Power Reduction Method for Recompression Evaporators

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ABSTRACT

In mechanical recompression evaporators vapor boiled off the liquid being evaporated is compressed, raising its temperature sufficiently to allow it to become heating steam. The vapor temperature increase necessary is the sum of the boiling point elevation of the liquid, plus the working temperature difference required for heat transfer.

The compressor power requirement is essentially proportional to this total temperature difference, therefore, any factor reducing this temperature difference will save power. If brine is filmed down the outside of the tubes, in contact with the compressed vapor, this brine will rise to a temperature higher than the saturation temperature of the compressed vapor since the vapor pressure of brine is lower than that of pure water at any given temperature. Thus, the brine will be hotter than the compressed vapor by an amount approaching the boiling point elevation of the brine.

In this arrangement the boiling point elevation of the brine being filmed down the outside of the tubes acts to partially cancel the boiling point rise of the liquid being evaporated. This reduces the temperature increase required of the compressor, and thereby reduces the compressor power demand.

This arrangement is feasible when solid salt is available which may be dissolved to produce or regenerate the brine being filmed down the tubes. Typical cases would include those in which impure salt, such as rock salt or solar salt, is being dissolved and reprecipitated as granular salt.

Pilot plant tests are reported and typical flowsheets described.

Selection of a brief but descriptive title for this paper presented difficulties. Alternate titles considered included the following:

"Partial Cancellation of Evaporator Boiling Point Elevation"

"Special Heating Element Design for More Effective Use of Temperature Difference"

"Boiling Point Rise Cancellation with Brine Film Type Heating Elements"

and so on.

Earlier discussions with engineering acquaintances of the ideas involved have shown that it may be helpful to first briefly review the pertinent basic principles. Accordingly, this will be done, and we ask the indulgence of those to whom these are already very familiar.

Figure 1 represents a vessel containing water at the atmospheric boiling point in contact with water vapor at atmospheric pressure. This represents an equilibrium condition wherein the number of molecules passing from the liquid to the vapor state equals those passing from vapor to liquid.

The top of the vessel is shown fitted with a piston. If this piston is moved upward, reducing the pressure on the vapor space, the equilibrium condition is upset, and there is a net flow of molecules from the liquid into the vapor state. Conversely if the piston is moved downwards, the vapor pressure is raised and molecules pass from the vapor state to the liquid state, i.e., vapor is condensed.

Figure 2 illustrates the same arrangement except that the water in the vessel has been replaced with saturated sodium chloride brine. In such a brine the vapor pressure at any given temperature is lower than that of water -- or, putting it another way, the temperature of brine must be higher than that of water in order to develop the same vapor pressure. This temperature differential is what is known as "boiling point rise" or "boiling point elevation," and will be assumed to be 15°F. for the purposes of this discussion.

Thus, in order for the brine in this case to be in equilibrium with water vapor at 14.7 psia, the brine temperature must be 227°F.

With temperatures fixed as above, we may again cause boiling to occur momentarily by raising the piston to reduce the pressure in the vapor space. Likewise, by moving the piston downward to compress the vapor we can cause it to condense in the brine.

The condensation of 212° vapor in 227° brine in some respects appears contradictory since it involves the flow of heat from a lower temperature to a higher temperature -- however, it is the vapor pressures of the two phases which control the net movement of molecules to or from the liquid phase -- and this is the key point of the entire discussion.

The next slide, Fig. 3 illustrates a simple steam jacketed kettle in which water is being boiled at atmospheric pressure and wherein a delta T or temperature difference of 15°F. is provided to cause heat to flow from the steam jacket into the water. This requires steam at 227°F. corresponding to a pressure of 19.7 psia.

Figure 4 illustrates this same kettle, but now containing brine boiling at atmospheric pressure. Because of the boiling point elevation of the brine, it is at a temperature of 227°F., and in order to provide the original 15° delta T the steam temperature must now be raised to 242°F. corresponding to a steam pressure of 25.7 psia.

Now referring to Fig. 5 we have a slightly more complicated arrangement in which the jacket as well as the kettle contains saturated brine. In order to provide the required 15° delta T, the brine in the jacket is at a temperature of 242°, but this brine temperature is achieved by contact with steam at 227° corresponding to saturation at 19.7 psia. Thus, by using the brine in the jacket as a heat transfer medium, and taking advantage of its boiling point rise or reduced vapor pressure, it is possible to boil brine with the same 19.7 psia steam pressure originally used to boil water.

