May 30, 1967 D. D. KAYS ET AL 3,322,648

MODULAR MULTIPLE-EFFECT FALLING-FILM EVAPORATOR

Filed April 29, 1966 5 Sheets-Sheet 1

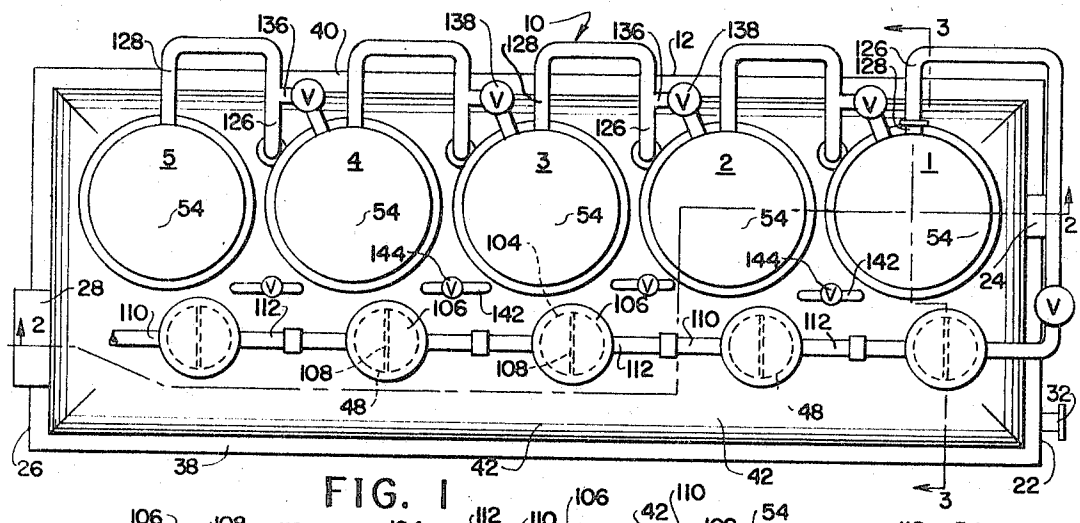


FIG. 1

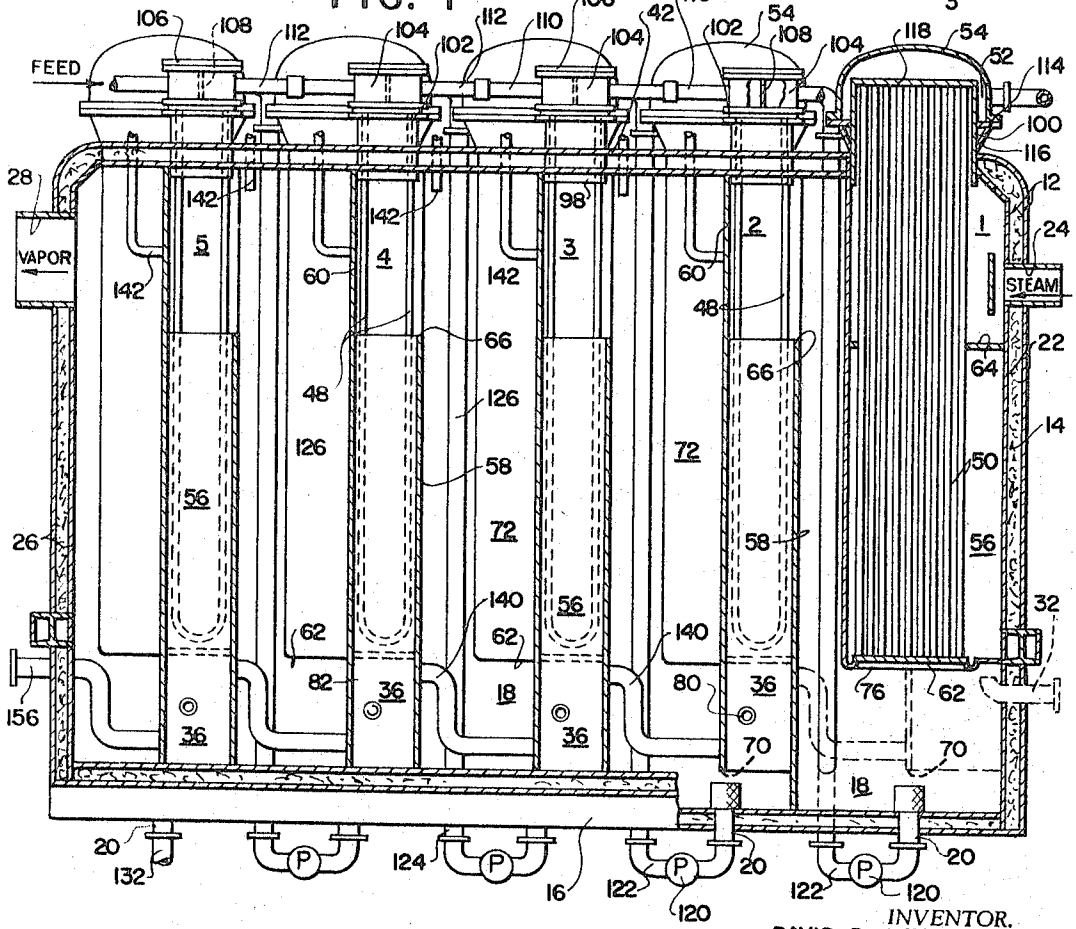


FIG. 2

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Filed April 29, 1966 5 Sheets-Sheet 2

