at higher compression ratios. Troubles with differential expansion, already touched on, are, however, more likely to be present and more difficult to eradicate. A trial of a compressor of this type will take place shortly.

Centrifugal compressors are used by Messrs. Escher Wyss in their large evaporating plants (100 tons/hour) which are designed for concentrating salt solution where the scaling problem is, relatively speaking, absent. For naval purposes the number of stages necessary to produce the required degree of compression is a disadvantage as it leads to rotors of considerable length, thus increasing the risk of damage due to shock. This, also, applies to axial-flow compressors, although their rotors are usually of stouter design. The disadvantages associated with the characteristics of axial-flow and centrifugal compressors can be offset to a certain degree by increasing the speed as scale forms on the heating surfaces, although their inherent instability renders their use undesirable if displacement compressors can be found to meet the requirements of the designer.

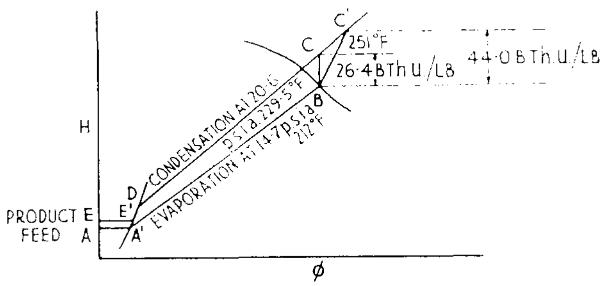

FIG. 2

Design

The cycle of operations can be shown on a Mollier diagram (Fig. 2), and the power consumption estimated from it. If the dry and saturated vapour be compressed adiabatically from 14.7 p.s.i.a., the condition after compression would be represented by the point C. However, due to the inefficiency of the compressor more heat must be added in order to reach the required delivery pressure, and the actual compression approximately follows the line BC^1.

Theoretically, the heat required to be added at the compressor in order to maintain the heat balance of the plant is equal to that rejected in the coil drain, brine, and radiation, etc., less the heat in the sea water feed.

Starting, therefore, with these losses as a basis for design and adopting certain assumptions, the size and power of the compressor can be estimated as follows :—

Assumptions :—

Output	1,000 lb./hr. (10.7 tons/day)
Evaporation pressure	14.7 p.s.i.a.
Brine density	20°
Sea temperature	60°F.

A well-designed heat exchanger should give :—

Temperature of product	70° F. at discharge
Temperature of brine	85° F. at discharge

The principal losses are then :—

Brine ...	1,000 lb./hr. $\times$ (85 − 32) B.Th.U./lb.	$=53\times10^3$ B.Th.U./hr.
Product ...	1,000 lb./hr. $\times$ (70 − 32) B.Th.U./lb.	$=38\times10^3$ B.Th.U./hr.
Radiation, non condensible gases, etc. (say)		$=9\times10^3$ B.Th.U./hr.
Total		$=100\times10^3$ B.Th.U./hr.
Less heat in feed, *i.e.*,	2,000 lb./hr. $\times$ (60 − 32) B.Th.U./lb.	$=56\times10^3$ B.Th.U./hr.
Heat required from compressor		$=44\times10^3$ B.Th.U./hr.
If the compressor has an adiabatic efficiency of 60%, adiabatic heat drop		$=44\times.60\times10^3$ B.Th.U./hr.
		$=26.4\times10^3$ B.Th.U./hr.

Reference to the Mollier diagram gives the condition of the steam after compression as 20.6 p.s.i.a. and 251.5°F. Thus, the useful temperature drop through the heating surface is 229.5°F.—212°F.=17.5°F., 229.5°F. being the saturation temperature at 20.6 p.s.i.a.

The compressor should, therefore, be capable of dealing with 1,000 pounds vapour per hour, compressing from 14.7 p.s.i.a., 212°F. to 20.6 p.s.i.a., 251.5°F.