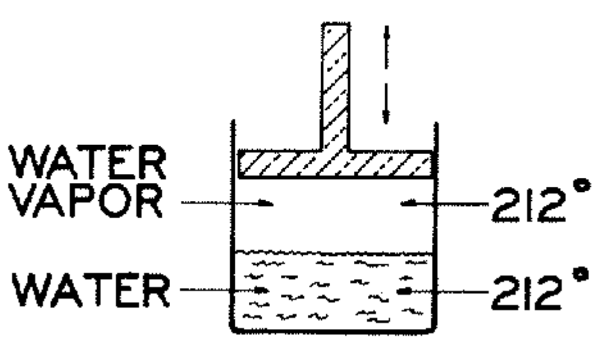

Figure 1

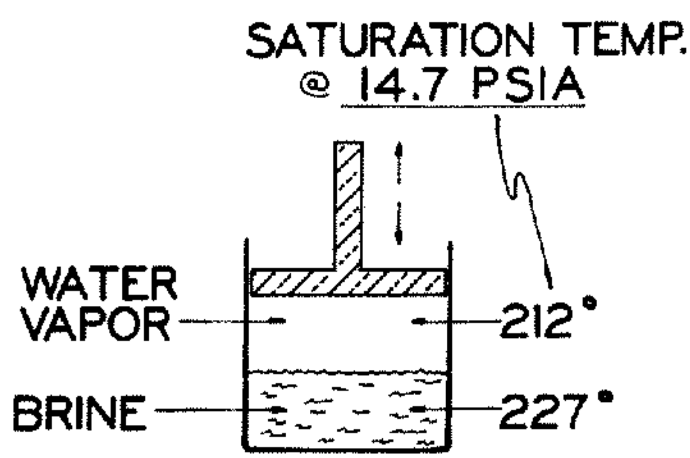

Figure 2

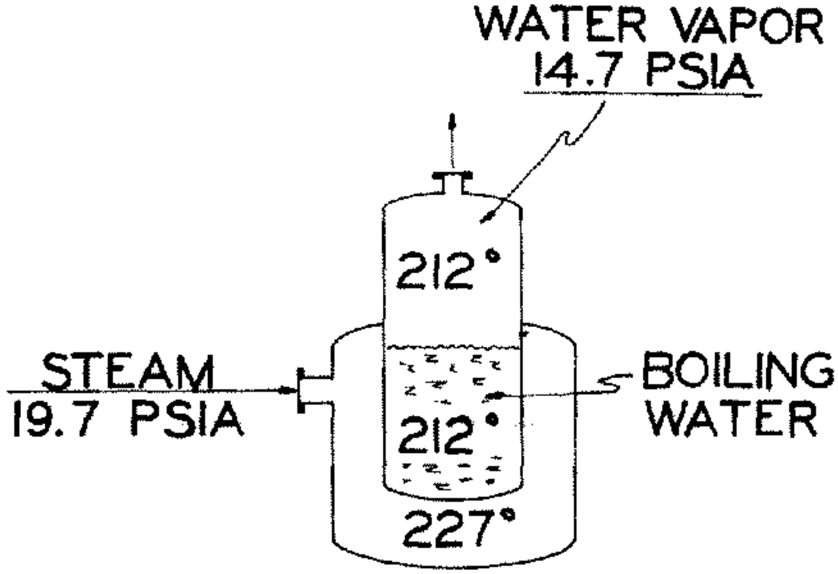

Figure 3

From the preceding information it is evident that, in this idealized case, it is possible to cancel out the affect of boiling point rise by using saturated brine as a heat transfer medium in contact with the steam and with the kettle wall.

Figure 6 illustrates schematically how this principle might be applied to the heating element of a conventional forced circulation evaporator. Here a false tube sheet has been provided, spaced somewhat below the regular upper tube sheet, and saturated brine brought into the space between the two tube sheets is filmed down the outside of the tubes. The heating steam, entering the top of the heating element, contacts this brine film and condenses in it, raising the temperature of the brine above that of the steam by an amount approaching the boiling point elevation of the brine.

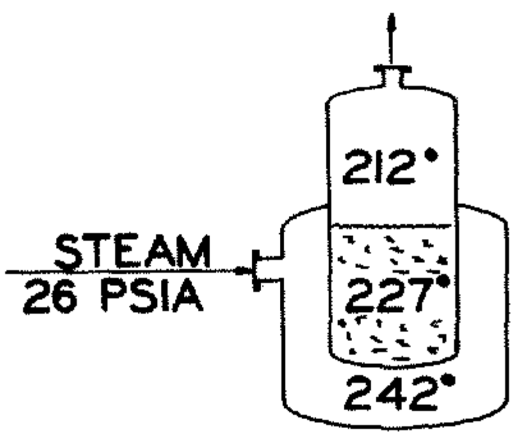

Figure 4

The condensation of the steam in the brine dilutes the brine and, therefore, in order to keep this simple system in equilibrium it is necessary to add solid salt as shown, and purge off diluted brine. This brings out one of the primary characteristics of such a system, which is that it can only be used where salt is available to be dissolved. This could be in connection with the purification of rock salt or solar salt by recrystallization, or in any situation in which salt is available as a waste material. One such case would be in connection with potash refining operations wherein salt is normally discarded.

Referring again to Fig. 6, it can be seen that there will be factors tending to make the performance of such a system less than ideal, as follows:

1. The thickness of the brine film streaming down the outside of the tube will tend to reduce the overall heat transfer rate -- i.e., there will be a temperature drop across the brine film.
2. If saturated brine is filmed down the tubes this brine will be diluted enroute by condensation of the heating steam which will cause the boiling point elevation at the bottom of the tube to be less than at the top.