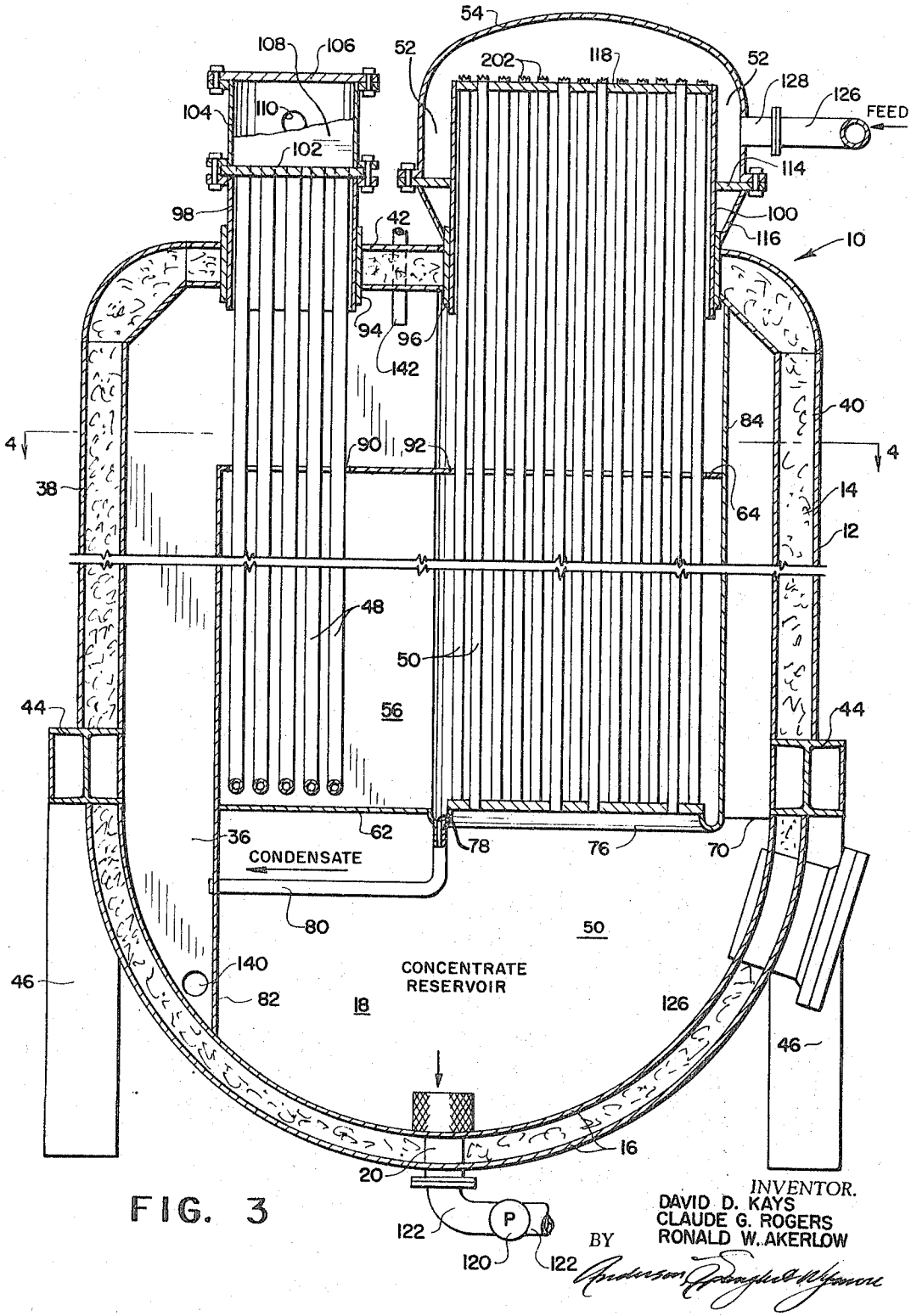


FIG. 3

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MODULAR MULTIPLE-EFFECT FALLING-FILM EVAPORATOR

Filed April 29, 1966 5 Sheets-Sheet 3

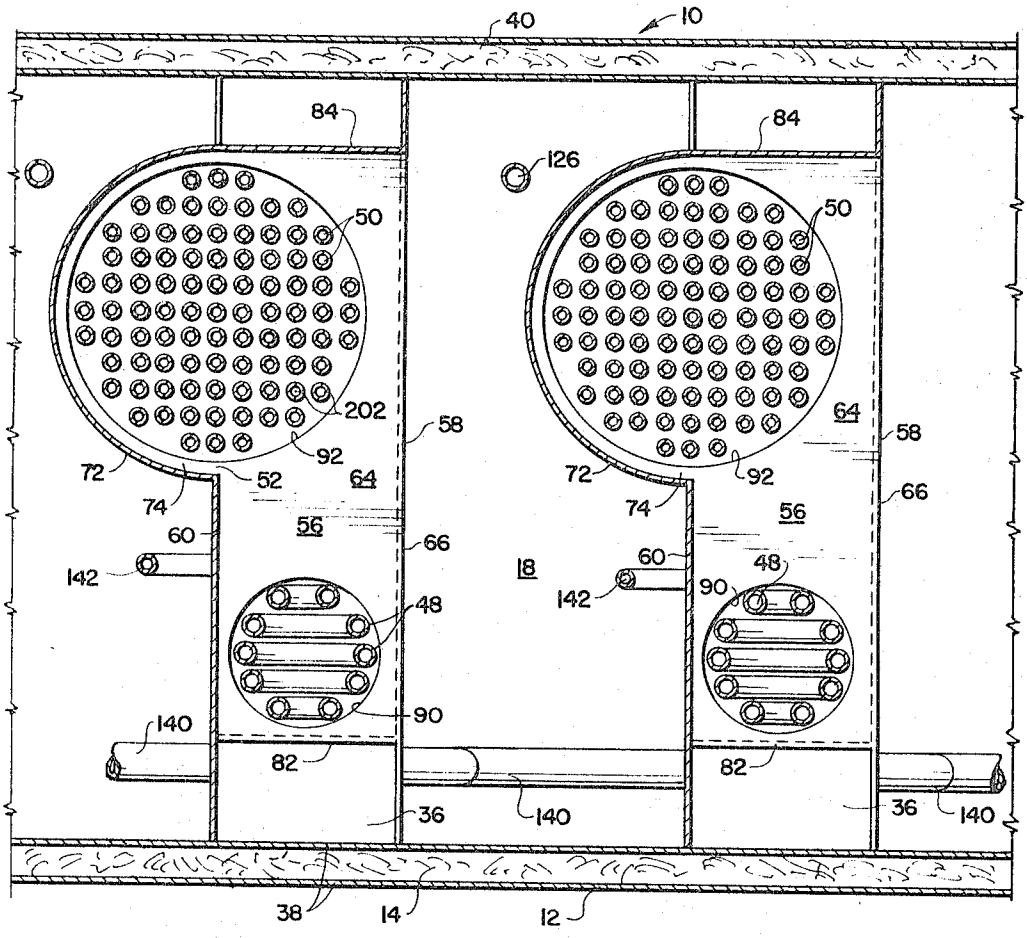


FIG. 4

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MODULAR MULTIPLE-EFFECT FALLING-FILM EVAPORATOR

Filed April 29, 1966 5 Sheets-Sheet 4

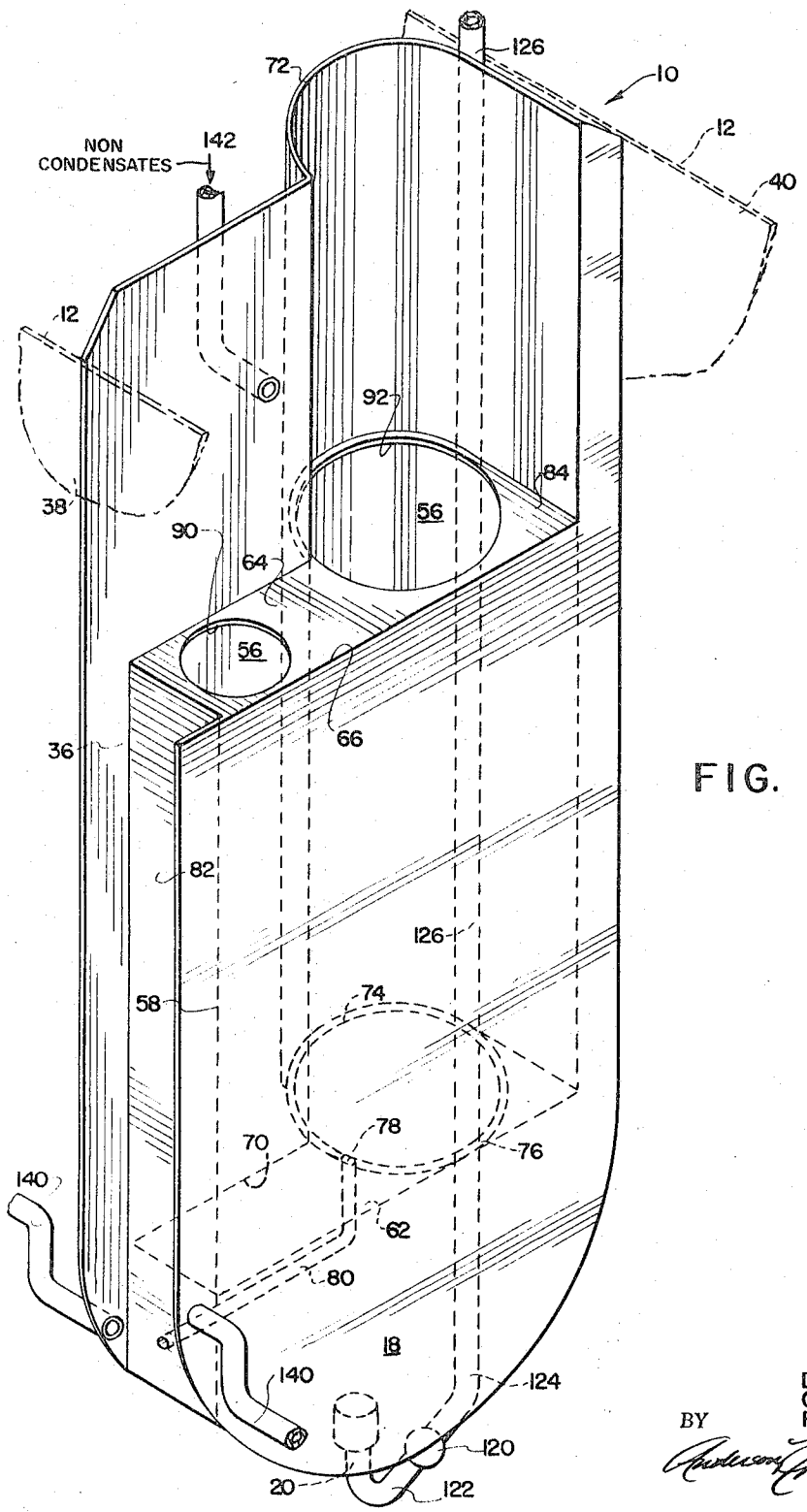


FIG. 5

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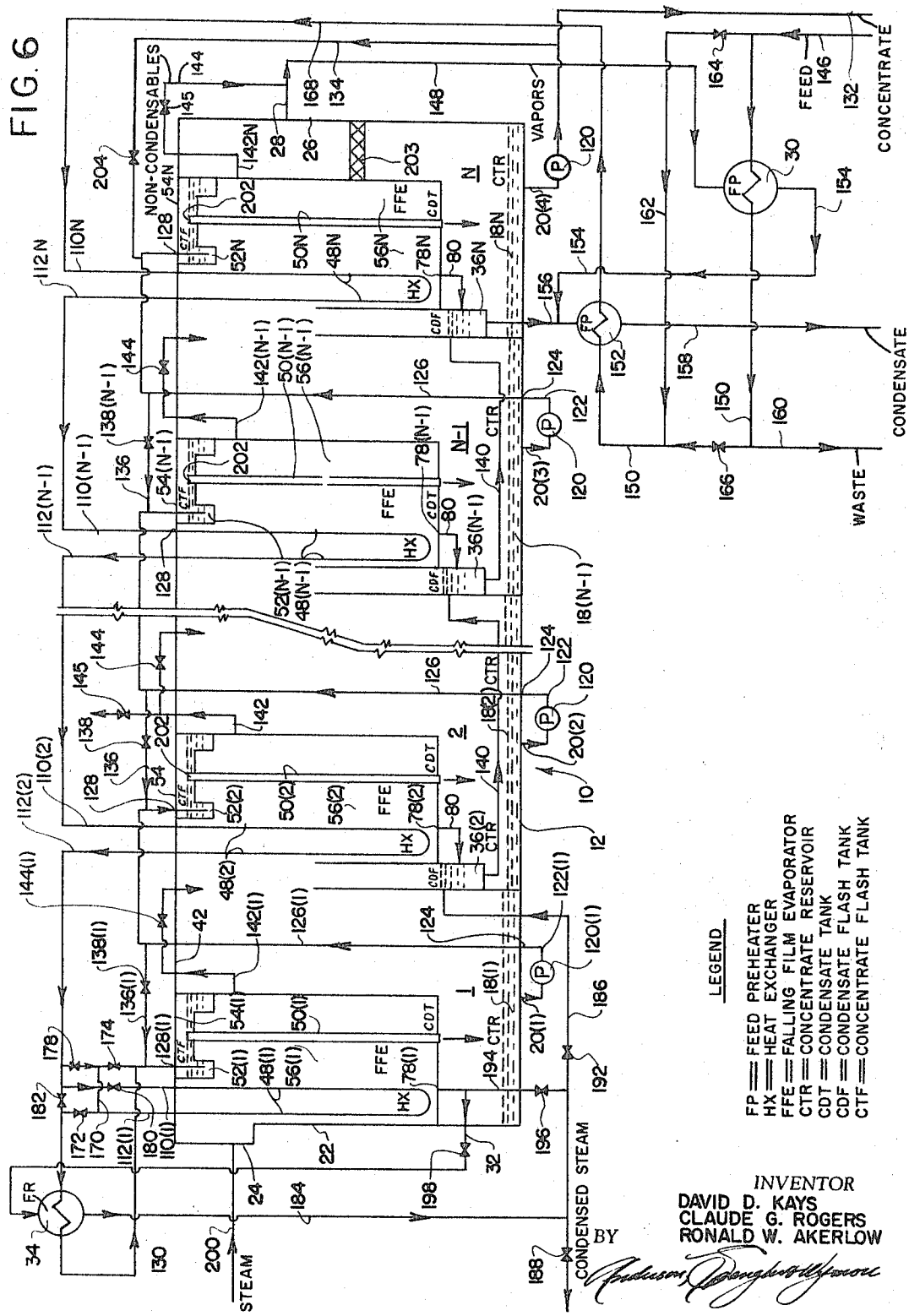
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MODULAR MULTIPLE-EFFECT FALLING-FILM EVAPORATOR

Filed April 29, 1966 5 Sheets-Sheet 5

FIG. 6



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3,322,648

MODULAR MULTIPLE-EFFECT FALLING-FILM EVAPORATOR

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Filed Apr. 29, 1966, Ser. No. 546,278
18 Claims. (Cl. 202—174)

This invention relates to a novel multiple-effect evaporator, together with the improved process for using same.

Multiple-effect evaporators are characterized by utilization of the warm vapors generated from the application of heat in one effect as the heat transfer medium which vaporizes a liquid in a subsequent effect. To accomplish this, a pressure and associated saturation temperature profile must be established over the several effects so that the heat transfer may take place across a suitable pressure barrier that causes the hotter vapor to condense on one side thereof and the cooler liquid to evaporate on the other side.

A considerable increase in thermal efficiency is achieved by providing several serially-connected effects at decreasing pressures. Further conservation of heat energy may be realized by recovering the heat from the hot condensate stepwise at approximately the same temperature level as the evaporation takes place in each effect. Some of the heat energy applied to each effect may be used to preheat the liquid feed to a temperature level only slightly below the operating temperature of that effect and, by employing an additional heat transfer surface for this purpose, a further increase in thermal efficiency results.

The invention forming the subject matter of the present application finds its maximum utility in multiple-effect evaporators of the type wherein the feed liquor is preheated in counter-current flow relation to the hot vapors, and when the liquor concentrated by evaporation in one effect becomes the feed to the subsequent effect in the series thereof. In such a system, the feed is customarily superheated upon introduction into the subsequent effect and a portion thereof vaporizes spontaneously thus cooling the remainder to the saturation temperature associated with the pressure in said subsequent effect. The result of this is to produce the temperature potential necessary to drive the heat transfer and thereby further evaporate the liquor and condense the vapor from the previous effect. Specifically, this useful process function is accomplished in a falling-film evaporator by causing the liquid to form a thin film and flow by gravity down one side of a heat transfer surface while it evaporates. Condensation of heating vapor takes place at a higher pressure on the other side of this heat transfer surface.

In order to keep a multiple-effect evaporator operating, several process requirements must be maintained. The first of these is a suitable temperature and pressure profile which is customarily brought about by causing the condensation and subsequent removal of the lowest pressure vapors produced at the saturation temperature obtainable by rejecting heat to the available heat sink in an indirect heat exchanger or condenser while, at the same time, applying heat to the high pressure end of the system. Secondly, condensation of a vapor on one side of a pressure-tight barrier through which heat is transferred must be brought about while evaporation of a liquid is being carried out on the other side. Both the condensed vapors (condensate) and the enriched liquor (concentrate) must