Heating Surface

The normal single effect evaporator has been shown to be capable of running for long periods without descaling other than by blowing down, fresh-water soaking and other routine methods. (*Journal of Naval Engineering*, Vol. 1, No. 4.) It appears that after a certain period the rate of scale removal becomes equal to the rate of formation and that the heat transfer co-efficient (k) for the scaled coils at this stage is reasonably steady at about 400 B.Th.U./ft.^{2} °F. hour. It is hoped that by using this as the design figure in determining the heating surface required in the type now under consideration, the plant will settle down in a similar manner.

In order to attain as constant conditions as possible and to remove another source of scaling, the omission of the brine cooler is contemplated, the resulting loss in economy being accepted in the interests of maintenance and stability of the heat balance, upon which the successful operation of the plant depends. This, of course, would normally necessitate a greatly increased heating surface and in order to keep the size down, and to avoid excessive use of heaters, it would be desirable to work with higher compression ratios—say 3 to 1.

Economy

In the above quoted example for an evaporator of 1,000 lb./hr. output, the theoretical power input to the compressor is given by 44×10^3 B.Th.U/hr. ÷ 3,420 B.Th.U./kW.hr. and equals 12.9 kW. Allowing an overall mechanical and electrical efficiency for the drive of 65%, this represents an input of approximately 20 kW. If this power is derived from a Diesel generator using .5 lb. fuel per kW. hour, 100 pounds of water could, therefore, be produced for the expenditure of one pound of fuel—compared with about 9 lb. per lb. of fuel in the normal single-effect evaporator. *Pro rata*, a 50 tons/day plant would require some 90 kW.

Dr. Kleinschmidt has claimed—for a 1,000 gallon per day plant—175 lb. of product for each lb. of fuel consumed. This plant, however, has a Diesel-driven compressor and the waste heat from exhaust, cooling water, etc., is used in the evaporator, thus reducing the work required of the compressor.

PRACTICAL CONSIDERATIONS

The various factors affecting the design of plants at present under contemplation for shipboard use have been placed in the following order of priority :—

Reliability.
Ease of maintenance.
Simplicity of operation.
Economy.
Weight and space.

Purity of the product has been omitted as this is largely a matter of size, baffling arrangements and stability of operation.

Reliability

The reliability of the plant is, virtually, the reliability of the compressor, as the other components are proven in this respect. Because of their practically fixed compression ratios, the ideal type for use in vapour compression evaporators is the displacement type, amongst which are included the Root's and Lysholm blowers. Possible alternatives are axial-flow and centrifugal compressors. So far as reliability is concerned these latter types should present little practical difficulty, although, as previously stated, their characteristics do not entirely suit the application.

The Root's and Lysholm blowers both depend on fine clearances for their volumetric efficiency and this leads to mechanical troubles due to differential expansion. These can be minimised, however, by passing the vapour through a jacket surrounding the main body either before or after compression, to ensure as even a temperature as possible.

Ease of Maintenance

Under this heading is also included freedom from scaling. Once having settled on a satisfactory design, the maintenance of the compressor and pumps would be expected to be little and of a nature requiring no new technique. A great deal, however, has yet to be learned about the formation of scale on heating surfaces and work on its inhibition and removal is constantly in hand at a laboratory level, assisted by full-scale trials at sea. Points which are known to assist in scale prevention (other than by chemical treatment of the feed) are :—

(i) Low heating steam temperature.
(ii) Low temperature difference between heating steam and brine.
(iii) Low shell pressure, and, consequently, a low brine temperature.
(iv) Low brine density.

The temperatures referred to are intimately connected by virtue of the principle employed. Low compression ratios are involved (of the order of 1.2 up to a maximum of about 3) and (ii) is therefore small ; and if (iii) is low, so also is (i). At present the vacuum is limited to about 20 in. Hg to meet the requirement that a temperature of not less than 165°F. must be attained at some point in the cycle in order to ensure removal of bacteria. Lengthy experiments, carried out in the United States using a low pressure evaporator, have shown, however, that safe water can be produced from heavily contaminated feed, with distillation temperatures at least as low as 140°F., provided the salinity of the product does not exceed 0.25 grains/gallon. It may be, therefore, that higher vacua and lower temperatures will be permitted at some future date.