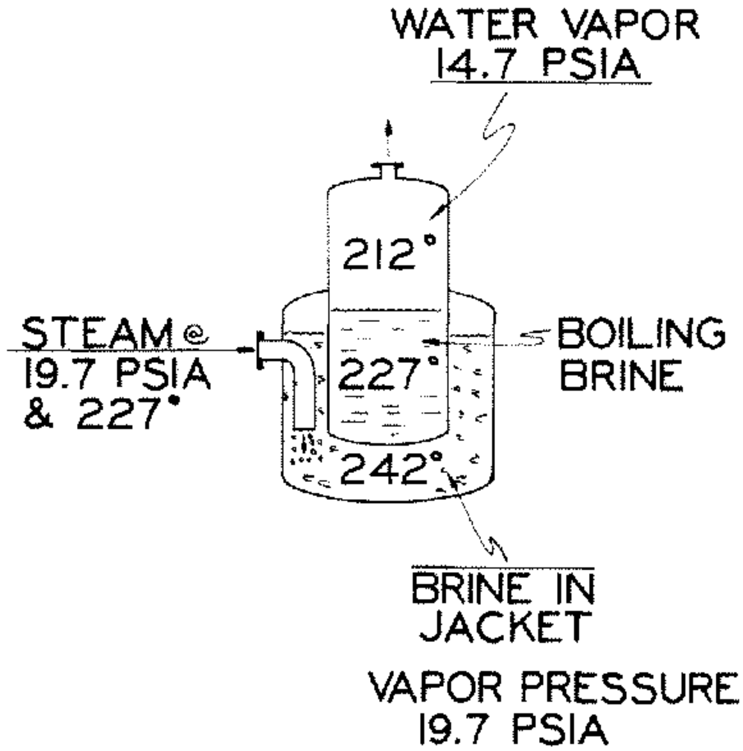

Figure 5

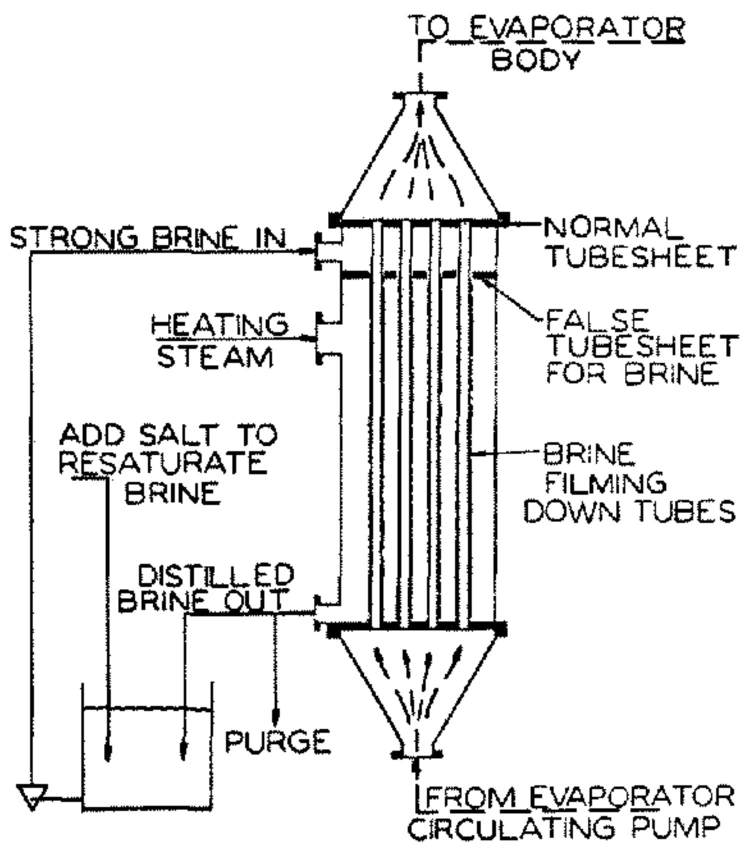

Figure 6

3. The preceding loss by dilution can be minimized by higher brine flow rates but these would also cause a thicker brine film which in turn would tend to reduce the heat transfer rates. It will be evident that for any given set of operating conditions there will be an optimum brine flow rate.

4. The loss of effectiveness of the brine film by dilution as outlined under 2 and 3 preceding can be virtually eliminated by filming a slurry down the outside of the tube. This is somewhat more difficult to accomplish mechanically, and the salt used in such a slurry must be very fine to avoid distribution problems.

The foregoing has been a discussion of the theory involved in the application of the brine film heater to partially offset the loss of available temperature drop due to boiling point elevation. Although the theory is quite straightforward, it was felt necessary to carry out an extensive test program in order to determine the actual operating characteristics of such an arrangement. Accordingly, pilot-sized equipment was set up in the laboratory and a series of test runs performed.

Figure 7A is a photograph showing the special heater which was used consisting of a single tube encased in a six-inch diameter glass heating element shell. This transparent shell allowed the action of the brine or slurry filming down the outside of the tube to be observed.

Figure 7B shows the top of the special heater protruding through the supporting platform, together with the vapor head. Two pipes are visible leading into the upper part of the heating element, the upper one being for the brine filmed down along the tube, and the lower one being the steam line.

Figure 7C is a view showing the bottom of the heating element.