then be delivered to the subsequent effect along with the hot vapors.

The concentrated liquor becomes the feed to the subsequent effect where a portion thereof immediately flashes due to its superheated condition in the lower-pressured environment of said subsequent effect. The heat energy used to evaporate the concentrated liquor delivered to a subsequent effect is derived from two sources, namely, the condensation of the vapors produced by evaporation of the feed to the previous effect and the vapors produced by flashing the condensate from the previous effect.

Now, the foregoing process steps are, for the most part, common to all multiple-effect evaporation systems; however, the equipment used to carry them out is quite different from that forming the subject matter of the instant invention. The prior art multiple-effect evaporators, for instance, are so designed that these various processing steps are carried out in separate vessels interconnected by a complex array of external piping carrying the various liquid and vapor fractions from chamber to chamber. Each of these small independent vessels requires its own insulation which increases the cost of the system substantially and, in addition, renders it less efficient and more expensive to operate due to the appreciable heat losses occurring therein. Even the complicated framework necessary to support the various vessels, piping and the like makes the plant a costly one. Furthermore, when comparing the evaporators of the instant invention with those of the prior art, the latter require a good deal of additional unit process equipment such as, for example, intereffect condensate pumps, flash tanks and indirect condensate to feed heat exchangers.

From a process standpoint, the existing multiple-effect evaporator plants have a numbered of serious limitations. It is difficult, for example, to maintain precise control over the process conditions while attempting to accommodate variations in flow-rates. Also, considerable losses of energy are suffered through the use of conventional methods for introducing liquor to the evaporator tubes. Ordinarily the liquor is sprayed onto an apertured plate in the form of a high velocity stream to feed the evaporator and this practice, along with others of like nature, wastes valuable energy that can well be utilized to increase the overall plant efficiency.

It has now been found in accordance with the teaching of the instant invention that these and other shortcomings of the prior art multiple-effect evaporators can, in large measure, be eliminated or substantially reduced by carrying out all the processing steps, with the single exception of the removal of low pressure vapor, in a single common multiple-effect enclosure of novel design. The several serially-interconnected effects are separated from one another by internal bulkheads around which the vapor phase flows in substantially unrestricted fashion, thus eliminating the need for any inter-effect vapor piping.

Heat is recovered from the condensate as soon as it enters an effect by flashing a portion thereof within the common enclosure, thus eliminating a function ordinarily performed by a separate flash tank. The requirements for piping and the attendant friction losses are also thus eliminated.

The feed delivered to the evaporator of each effect is permitted to flash in a specially-designed dome-like portion of the main unitary enclosure that houses the several effects. The bottoms of these dome-like portions confine the flashed liquid and deliver same directly to the upper extremities of the evaporator tube sheet with little or no

waste of energy such as would take place if the liquid were sprayed into the dome against some type of dispersion plate.