Simplicity of Operation

Despite the delicate heat balance on which operation depends, the Badger plants and those fitted in H.M. Submarines have proved very simple in operation. In the former (the larger plant) a simple manometer is fitted to the vapour space and when this is steady at atmospheric pressure, the pressure above the boiling brine is constant, and the unit is in balance. As most plants are provided with a fixed speed compressor only two of the variables are under the control of the operator. These are rate of feed and the number of heaters in use. If the manometer pressure falls, a loss of heat is indicated which can be corrected by switching on an additional heater, or by decreasing the feed rate.

Relation of Design to Economy

With a plant of this type running under steady conditions, the losses are :—

(i) Blow down losses.
(ii) Loss in made water.
(iii) Radiation.
(iv) Losses in non-condensible gases.
(v) Pump horse-power absorbed.
(vi) Motor inefficiency and mechanical losses.
(vii) In addition, a small quantity of steam is released in some plants to ensure stability.

Of the above, (i) increases with the lower densities carried ; (i) and (ii) can obviously be reduced by an efficient feed heater which would reduce the temperatures of both to something approaching that of the sea water ; (iii) can be minimised by efficient lagging and a high shell vacuum ; (iv) can be reduced by all-round low temperatures ; (v) depends on factors too numerous to discuss here and is in any case small ; (vi) is dependent on the size of the plant and the type of compressor and drive.

The power required for a given output will depend directly on keeping these losses as low as possible.

Weight and Space

Unfortunately, those factors which contribute towards a reduction in scaling have the reverse effect on weight and space. With a temperature difference between the brine and the heating steam of only 10°F. to 20°F., very large heating surfaces are necessary when compared with the normal type of evaporator using saturated or superheated steam in the coils. Similarly, with a high vacuum in the " shell " a much larger compressor is necessary to pass the large volume of steam representing the evaporator output. For example, a plant of a given capacity operating at 25 in. Hg (134°F.) would require a compressor capable of over five times the volumetric throughput of a plant of similar capacity operating at atmospheric pressure (212°F.). Similarly for 28 in. Hg the factor would be 12.7. Conversely, a given compressor could be employed in a 12½ tons/day plant operating at 20 in. or in a 35 tons/day plant at atmospheric pressure.

Again, the lower the brine density the larger the brine pump required because of the greater ratio of blow down to product. This is, however, a small point.

Some Alternative Arrangements

Fig. 3 shows an arrangement in which the compressor is turbine-driven, the turbine exhaust mixing with the compressor vapour before passing to the heating coils. Allowing for a 10 H.P. motor to drive the combined pump, representing about 200 lb. steam at the turbo-generator, such a plant would produce about 2.6 lb. water per pound of steam, as compared with the single effect evaporator's figure of something less than 1.