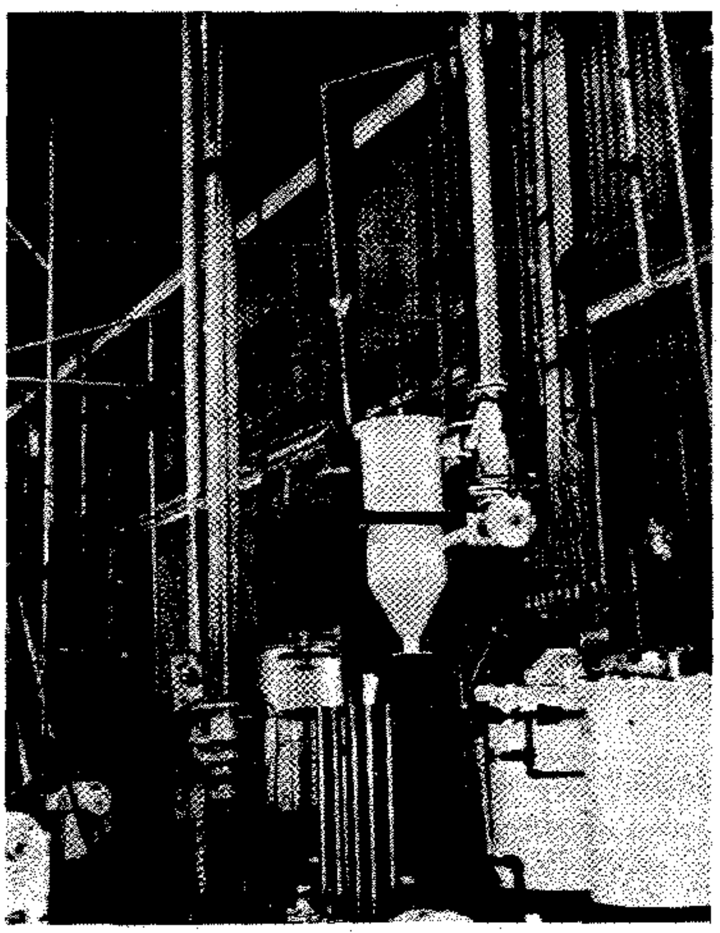

Figure 7A

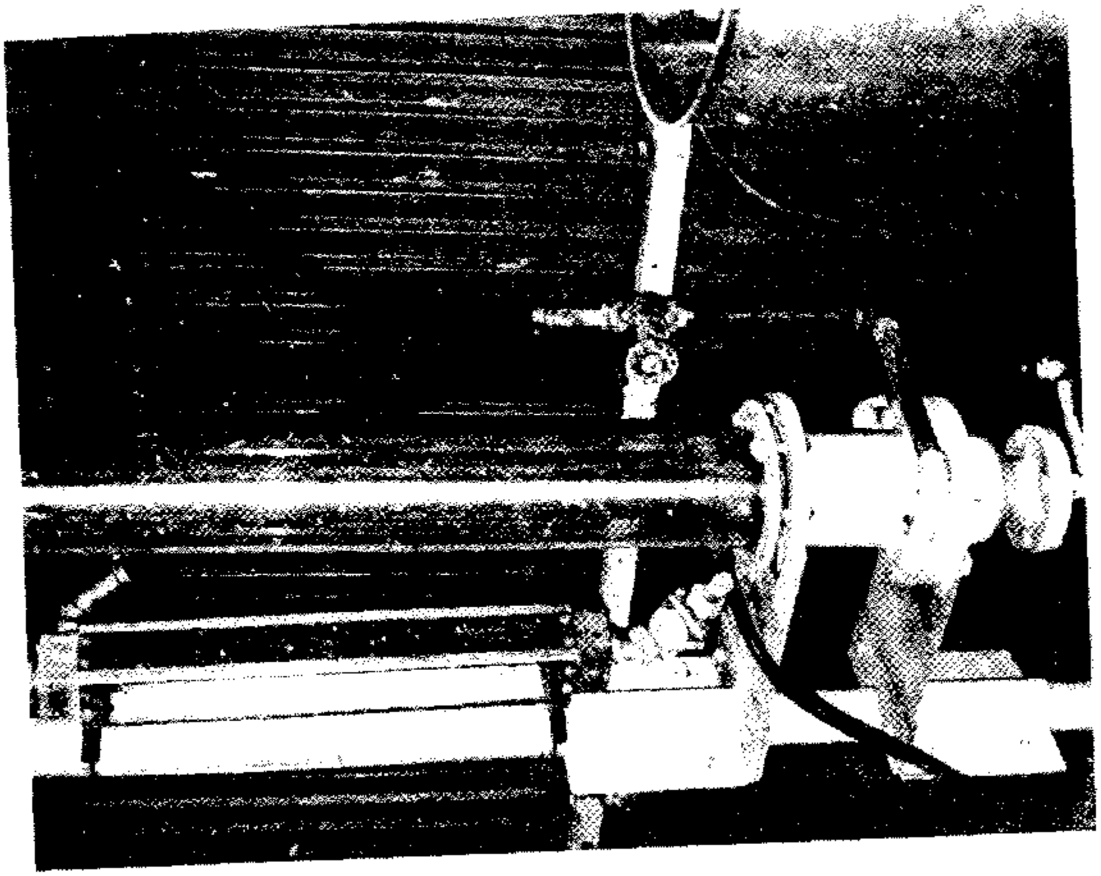

Figure 7C

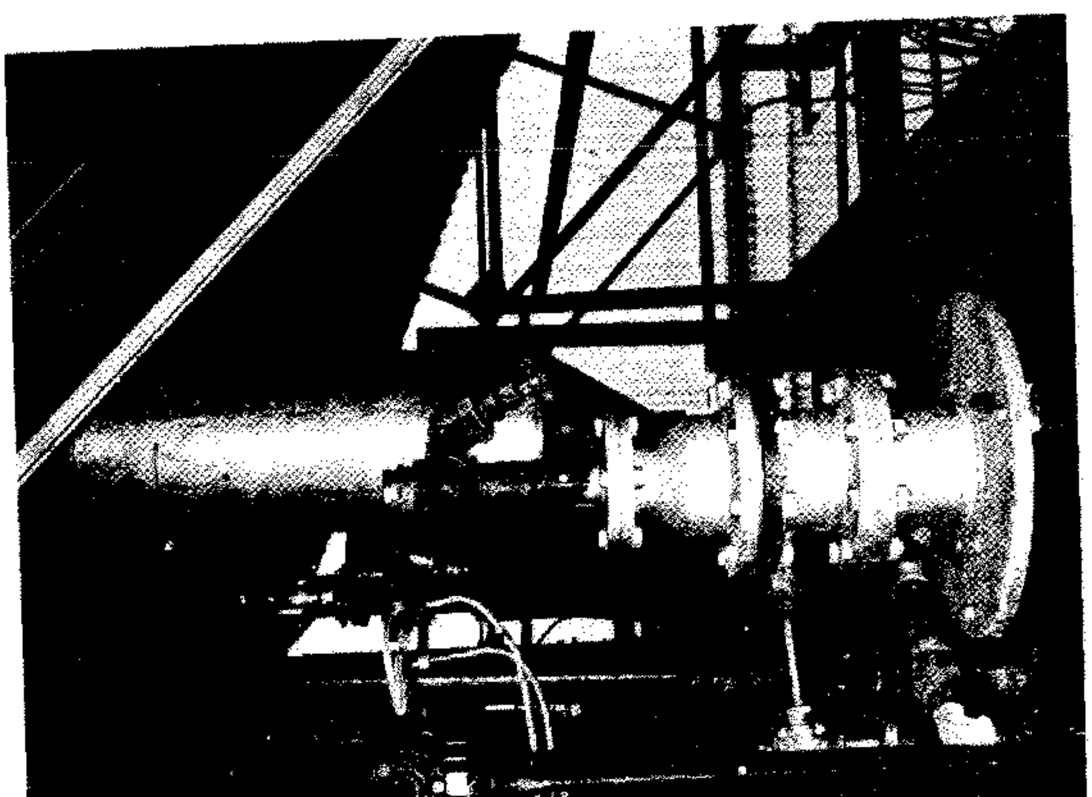

Figure 7B

Figure 8 is a diagram of the complete laboratory test setup, including the special heating element, vapor head, surface condenser, receiver, circulating pump, and saturator. Basically, the arrangement consists of a single-effect forced circulation evaporator with surface condenser and air eductor. A separate circulation loop is provided to permit filming saturated brine or slurry down the outside of the heating tube. Provision is made for measuring flow rates, pressures and temperatures throughout the test setup.

The cross section through the special heater shows how the brine filming down the tube was caught in a central receiving compartment at the lower tube sheet and discharged from the heating element separately from the condensate which formed on the inside of the glass shell. This is important, since the shell is relatively large, and capable of condensing an appreciable quantity of steam.

Throughout the test series, water rather than brine was circulated through the heating tube to the vapor head and back, for the sake of ease of operation. The usual procedure was to maintain atmospheric pressure in the steam chest of the heating element, varying the absolute pressure in the surface condenser by means of an air bleed control in order to maintain the desired total temperature difference between heating steam and vapor. Use of atmospheric pressure in the heating element avoided problems with boiling in the saturator which would have resulted from pressure operation and also permitted barometric discharge to the saturator. This would have been more difficult with vacuum in the steam chest, since the physical arrangement of the equipment permitted only a small difference in elevation between the bottom of the heating element and the saturator.

In operation, the measured circulation through the inside of the tube together with the temperature rise across the tube from inlet to outlet was recorded, permitting calculation of the heat input to be used in determining the overall heat transfer coefficient. This heat input could be cross-checked in two ways:

1. The condensate from the surface condenser was measured, and knowing this condensate rate, it was possible to calculate the heat given up by the vapor to the condenser cooling water. The condensate outlet temperature was measured together with the flow since there was always some subcooling of the condensate which had to be taken into account.
2. The condenser water flow was measured together with the temperature rise of this water passing through the condenser and from these figures the heat absorbed in the condenser water could be calculated and checked against that removed from the condensate.

The amount of brine or slurry being filmed down the outside of the tube was measured by another rotameter and the specific gravity of the brine discharged from the heating element was measured to check the dilution from condensed steam. Heat and material balances around the system checked out very closely.

The test program involved the following steps:

Series 1

Tests were first run on the equipment operating as a simple single-effect evaporator without any liquid or slurry being filmed down the outside of the heating tube. Under the test conditions employed, the coefficient of heat transfer ranged from 615 to 640 Btus/hr./sq.ft./°F. The results of this series then served as a standard of comparison for the following series.

Series 2

In this series, water instead of brine was filmed down the outside of the tube in order to develop information on the resultant reduction in heat transfer as compared to operation under Case 1 above. The overall coefficients of heat transfer were of the order of 500-530.

Stated in another manner, the additional resistance imposed by the water film required an increase in temperature drop of 3 to 5°F. in order to maintain the same rate of heat transfer as existed in the Series 1 tests. This data is of interest since it indicates to some extent the departure from ideal performance which is to be expected when filming brine or slurry down the tube.