Also housed within this common enclosure are the heat transfer surfaces that preheat the feed liquor and evaporate the falling liquid film. Both of the heat transfer surfaces communicate with the same source of hot vapor and they also deliver condensate to a common collection sump.

The main unitary enclosure that houses the several effects provides the structural support for the various elements housed therein, including the preheating exchange surfaces and the evaporating surfaces. Each of these multiple-effect modules are most efficient units in terms of heat conservation and, in addition supply the structural rigidity necessary to resist the internal and external pressure profiles without requiring nearly the external bracing so necessary in the prior art units.

It is, therefore, the principal object of the present invention to provide a novel and improved modular multiple-effect evaporator unit.

A second objective of the invention herein disclosed and claimed is the provision of an improved falling-film-type evaporative process for purifying contaminated liquids that is more efficient than prior art processes for the same purpose.

Another object of the invention is to provide a multiple-effect evaporator wherein two or more effects are housed in a common enclosure that provides structural support therefor while contributing materially to the flow, distribution and process interaction of the liquid and vapor phases undergoing purification therein.

Still another objective is the provision of a multiple-effect modular unit, two or more of which are preferably serially connected to further multiply the evaporative stages of a purification system.

An additional object of the invention forming the subject matter hereof is to provide improved means in the form of a common enclosure for several effects of a falling-film evaporator that facilitates the transfer of the liquid and vapor phases of the materials undergoing purification from effect to effect while conserving energy in so doing.

Further objects are to provide a falling-film evaporator plant that is less expensive to install than prior art facilities for the same purpose, one that is more economical to operate, permits the exercise of more precise control to accommodate variations in flow-rates and the like, is extremely versatile in that it is readily adapted for use in processing various different feed liquors, and a facility of the type aforementioned that is much less complicated than existing installations of the same general type.

Other objects are in part apparent and in part pointed out specifically hereinafter in connection with the description of the drawings that follows, and in which:

FIGURE 1 is a top plan view of a module containing five evaporative effects along with a corresponding number of feed preheaters;

FIGURE 2 is a vertical section taken along line **2—2** of FIGURE 1;

FIGURE 3 is a vertical section to an enlarged scale taken along line **3—3** of FIGURE 1 showing the compartmentalization within each effect, portions having been broken away to more clearly reveal certain structural features;

FIGURE 4 is a horizontal section taken along line **4—4** of FIGURE 3 revealing the details of the module compartmentalization;

FIGURE 5 is a fragmentary perspective view looking downwardly and to the left upon adjacent compartments of the module, portions of the partition walls and other interior features having been broken away to better reveal the interior construction; and

FIGURE 6 is a schematic flow diagram of a multiple-effect falling-film evaporative plant constructed in accordance with the instant invention.

Referring now to the drawings for a detailed description of the present invention and, initially, to FIGURES 1–4, inclusive, for this purpose, reference numeral **10** has been chosen to represent in a general way the entire modular unit that contains, in the particular form shown, five serially-interconnected effects (**1–5**) housed within a single common double-walled envelope or enclosure **12**. The double chamber walls are, of course, packed with an insulating material **14** which cooperates with the dead-air space therebetween to confine the heat and also to resist the internal pressures developed therein. The semi-cylindrical bottom wall **16** defines, as will be shown presently, a concentrate reservoir **18** containing an outlet **20** through which said concentrate can be withdrawn from each of the five effects.

The front end wall **22** contains a steam inlet port **24** through which steam is piped into the first effect from a suitable boiler installation (not shown). Rear end wall **26** includes an outlet **28** through which the vapors generated in the fifth effect leave the module **10** and are fed back into the inlet **24** of a second module or are exhausted to a heat exchanger **30** where they are condensed and the latent heat of condensation is utilized to warm the incoming raw feed. For purposes of the present description, the term "front" will be used to designate the end of the module into which the preheated raw feed is introduced preparatory to evaporating same in the first effect; whereas, the term "rear" will be similarly employed to designate the end of the module from which the hot vapors are withdrawn. Also, throughout the remainder of the specification and claims, the adjectives "previous" and "subsequent" when used to designate a particular effect in the series thereof, refer to same with reference to vapor flow through the system rather than the raw incoming liquid feed which flows counter thereto while being preheated. FIGURES 1 and 2 also show an outlet **32** in the front wall through which the hot condensate from the first effect may be withdrawn, if desired, and cycled through heat exchanger **34** (FIGURE 6) to extract heat therefrom for further preheating of the incoming raw feed before said condensate is delivered to the flash tank **36** of the second effect. As will be seen presently in connection with the flow diagram of FIGURE 6, if only a portion of the heating steam condensate is taken from the first effect to preheat the raw feed, this portion may, if desired, be cycled back to the boiler instead of being pumped on into the second effect flash tank.

The sidewalls **38** and **40** of the enclosure **10** cooperate with the end walls **22** and **26**, bottom **16** and a double-walled cover **42** to produce the insulated double-walled pressure vessel **10** that houses the several evaporation chambers (**1–5**) and also provides the structural support therefor. Integrated into the side and end walls are horizontal beam elements **44** that rest upon ground-supported uprights **46** and together these elements comprise essentially the entire frame required to support the multiple-effect module.

One of the main features of the invention is the compartmentalization of enclosure **10** to divide same into a plurality of separate pressure chambers, each of which contains a U-tube heat exchanger **48** to preheat the incoming raw feed, a bank or bundle of falling-film evaporator tubes **50**, an annular concentrate chamber **52** housed in a dome **54** surrounding the top of the evaporator tube bundle, the concentrate reservoir **18** and a condensate tank **56**. A flash tank **36** is also provided in each pressure chamber other than the first of said chambers. This compartmentalization is brought about by a pair of partial partition walls **58** and **60** together with vertically-spaced horizontal plates **62** and **64** that interconnect the aforementioned partition walls. Partial partition wall **58** extends from the bottom of enclosure **10** upwardly to a point where the top horizontal edge **66** thereof terminates at

plate 64 in spaced relation beneath the cover 42. Partial wall 60, on the other hand, lies in spaced parallel relation behind wall 58 and extends from cover 42 down to a level well below the top edge 66 of wall 58 where the horizontal bottom edge 70 terminates short of the bottom 16 of the enclosure 10 as shown most clearly in FIGURES 2 and 3. Lower horizontal plate 62 bridges the gap between partial walls 58 and 60 thus sealing off the enclosure 10 into a plurality of separate pressure-tight compartments and, in addition, cooperating therewith to form open-topped condensate tank 56. As seen most clearly in FIGURE 4, the evaporation tube sheet 50 is approximately twice the diameter of the U-tube heat exchanger tube bundle 48 and, in the particular form shown, these elements are not transversely aligned, but instead, the evaporator tubes are offset rearwardly of the heat exchanger tubes. Accordingly, rear partial wall 60 runs transversely along behind the U-tube bundle and is provided with a semi-circular portion 72 adapted to enclose the offset back half of the evaporator tube bundle. Bottom plate 62 is, of course, provided with a semi-circular hump 74 (FIGURE 4) to accommodate portion 72 of rear partition wall 60. This bottom plate also includes an integrally-formed circular trough 76 (FIGURES 2 and 3) encircling the bottom of the evaporator tube bundle 50 adapted to catch and hold the condensate draining down the tubes and also provide for absorption of possible differential expansion.

A drain opening 78 (FIGURE 3) in the bottom of the condensate tank connects into a pipe 80 that empties into the flash tank 36 housed in the same pressure chamber or effect with the exception of the first effect where, as previously mentioned, the condensate is cycled through heat exchanger 34. This flash tank 36 is formed between partial partition walls 58 and 60 alongside the U-tube heat exchanger bundle 48. Walls 58 and 60 form the front and back thereof, side wall 38 and a portion of curved bottom wall 16 of the main enclosure provide the outside wall and bottom, and a partition wall 82 spaced inside wall 38 separates said flash tank from the condensate tank. A similar partition wall 84 spanning the gap between walls 58 and 60 is located adjacent the outside of the evaporator tube bundle 50 and functions merely as a stiffening member. The latter wall terminates at plate 62 as shown in FIGURE 3 and, therefore, does not reach the bottom 16 of the enclosure to produce a sealed chamber as was the case with wall 82. Horizontal wall 64 provides a cover over the top of the condensate tank 56 and it contains openings 90 and 92 adapted to pass the tube bundles 48 and 50 while allowing the hot vapors to circulate therearound.

