INTERFACE ENHANCEMENT APPLIED TO EVAPORATION OF LIQUIDS

Filed Jan. 31, 1972 3 Sheets-Sheet 1

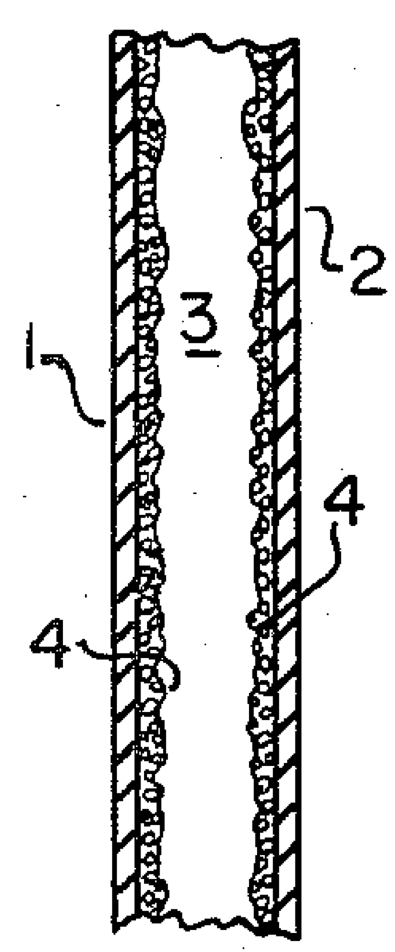

FIG. I