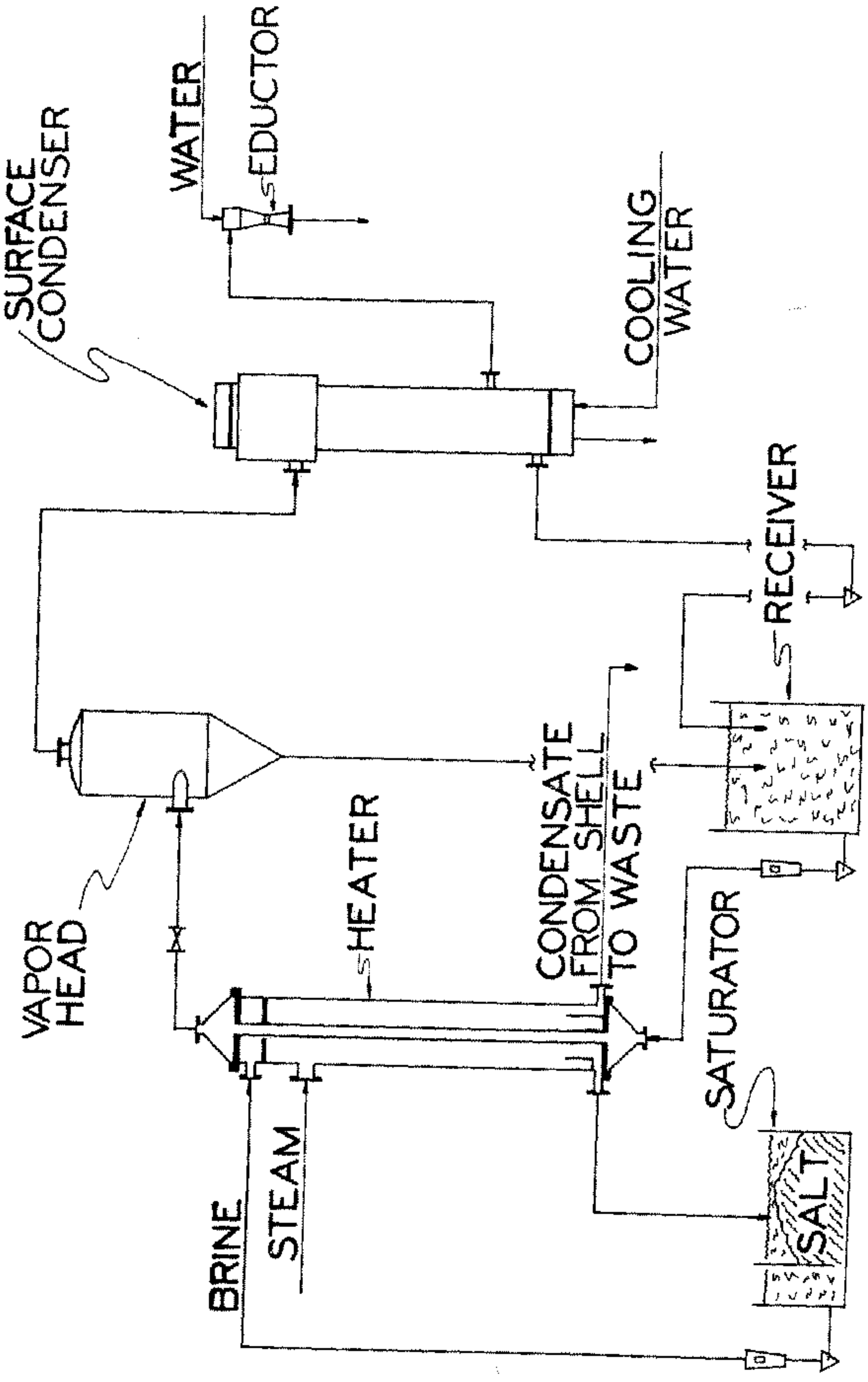
SURFACE CONDENSER
WATER
EDUCTOR
COOLING WATER
RECEIVER
VAPOR HEAD
HEATER
CONDENSATE FROM SHELL TO WASTE
SATURATOR
BRINE
STEAM
SALT

Figure 8

Series 3

In this case, clear brine as close to saturation as possible was filmed down the outside of the tube at various rates. In a typical run, the saturated brine applied to the top of the tube had a boiling point rise of 14° and that leaving the tube at the bottom, which of course had been diluted by condensed steam, had a boiling point rise of 8°. The average of these would be 11°, and in the ideal case the working temperature drop could be decreased to this extent while still maintaining the same heat transfer rate as in a normal evaporator. Actually the gain in effective temperature drop was of the order of 5°F. A large part of this departure from ideal performance can be explained by the resistance of the liquid film as determined in the runs under Series 2.

A typical sample calculation showing how this saving in temperature drop was determined is shown in Fig. 9.

Series 4

In this final case, slurry rather than clear brine was filmed down the tube. The presence of suspended salt assured that the brine film would remain close to saturation throughout its passage down the tube. Therefore, ideally the effective temperature drop would be increased to the extent of the 14° boiling point rise of this brine film. The actual gain showed by the tests was again less than this ideal amount due to the resistance of the film as developed in the Series 2 tests, and worked out to be approximately 9°F.

Summarizing the above testwork, it was found that a film of pure water imposed a barrier requiring an additional temperature drop of 3-5°F. Using clear brine as a filming medium gave an effective gain in temperature drop of the order of 5-6°F. Using slurry, the gain was somewhat greater amounting to approximately 9°F. In other words, gains were realized due to the reduced vapor pressure of the filming medium, but these gains were less than the theoretical 14° due to the resistance to heat flow of the brine film, and to the dilution of the brine in the case where solid salt was not present.

Figure 10 illustrates the flowsheet for a single-effect recompression type evaporator with the brine filming arrangement. In this particular case, the setup shown is for the production of granulated salt from rock salt. The rock salt is fed into a dissolving and saturating tank and the resultant brine is filmed down the outside of the heat exchanger tubes. The somewhat diluted brine discharged from the bottom of the heat exchanger is returned to the saturation tank, and the clear brine feed to the evaporator proper is also taken off this tank.

CALCULATION OF Δt SAVING:

① Heat Transferred = 107,720 BTU/hr.