At the top of enclosure 10, both the evaporator tube bundle 50 and the heat exchanger tubes 48 extend above top wall 42 and are sealed therein in pressure-tight relation by collars 94 and 96. Inside these collars are upstanding flanged tubes 98 and 100 that can be seen in both FIGURES 2 and 3. Atop the flange tube 98 rests an apertured plate 102 which supports the U-tubes of the heat exchanger 48. A second flanged tube 104 rests on top of this plate and is bolted to the first flanged tube 98 clamping said plate 102 therebetween. A cap 106 covers the top of the second flanged tube 106 and cooperates with an upstanding divider plate 108 (FIGURE 2) to separate the inlet ends of the U-tubes from the outlet ends thereof. A raw feed inlet 110 is provided in the upper flanged tubular member 104 adapted to deliver the raw feed to the inlet side of the U-tubes. An outlet 112 on the opposite side of divider plate 108 takes the preheated raw feed from the exchanger and delivers same to the preceding effect in counter-current flow relation to the concentrate.

The flange 114 on tubular member 100 that encircles the top of the evaporator tube sheet is located intermediate the ends thereof and is supported on its underside by a flared ring 116. Resting atop the tubular member 100 is an apertured plate 118, from the underside of which are suspended the evaporator tubes 50. The flanged dome 54 rests on flange 114 and the inside surface thereof lies spaced outwardly of the tubular member 100 to define the annular concentrate chamber 52. The concentrate falling into the concentrate reservoir 18 of each effect after leaving the evaporator tubes 50, is drawn off through outlet 20 and pumped by means of pumps 120 through line 122 into connection 124 (FIGURE 5) up through line 126 that passes behind the tube sheets 48 and 50 in the same effect and enters the dome 54 of the subsequent effect through inlet 128. Thus, by eliminating a major external run, heat losses to the environment are virtually eliminated and such heat as is transferred is utilized in the subsequent effect. The dome 54 of the first effect receives the preheated raw feed through line 130 (FIGURE 6) that comes from heat exchanger 34 in most instances. Alternate routes for the preheated feed entering the dome of the first effect are provided in the flow diagram of FIGURE 6 which will be explained presently. The concentrate drawn off the final effect can be further processed to recover any values it may contain, exhausted to waste through line 132 (FIGURE 6) or recycled to the final effect evaporator through line 134. As shown in FIGURE 6, a branch line 136 controlled by a valve 138 leads from line 126 back to the dome 54 of the same effect through which the concentrate just passed. Thus, means are provided for recycling a portion of the concentrate at each evaporator stage.

The vapor condensing out on the evaporator tubes 50 and the feed preheater tubes 48 of all but the first effect is drawn off of the condensate reservoir 56 and delivered to flash tank 36 of the same effect through line 80. At this point, of course, the liquid condensate does not flash due to the fact that the entire effect is at substantially the same temperature and pressure. Flashing of a portion of the condensate does occur, however, as it is drawn off the bottom of the flash tank through line 140 and delivered to the flash tank of the succeeding effect which is at a lower pressure. This hot vapor is combined with the uncondensed vapor from the preceding effect evaporator which passes into concentrate chamber 18, up along partial wall 58 and over the top edge 66 thereof and impinges upon tube bundles 48 and 50. The non-condensables left in condensate chamber 56 are drawn off through line 142 where they ordinarily are vented to the same chamber of the subsequent effect through valve 144. If desired, these non-condensables may be vented to other processes through valve 145.

The advantages of the instant purification process are thus derived primarily through the use of the common enclosure 10 housing a plurality of falling-film evaporator effects and heat exchangers adapted to preheat the incoming feed prior to the time it enters the first evaporator tube bank up to nearly the inlet steam temperature. Depending upon the requirements of the particularly process, two or more modules, each of which contains a plurality of effects (usually 5 or 6), are connected in series with one another. These advantages can, perhaps, best be appreciated by reviewing the flow diagram of FIGURE 6 and relating same to an actual processing problem. For this purpose, the desalination of sea water has been selected as the processing problem although the equipment and method of using same are equally well-suited for use in other processes such as, for example, food processing, chemical plants, refineries, mining processes, sugar beet processing plants, power generation of both the nuclear and conventional types, etc. The desalination of sea water is, however, an ideal example for the reason that the ultimate in efficiency is necessary in order to render such a process commercially feasible.

With specific reference to FIGURE 6, therefore, it will be seen that the plant consists of N total effects with the first being designated by reference numeral 1, the second by reference numeral 2, the next to last by N–1 and the final effect by N. Between effects 2 and N–1 there would ordinarily be several additional effects al-

though the basic features of the process are found in the four effects shown. No attempt has been made to illustrate the individual modules housing the several effects although, as aforementioned, probably five or six individual effects would be provided in each such module.

The incoming raw sea water is taken from the source into line **146** and passed through a heat exchanger **30** where it is warmed by the hot vapors issuing from vapor outlet **28** of the final effect N and passed to said heat exchanger through line **148**. The warm sea water then is fed through line **150** to a second heat exchanger **152** where additional heat is extracted from the condensate issuing from the first heat exchanger **30**, the latter condensate being carried through line **154** and joined with the condensate taken through line **156** from the final stage flash tank **36N** prior to being delivered to said second heat exchanger **152**. The condensate from heat exchanger **152** constitutes the final purified product and is drawn off through line **158** for use or further processing. The heat exchanger **30**, of course, performs the valuable function of condensing all but the non-condensable vapors issuing from the final effect, thus maintaining the necessary temperature and pressure profile throughout the system. The feed requirements of the plant, on the other hand, may not be sufficient to accomplish this desired comdensation; therefore, provision is made for introducing an excess of raw cold sea water to heat exchanger **30** over and above that needed for processing and this excess is bled off through line **160** to waste. On the other hand, conditions may well be such that a cooler feed to exchanger **152** is desirable to establish a lower condensate temperature. If so, a by-pass line **162** connecting directly with line **150** downstream of the first heat exchanger **30** may be employed. By-pass valves **164** and **166** are used to control the flow of the raw feed through these alternate paths.

From heat exchanger **152**, the warmed raw feed moves through line **168** into U-tube heat exchanger **48N** of the final effect where it picks up heat from the hot vapors generated in flash tank **36N** as well as the vapors entering effect N from the preceding effect N–1. Note in the final effect N that the non-condensables from condensate chamber **56** pass out through line **142N** and join with the vapor from the final effect evaporator tubes **50N** that moves into the concentrate reservoir **18N** and are discharged through port **28** into line **148**.

The raw feed proceeds through heat exchanger **48** (N–1), thence on through successive heat exchangers (**48**) until it reaches exchanger **48(2)** and last of all exchanger **48(1)** in countercurrent flow relation to the vapors which are progressing through the system in the opposite direction. As the raw feed moves from effect to effect, it gets steadily hotter as does the vapor it extracts heat from. From line **168**, it moves into heat exchanger **48N** through inlet **110N** and emerges through outlet **112N** before proceeding on to exchanger **48**(N–1) where it enters through inlet **110**(N–1), etc. When the preheated raw feed leaves the second effect (**2**) through outlet **112(2)**, however, it may follow several alternative routes depending upon the requirements of the particular plant and, more particularly, the needs of a particular plant under a given set of existing conditions. As previously mentioned, the raw feed should be preheated to a temperature nearly as high as that of the processing steam entering the first effect before the feed is introduced into the first effect evaporator **48(1)**. These requirements may vary from day to day depending on the initial temperature of the sea water, atmospheric conditions, flow-rates, etc. Accordingly, means are preferably provided for regulating the temperature of the raw feed leaving the second effect before it is introduced into the evaporator of the first effect.

The first condition is where the heat that will be added by the U-tube heat exchanger **48(1)** of the first effect (**1**) is approximately what is required to bring it up to near the temperature of the process steam. In this event, the raw feed is merely cycled through the heat exchanger **48(1)** and sent directly therefrom through by-pass line **170** into the inlet **128** of the first effect evaporator **50(1)**. Valve **172** in outlet line **112(1)** from heat exchanger **48(1)** that is located downstream of by-pass **172** must, of course, be closed and valve **174** in the evaporator inlet **128** must be open.

A second condition is where the raw feed from exchanger **48(2)** is already preheated to the required temperature without even having to pass through the first effect heat exchanger **48(1)**. In this instance, the preheated feed is shunted off directly into the first effect evaporator through line **176** that interconnects lines **112(2)** and **128(1)**. This line **176** contains a valve **178** that is opened along with valve **174** while valve **180** in line **110(1)** is closed along with valve **182** that controls the flow of feed in line **112(2)** into the auxiliary heat exchanger **34**.