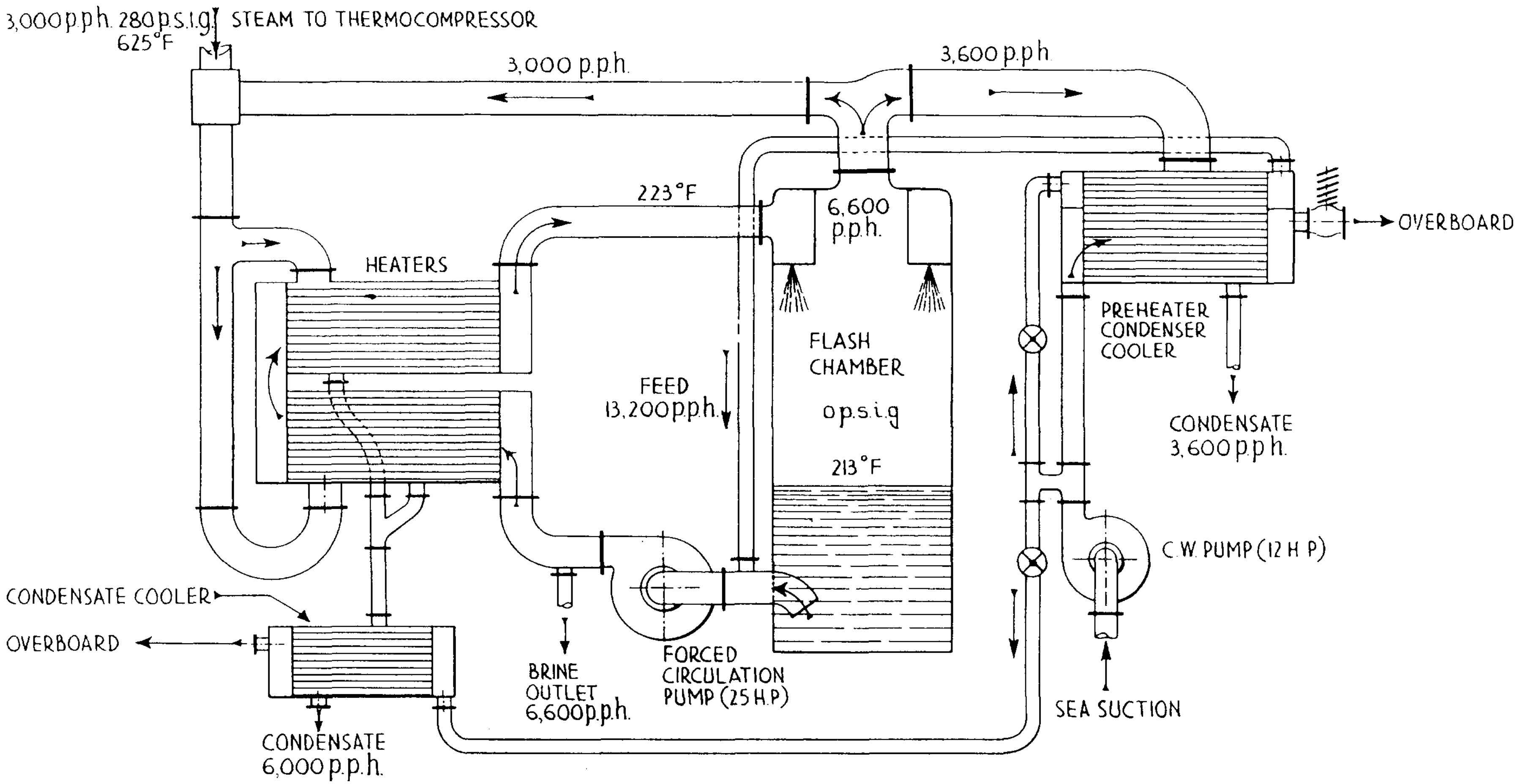

FIG. 4.—FORCED CIRCULATION—"P & B" EVAPORATOR

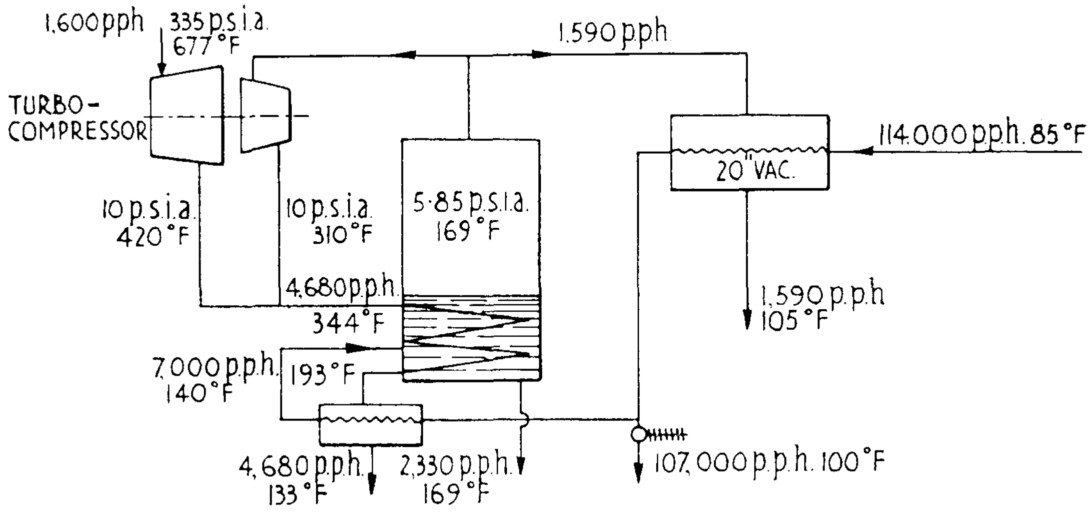

Fig. 3.—V.-C. Plant using Turbo-Compressor

Fig. 4 shows a diagrammatic arrangement of a Prache and Bouillon ("P & B") type evaporator. The plant is similar in principle to that in Fig. 3, except that a thermo-compressor is used instead of the mechanical compressor, and that the heating takes place externally to the shell, where approximately 1% of the circulating brine is flashed off as a vapour. The figures given on the diagram are approximate. The ratio of the amount of vapour passing to the thermo-compressor to that passing to the "pre-heater-condenser-cooler" is that claimed by the makers. Using this ratio and trial figures as a guide, this plant should produce about 1¾ lb. water (nett)/per lb. steam supplied.

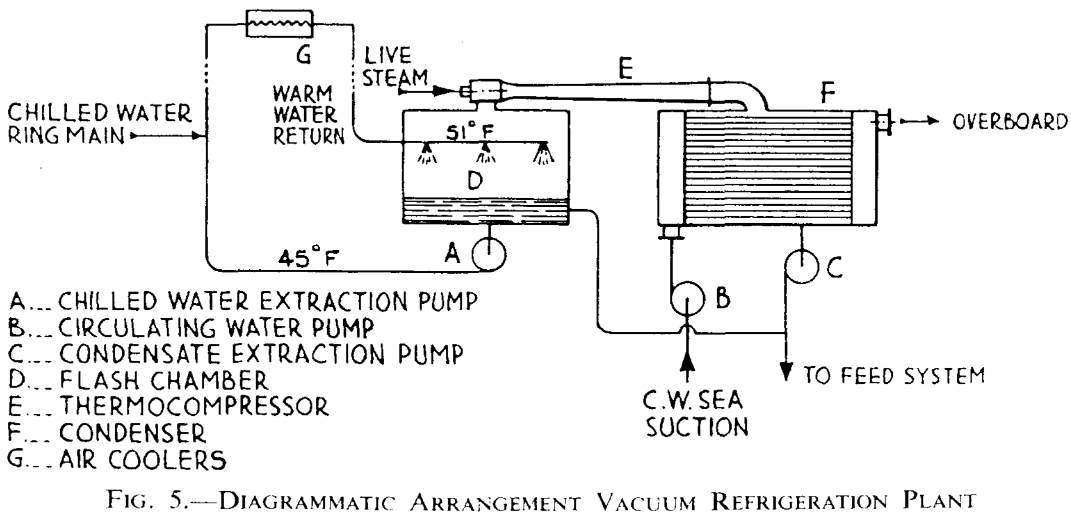

Fig. 5.—Diagrammatic Arrangement Vacuum Refrigeration Plant

A variation of this type of plant is the so-called "vacuum refrigeration plant" now used extensively for air-conditioning. A typical arrangement of such an installation is shown diagrammatically in Fig. 5 and in the photograph reproduced on page (ii) of *Journal of Naval Engineering*, Vol. 1, No. 2. The flash chamber in this case is under very high vacuum (about 29.7 in. Hg.) and the brine is replaced by distilled water which is pumped round the ship through the coolers in the ventilation system, where it absorbs heat. On return to the flash chamber a proportion is "flashed off," cooling the remainder in so doing. Further distilled water is added as make-up to keep the quantity in circulation constant. The "flashed off vapour" is entrained in the thermo-compressor and passes to the condenser whence it is returned to the feed system.

Conclusion

From the foregoing it would appear that while the general adoption of vapour compression plants for H.M. ships would be desirable from the economy aspect, there are at present too many unknown factors to contend with, the most important being scale and its effect on operation, and the lack of a suitable tried and proved compressor. A somewhat lengthy period of trial (and, no doubt, tribulation) will have to be covered before a plant of sufficient reliability can be produced for service in H.M. ships.