② Log Mean Δt req'd. without brine film:-

$$= \frac{Q}{A \times U} = \frac{107,720}{5.87 \times 615} = 29.70°F$$

③ Log Mean Δt req'd. with brine film:-

$$= \frac{LT_2 - LT_1}{2.3 \log \frac{(St.T. - LT_1)}{(St.T. - LT_2)}} = \frac{190 - 181}{2.3 \log \frac{(210 - 181)}{(210 - 190)}} = 24.15°F$$

④ Δt Saving = 29.70 − 24.15 = 5.55°F

Figure 9

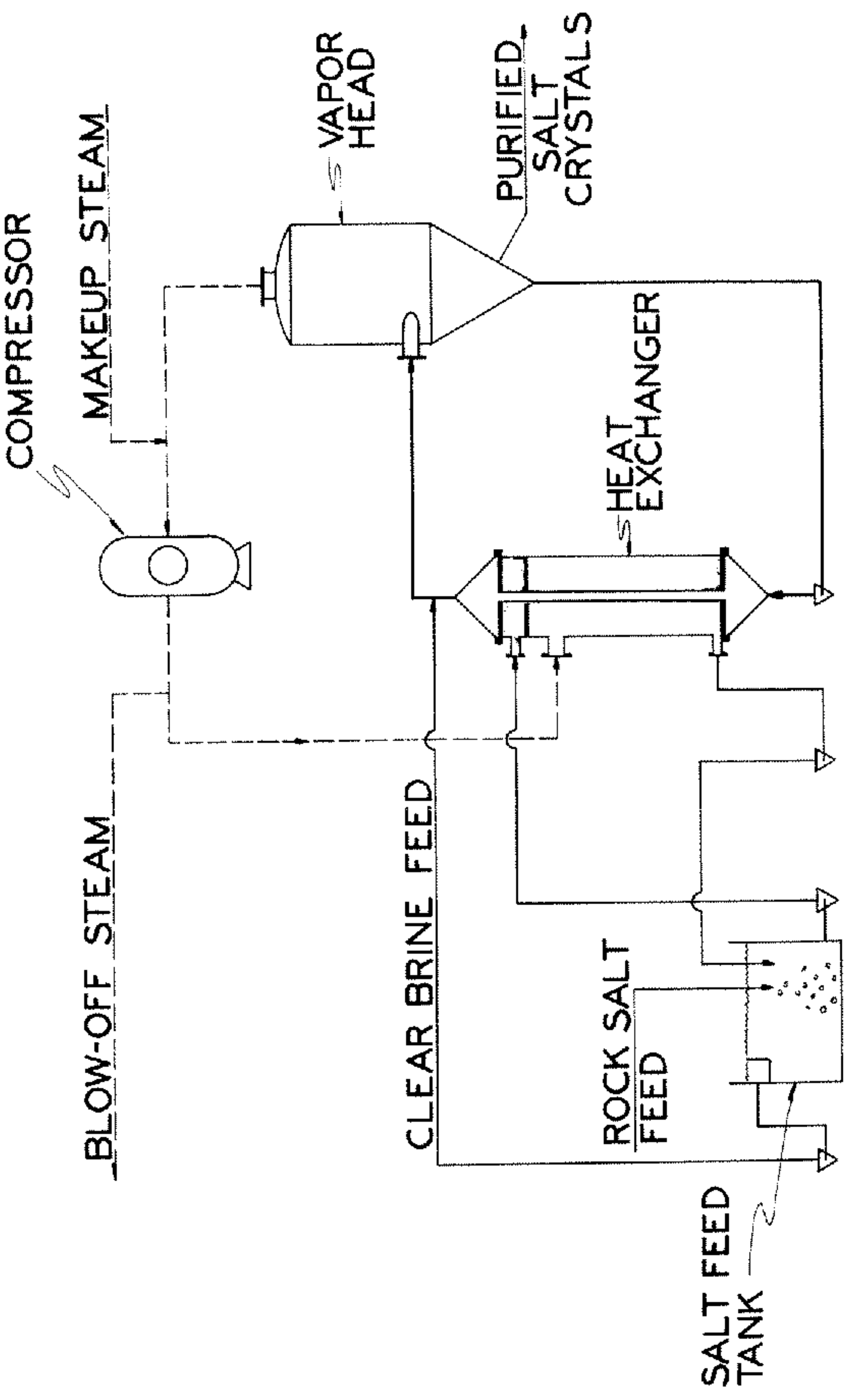
COMPRESSOR
MAKEUP STEAM
VAPOR HEAD
PURIFIED SALT CRYSTALS
HEAT EXCHANGER
BLOW-OFF STEAM
CLEAR BRINE FEED
ROCK SALT FEED
SALT FEED TANK

Figure 10

Use of the brine filming heater is especially advantageous in the case of a recompression evaporator, since it can result in a significant savings in power for the compressor. In a typical case, without the brine filming heater, the compressor might be required to work across a total range of 30°, made up of 15° of working temperature drop plus 15° of boiling point elevation of the brine.

If this total temperature range can be reduced by 6° by the use of the brine filming heater, the compressor will only be compressing across 24° instead of 30°. Since the compressor power requirements are essentially proportional to the temperature range, the power will be reduced by at least 20 percent.

Power requirements for a recompression evaporator are, of course, also dependent upon the amount of heating surface provided. As the heating surface is increased, less working temperature drop is required to transfer heat through the tubes at any given rate. In the case of a recompression evaporator handling pure water (i.e., with no boiling rise) the working temperature drop required would thus be inversely proportional to the heating surface. In a recompression evaporator handling brine, only the working temperature drop is affected by the amount of heating surface. Thus, in the case above, the 15° working drop could be reduced to 7-1/2°F. by doubling the surface. An economic balance is involved in determining the optimum heating surface and depends upon the cost of power and the cost of the heating surface material involved.

Figure 11 shows the relative affects of varying heating surface, with no film, with brine film and with slurry film, based upon the case outlined above. The upper left-hand end of the upper curve, at unity values of heating surface and relative power, corresponds to a total temperature drop of 30°F. and no film.

The upper curve shows how power is reduced with increasing surface and no film. The two lower curves show the equivalent relationships with brine and slurry films.

It is interesting to note that the proportional power savings due to use of the brine filming heater increases with increase in heating surface -- i.e., at relative surface of 1.0, the power requirement with the slurry film is $\frac{0.75}{1.00}$ = 0.75 times the power required with no film. At a relative surface of 2.5 the ratio is $\frac{0.4}{0.625}$ = 0.64.