The last condition would be one in which additional preheating of the raw feed preparatory to introduction thereof into the first effect was needed, yet, less heat was needed than would be supplied if the feed were passed through heat exchanger **48(1)**. In this instance, valve **182** would be opened and valves **172** and **180** closed to shunt the feed directly through to auxiliary heat exchanger **34** where additional heat is added thereto taken from the hot condensate tapped off of the condensate chamber **56(1)** of the first effect and delivered to said heat exchanger through line **32**. The feed thus preheated is introduced directly from the auxiliary heat exchanger **34** into the first effect evaporator **50(1)** through line **130** that connects into inlet line **128** downstream of valve **174**. The condensate leaving the heat exchanger **34** through line **184** will customarily be sent to the flash tank **36(2)** of the second effect through line **186**; however, branch line **188** may be employed to carry the condensate elsewhere. Valve **190** in line **188**, together with valve **192** in line **186**, controls these alternate condensate flow paths. A line **194** containing valve **196** takes the condensate from the condensate tank **56(1)** of the first effect and delivers it either to line **186** or **32** as required. Valve **198** in line **32** shuts the flow of condensate off to the auxiliary heat exchanger **34**.

As above-described, the plant provides maximum versatility in controlling the inlet temperature of the feed to the first effect evaporator. As a practical matter, however, one or both of heat exchangers **48(1)** and **34** would be eliminated.

Process steam enters the condensate chamber **56(1)** of the first effect through line **200** and steam inlet **24**. It flows around the tubes of both the U-tube heat exchanger **48(1)** and the falling-film evaporator **50(1)**. The preheated feed enters dome **54(1)** of the first effect and drops down into annular chamber **52(1)** where a portion thereof may vaporize if the feed has been superheated with respect to the pressure existing in annular sea water flash chamber **52(1)** of dome **54(1)**. The liquid level in this annular chamber rises to a point where it begins to flow over weirs **202** connected into the tops of the evaporator tubes. As it passes over the weirs, a thin film of liquid forms on the inside of the tubes which vaporizes readily under the influence of the hot steam impinging against the outside thereof. The flashed vapor fractions of the feed drops down the inside surface of the tube and enters concentrate chamber **18(1)** along with the liquid fraction or concentrate which has become richer in impurities by reason of the evaporation process. These vapors within the concentrate chamber pass freely into the next effect (**2**) over the top of partial wall **58** as aforementioned. Such non-condensables as may be present in the process steam can pass from the condensate chamber **56(1)** of the first effect to the condensate chamber **56(2)** of the second effect by means of vapor line **142(1)**. This line contains a valve **144(1)** to drop the

pressure and control the rate of flow of the vent stream to the second effect.

The condensate is drawn off from condensate chamber **56(1)** of the first effect and, in most instances, is fed to the flash tank **36(2)** of the second effect where a portion thereof immediately vaporizes in the lower pressure environment of said second effect to join the vapors generated in the first effect evaporator **50(1)** for further preheating of the incoming feed and vaporization of the concentrate in the evaporator **50(2)**. In the meantime, the concentrate has been drawn off of the bottom of concentrate chamber **18(1)** and pumped by pump **120(1)** up into the evaporator dome **54(2)** of the second effect through inlet **122(1)** and concentrate line **126(1)**. If desired, a portion of the concentrate may be recycled back into the first effect evaporator **50(1)** by means of recycle line **136(1)** controlled by valve **138(1)**.

This procedure continues through the several effects, each of which operates at a slightly lower pressure than the preceding one until, ultimately, the Nth effect is reached. Here, as aforesaid, the non-condensable gases taken from the condensate tank **56N** are combined with the condensable vapors from the concentrate reservoir **18N** and fed to the heat exchanger **30** for final condensation. If desired, an entrainment separator **203** may be provided in the concentrate reservoir of the final effect to remove entrained liquid from the vapors therein before the latter are fed to the heat exchanger.

The concentrate from the Nth effect is pumped out of the concentrate reservoir and either thrown away or processed to recover any values it may contain. Alternatively, the concentrate from the final effect may be recycled back through the Nth effect evaporator **50N** by means of line **134** controlled by recycle valve **204**.

In closing, it would be helpful to examine briefly the heat and material balance that exists around a particular effect. From this, the production from said effect can be determined and, most significant, the thermal efficiency in terms of a gain ratio. In order that these formulas will be both intelligible and meaningful, it will be necessary to define the terms employed.

Employing the above terms, a reasonably accurate formula setting forth the heat and material balance around any one of the several effects is as follows:

$$W_{p(n)}h_{fgp(n)}=W'_{c(n)}\Delta t_{v(n-1)}+W'_{p(n)}h'_{fgp}+[W_{swf}-W'_{c(n)}-W'_{p(n)}]C_b-W_{swf}C_{swf}\Delta t_{swf(n)}-Q_{l(n)}$$

From the above heat and material balance, the production from effect "*n*" can be calculated and the sources of the extracted vapor defined as follows:

$$W_{p(n)}=\underbrace{\frac{W'_c\Delta t_{v(n-1)}}{h_{fgp(n)}}}_{\text{(Term I)}}+\underbrace{\frac{W'_{p(n)}h'_{fgp(n)}}{h_{fgp(n)}}}_{\text{(Term II)}}+\underbrace{\frac{[W_{swf}-W'_{c(n)}-W'_{p(n)}]C_b\Delta t_{b(n)}}{h_{fgp(n)}}}_{\text{(Term III)}}-\underbrace{\frac{W_{swf}C_{swf}\Delta t_{swf}}{h_{fgp(n)}}}_{\text{(Term IV)}}-\underbrace{\frac{Q_{l(n)}}{h_{fgp(n)}}}_{\text{(Term V)}}$$

Term I above is numerically equal to the water extracted by the condensation of vapor that results when the condensate flashes in the *n*th effect and drops from the condensing temperature in the $(n-1)$ effect to the condensing temperature in said *n*th effect.

Term II is numerically equal to the water extracted by the condensation of the vapor produced in effect $(n-1)$ and delivered to effect *n*.

Term III is numerically equal to the water extracted by the flashing of the raw feed as it drops from the vaporizing temperature of effect $(n-1)$ to the vaporizing temperature of effect *n*.

Term IV is numerically equal to the reduction in the amount of water extracted in Terms I and II about due to the removal of the latent heat of vaporization of the vapor fed to effect *n* and condensed out on preheater **48(N)** while warming the incoming raw feed.

Term V is numerically equal to the reduction in the amount of water extracted in Terms I and II by direct loss of heat energy to the environment.

Probably the most meaningful way of evaluating efficiency in an evaporator of this type is in terms of the

Symbol	Definition	Units
"W"	Mass rate of flow	Lbs./hr.
Subscript "p"	Product (extracted water) vapor	
Subscript "b"	Sea water or concentrate	
Subscript "c"	Condensate or product or process steam	
Subscript (1)	As related to first effect	
Subscript (n)	As related to *n*th effect of an N effect evaporator, i.e. $n=1, 2 \ldots N-1, N$.	
Subscript "N"	As related to the final effect of an N effect evaporator, i.e. $N=2, 3 \ldots N$.	
Subscript "fr"	Flashed vapor from flash tank 36	
Subscript "swf"	Raw sea water fed to evaporator prior to evaporation.	
Superscript prime "'".	A quantity entering an effect under consideration.	
"h"	Specific total enthalpy	B.t.u./lb.
Subscript "fg"	Relates the quantity identified thereby to the change in said quantity that takes place when fluid is either vaporized or condensed.	
"Δ"	A change computed by subtracting an inlet property from a corresponding outlet property.	
Subscript "v"	A value of the vapor phase	
Subscript "l"	A direct loss, either of heat (when associated with Q) or mass (when associated with vent to the atmosphere.)	
"Q"	Heat flow rate	B.t.u./hr.
"t"	Temperature	° F.
"C"	Specific heat of the fluid	B.t.u./lb./° F.
"GR_N"	Gain ratio of an N effect evaporator	Lb./lb.
"gr_n"	Gain ratio of the individual effect *n* of an N effect evaporator.	Lb./lb.
"U"	Overall heat transfer coefficient	B.t.u./hr./ft.²/° F.
"A"	Heat transfer area	Ft.²
"MTD"	Mean temperature difference	° F.
Subscript "i"	Refers to the value at the inlet to the equipment.	
Subscript "o"	Refers to the value at the outlet from the equipment.	

"gain ratio" achieved in each individual effect and overall. For an individual effect other than the first, this gain ratio may be defined as the ratio of water vapor extracted in effect n to water vapor extracted in effect $n-1$. In the first effect, the gain ratio is the ratio of water vapor extracted in effect 1 to the process steam fed to said effect expressed in units of "pounds per pound." Thus,

$$gr_n=\frac{W_{(n)}}{W_{p(n-1)}}$$

and for the first effect:

$$gr(1)=\frac{W_{p(1)}}{W'_{p(1)}}$$

The gain ratio for an N effect evaporator (GR_N) is the ratio of the net water extracted in the plant to the process steam supplied to the first effect. Thus:

$$GR_N=\frac{[W_{p(1)}+W_{p(2)}\cdots W_{p(n-1)}+W_{p(n)}]-\sum_{n=1}^{n=N}\text{Vent}_1}{W'_{p(1)}}$$

The relationship of the individual effect gain ratio (gr_n) is given by the following expression:

$$GR_N=gr_{(1)}+[gr_{(1)}-gr_{(2)}]+[gr_{(1)}-gr_{(2)}-gr_{(3)}]+\cdots+[\cdots gr_{(n-2)}-gr_{(n-1)}-gr_{(n)}]$$

From the foregoing relationship, it becomes apparent that the performance of the first effect influences the overall performance "n" times, the performance of the second effect influences the overall performance $(n-1)$ times, etc., until the performance of effect "N" is a factor of the overall performance only one time. It is essential, therefore, that, within the limits of practicality, as much preheating of the incoming raw feed be accomplished in each effect other than the first so that the latter will not be burdened with an unusually large preheating load (see Term IV of the production equation). Practically speaking, every effort must be made to preheat the raw feed to a temperature such that as it leaves the preheater **48** in each effect other than the first, it closely approximates the temperature of the steam entering said effect. The modular design disclosed herein is ideally suited to realization of the above ends because it maximizes the opportunities for effective preheating of the incoming raw feed due to the combined exposure of the U-tube heat exchangers **48** as well as the evaporator tubes to the same steam. This assures the fact that the feed preheaters will not be starved for heating steam. The prior art multiple-effect evaporators, on the other hand, do suffer from an inadequate supply of heating steam for the preheaters due to the restrictive effects of a separate preheater steam supply pipeline tapped off of the main steam supply leading to the evaporator.

From Term V of the production equation, it will be noted that a reduction in environmental heat losses contributes materially to the overall efficiency and economy of the plant. The instant modular design concept takes full advantage of this factor by enclosing several effects in a unitary double-walled insulated enclosure which is relatively small considering the equipment housed therein and presents, for this reason, a minimum of surface area through which heat may escape to the atmosphere.

The principal term of the production equation in terms of an efficiency evaluation is Term II. If one neglects the remaining terms of the production equation as being of lesser significance, the gain ratio of the individual effects can be stated as follows:

$$\frac{W_{p(n)}}{W'_{p(n)}}=\frac{h'_{fgp}}{h_{fgp}}$$

or, in other words, the ratio of the latent heats. In order to maximize the ratio of the latent heats, one must minimize Δt_v; therefore, GR is maximized by minimizing Δt_v. The pressure drop by which the condensate and vapor are made to flow from effect to effect is, likewise, directly proportional to Δt_v. Accordingly, the compact modular design that shortens the distances the vapors must traverse and produces the large unrestricted vapor flow paths along with the relatively small drops in pressure between effects, enables more effects to be used to cover a given range of operating temperatures. The overall result is a considerable gain in efficiency and reduced operating costs.

Other features contributing materially to the overall improvement in efficiency of the plant and process are the use of the evaporator dome wherein the concentrate builds up to a liquid level where it slowly and steadily overflows the weirs atop the evaporator tubes. In so doing, the distribution devices normally associated with the prior art falling-film evaporators are eliminated along with the high pressure drops ordinarily associated therewith. Reduction of the pressure drop experienced upon introduction of the raw feed reduces the pumping head necessary to transfer the concentrated brine from effect to effect and establish the falling-film therein. The construction of the upper falling-film tube sheet and annular sea water flash chamber cooperate to assure and extremely close approach to equilibrium by exposure to the nth effect pressure under turbulent, low static head conditions.

Condensate flow from the flash chamber of one effect to a like chamber in the next effect is accomplished by gravity flow which further reduces the mechanical energy requirements along with the required inter-effect pressure drop. Despite the fact that several effects are housed within a common enclosure, each effect is effectively and positively sealed off from the adjoining effects. This seal is accomplished either through the use of an impermeable metal barrier or a liquid loop, both of which prevent the bypassing of heating steam which is a bothersome problem in the prior art multiple-effect evaporators that results in a loss of efficiency.

The equation or heat transfer may be expressed as follows:

$$Q=UA(MTD)$$

If we solve this equation for area (A) thus:

$$A=\frac{Q}{UMTD}$$

it will be seen that the area requirements are minimized by increasing the mean temperature difference because the overall heat transfer coefficient (U) remain fairly constant and at a maximized value due to the benefits derived from equal distribution and carefully controlled flow-rates. The quantity "Q" represents the amount of heat that must be transferred to maintain a given production level.

In the preheaters **48**, MTD is defined as follows:

$$MTD=\frac{\Delta t_i-\Delta t_o}{l_n\Delta t_i/\Delta t_o}$$

in the normal manner for countercurrent flow and also for condensing heaters. The factors Δt_i and Δt_o in the foregoing equation may be expressed:

$$\Delta t_i=t_{W'p(n)}-t_{swfi(n)}$$

and

$$\Delta t_o=t_{W'p(n)}-t_{swfo(n)}$$

Substituting these values in the above equation and assigning an approximate value of "2" for the term

"$l_n\Delta t_i/\Delta t_o$"

in the denominator, one can arrive at a reasonably accurate value for the mean temperature difference of the evaporator in effect (n) as follows:

$$MTD=\frac{[t_{W'p(n)}-t_{b(\text{out of tube})}]}{2}+\frac{[t_{W'p(n)}-t_{b(\text{into tube})}]}{2}$$

Thus, it is easy to see that since the term $t_{W'p(n)}$ is reduced in proportion to the pressure drop in the vapor flow space, MTD for both cases above is maximized by

minimizing the pressure drop. The instant design, as previously mentioned, does, in fact, minimize the pressure drop thereby improving the efficiency. This same factor enables the surface area to be reduced and still provide a system that will function within a pre-selected temperature range and produce the anticipated flow of product. Full advantage of this fact is taken in the design of the heat transfer surfaces of the instant system thus resulting in a more efficient plant. The previously-mentioned characteristics of the evaporator dome, i.e., open-topped evaporator tubes, low head requirements and a close approach to equilibrium conditions bring the factor "$t_{b(\text{into tube})}$" in the above equation very close to the factor "$t_{b(\text{out of tube})}$" thus further increasing the mean temperature difference for the evaporator and contributing to an overall increase in efficiency.

Having thus described the several useful and novel features of the modular multiple-effect falling-film evaporator and method of using same, it will be apparent that many worthwhile objects for which it was designed have been achieved. Although but a single specific embodiment of the invention has been illustrated and described herein, we realize that certain changes and modifications therein may well occur to those skilled in the art within the broad teaching hereof; hence, it is our intention that the scope of protection afforded hereby shall be limited only insofar as said limitations are set forth in the appended claims.

What is claimed is:

1. The modular multiple-effect falling-film evaporator which comprises: an elongate insulated unitary pressure vessel having sidewalls, front and rear endwalls, a bottom and a top; at least two first transverse vertical partial partition walls arranged in longitudinally-spaced relation to the vessel endwalls and to one another, said partition walls terminating in spaced relation beneath the top of the vessel while extending all the way to the bottom thereof, and said partition walls cooperating with the adjoining vessel walls to divide the lower portion of the latter into a plurality of liquid-tight compartments arranged in end-to-end relation and adapted to receive progressively richer concentrated liquors beginning at the front end; a second transverse vertical partial partition wall corresponding to each of the first partial partition walls positioned in longitudinally spaced relation therebehind, each of said second partition walls extending from the top of the vessel to a level considerably below the upper margin of the adjacent first partition wall; a vertical longitudinal partition wall bridging the space between each set of adjacent first and second partition walls; a horizontal longitudinal partition wall joined to the vertical longitudinal partition wall and bridging the gap between each set of adjacent first and second partition walls in spaced relation beneath the top edges thereof and spaced above the bottom of the vessel, said vertical and longitudinal partition walls cooperating with one another, the adjacent vessel walls and said first and second partition walls to compartmentalize the space between the latter into an open-topped liquid-tight flash tank and an open-topped liquid-tight condensate tank arranged in side-by-side relation, and said horizontal partition wall further cooperating with the adjoining wall members to seal off the interior of the vessel into a plurality of separate vapor compartments adapted to receive hot condensable processing vapors generated in the preceding vapor compartment nearer the front end of said vessel and maintain same at a slightly reduced pressure; means comprising enclosed concentrated liquor reservoirs mounted in the top of the vessel in spaced relation above each of the condensate tanks sealed off from the vapor compartments therebeneath; means including a pump connected to withdraw the concentrated liquors from each compartment except the last and deliver same to the concentrated liquor reservoir of the subsequent effect; means comprising a plurality of open-ended evaporator tubes arranged in vertically-disposed spaced parallel relation to one another mounted within each vapor compartment in the path of hot processing vapors passing over the top of the adjacent first partial partition wall and down into the condensate tank, the upper open ends of the tubes being fastened in liquid-tight sealed relation within the corresponding concentrated liquor reservoir in position to continuously receive concentrated liquors therefrom and allow same to gravitate down the inside thereof, and the lower open ends of said tubes being connected through the horizontal longitudinal wall member in liquid-tight sealed relation thereto so as to deliver the hot processing vapors generated therein along with the more highly-concentrated liquor fraction directly into the subsequent concentrated liquor compartment and next lower-pressured vapor compartment; means connectable to a source of liquid evaporatable feed adapted to preheat same prior to introduction thereof into the concentrated liquor reservoir of the highest-pressured chamber, said means including at least two serially-interconnected multiple-pass heat exchangers mounted vertically within adjacent vapor compartments in position to extend downwardly into the condensate tank alongside the evaporator tubes, the colder feed entering the heat exchanger nearest the rear end of the pressure vessel and flowing therefrom through the remainder of said heat exchangers in counter-current flow relation to the flow of hot processing vapors, and the pre-warmed feed entering the first of the concentrated liquor reservoirs being taken from the heat exchanger located nearest the front end of the pressure vessel; means connected into the interior of the condensate tank of the highest-pressure vapor compartment adapted to withdraw vapors condensing out of the evaporator tubes therein and deliver same to the flash tank within the next lower-pressured vapor compartment; means opening into the interior of each of the remaining condensate tanks adapted to receive the vapors condensing on the outside surfaces of the respective evaporator and heat exchanger tubes therein and pass same to the flash tank alongside thereof; means connected to withdraw the condensate from the last-mentioned flash tank within each vapor compartment except the lowest-pressured one and deliver same to the flash tank in the next lower-pressured vapor compartment where a portion thereof vaporizes and joins the vapors generated within the evaporator tubes; vented means connected to receive the non-condensable gases from each of the vapor compartments and vent same; means connected into the interior of the highest-pressured vapor compartment and connectable to a source of hot processing vapors adapted to introduce the latter under pressure; condensing means connected into the interior of the lowest-pressured vapor compartment adapted to withdraw the condensable vapors therefrom and condense same; means connected to withdraw condensate from the flash tank of the lowest-pressured compartment; and means connected to withdraw the concentrated liquor from the concentrated liquor compartment in the lowest-pressured vapor compartment.

2. The modular multiple-effect evaporator as set forth in claim 1 in which: each of the second partial partition walls includes a portion extending along the bottom of the condensate tank that lies in spaced relation above the bottom of the vessel and another portion adjacent one the vessel sidewalls that extends all the way to the bottom of latter; the vertical longitudinal partition walls also extend all the way to the bottom of the pressure vessel and are joined to that portion of the second partial partition wall that also reaches the bottom thereof so as to cooperate with the latter, the adjoining first partial partition wall and the adjacent vessel sidewall to form the flash tanks; and, in which the horizontal longitudinal partition wall extends from the inside of the adjoining longitudinal vertical partition wall to the opposite sidewall of the vessel.

3. The modular multiple-effect evaporator as set forth in claim 1 in which: the multiple-pass heat exchangers are of the U-tube type.

4. The modular multiple-effect evaporator as set forth in claim 1 in which: at least one of the vented means is

connected to deliver the non-condensable gases to the next lower-pressured vapor compartment.

5. The modular multiple-effect evaporator as set forth in claim 1 in which: the means adapted to preheat the liquid feed prior to introduction into the liquid reservoir of the highest-pressured chamber is mounted within each of the vapor compartments.

6. The modular multiple-effect evaporator as set forth in claim 1 in which: the means for transferring the concentrated liquors from the concentrated liquor compartment of one effect to the concentrated liquor reservoir of the subsequent effect is provided with valved recycling means connected to recycle a portion of said concentrated liquor back through the concentrated liquor reservoir from whence it came.

7. The modular multiple-effect evaporator as set forth in claim 1 in which: the means for transferring the concentrated liquors from the concentrated liquor compartments to the concentrated liquor reservoirs have the major portion thereof passing up through the vapor compartments overlying said concentrated liquor compartments from whence said concentrated liquors were withdrawn.

8. The modular multiple-effect evaporator as set forth in claim 1 in which: the front, rear, sidewalls, bottom and top of the pressure vessel are double walls and include a dead air space therebetween packed with insulation.

9. The modular multiple-effect evaporator as set forth in claim 1 in which: the condensing means is connected to the source of cold feed and is adapted to pass the latter in heat-exchange relation to the condensable vapors taken from the lowest-pressured vapor compartment so as to condense same, and in which said condensing means is connected to deliver the feed thus pre-warmed into the first of the series of multiple-pass heat exchangers located within the lowest-pressured vapor compartment of those equipped with said heat exchangers.

10. The modular multiple-effect evaporator as set forth in claim 1 in which: the condensing means comprises the evaporator tubes mounted within the highest-pressured vapor compartment of a second modular multiple-effect evaporator serially connected to the first.

11. The modular multiple-effect evaporator as set forth in claim 1 in which: an external heat exchanger means is connected to the means for withdrawing the condensate from the flash tank within the lowest-pressured vapor chamber, said external heat exchanger means being connectable to the source of cold feed and adapted to pass the latter in heat exchange relation to said condensate, and said external heat exchanger means being connected to deliver the feed thus pre-warmed to the first of the series of multiple-pass heat exchangers located within the lowest-pressured vapor compartment of those equipped with said heat exchangers.

12. The modular multiple-effect evaporator as set forth in claim 1 in which: the means for transferring the condensate from one flash tank to the flash tank in the adjacent lower-pressured vapor compartment is contained entirely within said lower-pressured vapor compartment.

13. The modular multiple-effect evaporator as set forth in claim 1 in which: means comprising an external heat exchanger is connected between the final multiple-pass heat exchanger in the series thereof and the concentrated liquor reservoir within the highest-pressured vapor compartment; and in which the means for withdrawing the condensate from the condensate tank of the highest-pressured vapor compartment is connected into said external heat-exchanger so as to pass said condensate therethrough in heat exchange relation to the preheated feed prior to delivery of said condensate to the flash tank within the next lower-pressured vapor compartment.

14. The modular multiple-effect evaporator as set forth in claim 1 in which: the means for withdrawing the concentrated liquors from the concentrated liquor compartment of the lowest-pressured vapor compartment is connected to deliver same to a concentrated liquor reservoir located within the highest-pressured vapor compartment of a second modular multiple-effect evaporator serially connected to the first.

15. The modular multiple-effect evaporator as set forth in claim 1 in which: the concentrated liquor reservoirs comprise an apertured plate fastened to the upper open ends of the evaporator tubes in liquid-tight sealed relation, an inside continuous annular wall member connected to the peripheral edge of the apertured plate extending downwardly therefrom through the upper wall of the vessel, an outside continuous annular wall member spaced radially outward from the inside wall member and projecting thereabove, means bridging the space between the inside and outside annular wall members beneath the upper margins thereof and cooperating therewith to define a continuous annular trough adapted to receive the concentrated liquors and allow same to flow across the apertured plate into the evaporator tubes, and a cap bridging the upper margin of the outside annular wall member.

16. The modular multiple-effect evaporator as set forth in claim 2 in which: the means for transferring the condensate from the condensate tank to the contiguous flash tank comprises a tube having its inlet end opening through the horizontal longitudinal partition wall and its outlet end opening through the vertical longitudinal partition wall below said condensate tank.

17. The modular multiple-effect evaporator as set forth in claim 9 in which: the condensing means is connected to deliver the condensable vapors condensed therein to the means for withdrawing the condensate from the flask tank of the lowest-pressured vapor compartment, an external heat exchanger is connected to receive the warmed feed from the condensing means and deliver same to the first multiple-pass heat exchanger of the series thereof, and in which the means for withdrawing the condensate from the flash tank in the lowest-pressured vapor compartment is connected to deliver said condensate along with the condensed vapors from the condensing means to said external heat exchanger in heat exchange relation to the warm feed passing therethrough.

18. The multi-effect evaporator as set forth in claim 15 in which: means comprising upstanding hollow circular weirs are mounted atop each evaporator tube forming a continuation thereof, said weirs cooperating with the apertured plate and with the annular trough to cause the concentrated liquors to form a thin film on the inside of the tubes as it passes thereover.

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