Although the brine filming heater has its most important application in connection with recompression evaporators, it might also be used with multiple effect units. In this case the savings

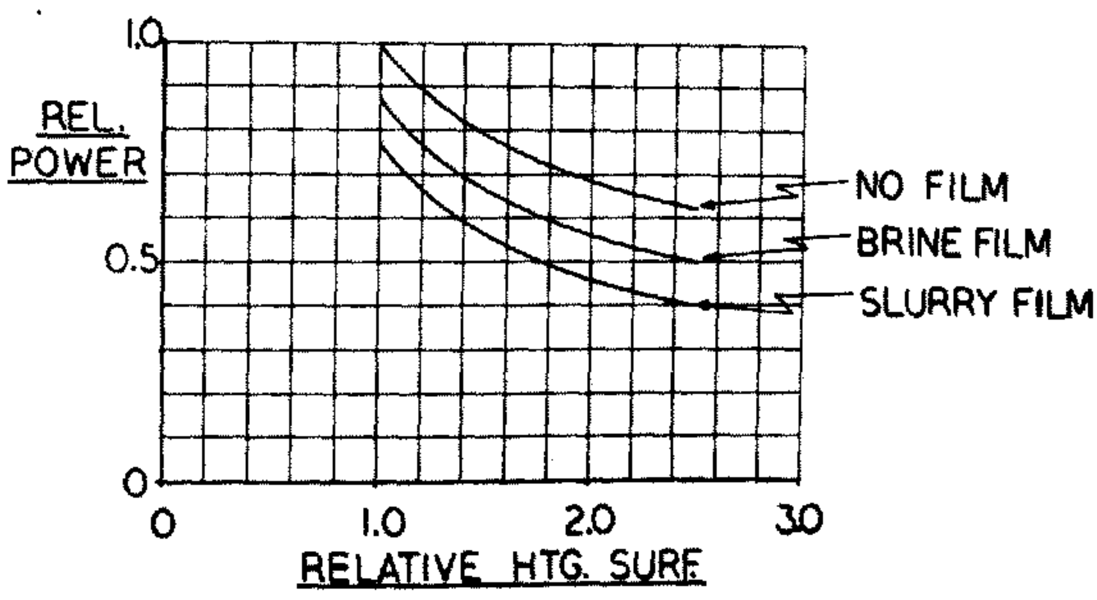

Figure 11

in working temperature drop could be used either to increase the number of effects possible with a given steam pressure, or to reduce the heating surface requirements for a given number of effects.

Figure 12 illustrates another possible method of employing the same general principal. In this case, brine resulting from the dissolution of rock salt is heated in a direct-contact brine heater using compressed vapor from the recompression-type evaporator. Heated brine is then circulated through the shell of the evaporator heating element which in this case is a liquid-to-liquid type exchanger.

Summing up, the field of application of the brine film type heater appears to be in cases where solid salt is available either as feed for recrystallization or as a waste material which can be dissolved without loss. Under these conditions the brine film heater offers significant power savings for recompression evaporators. The same principal can be applied to multiple-effect evaporators also.

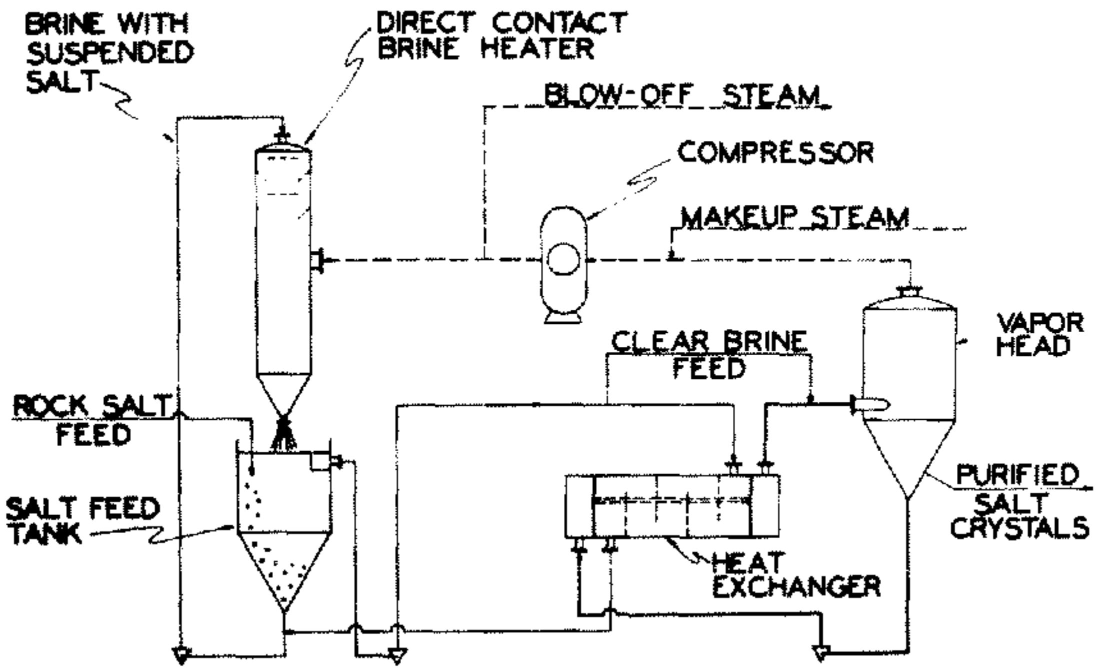

Figure 12