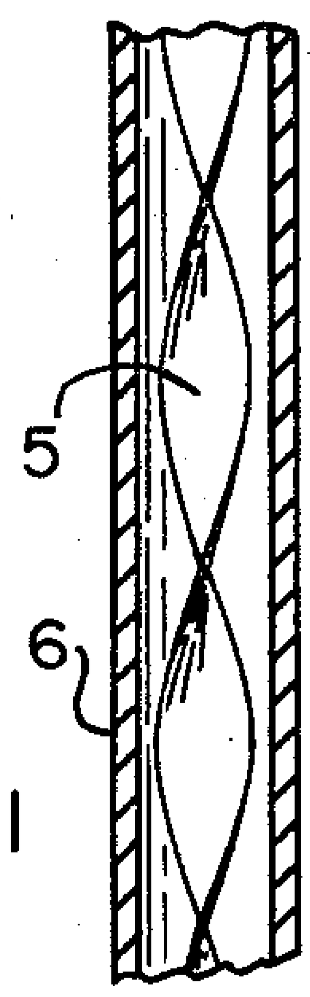

FIG. II

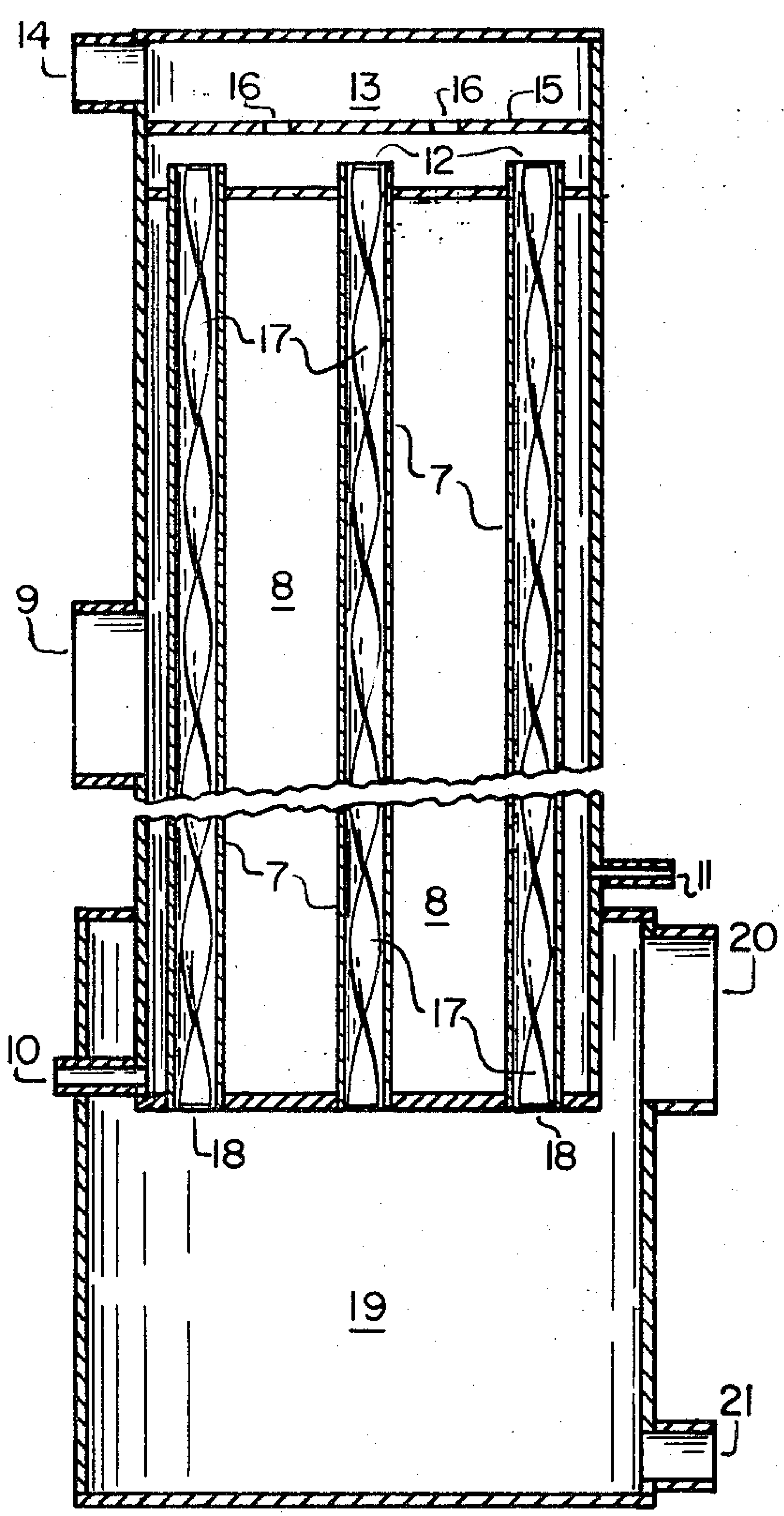

FIG. III

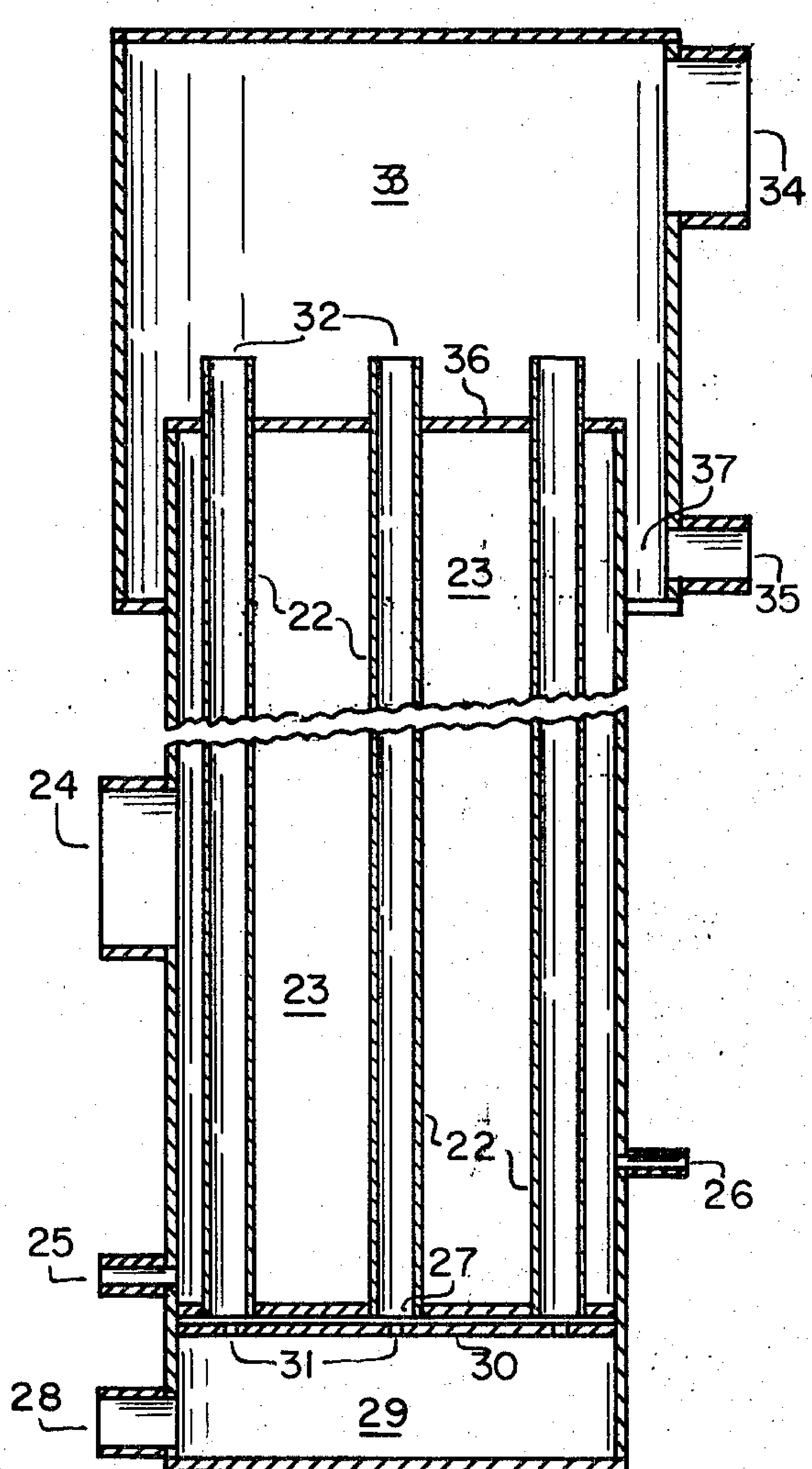

FIG. IV

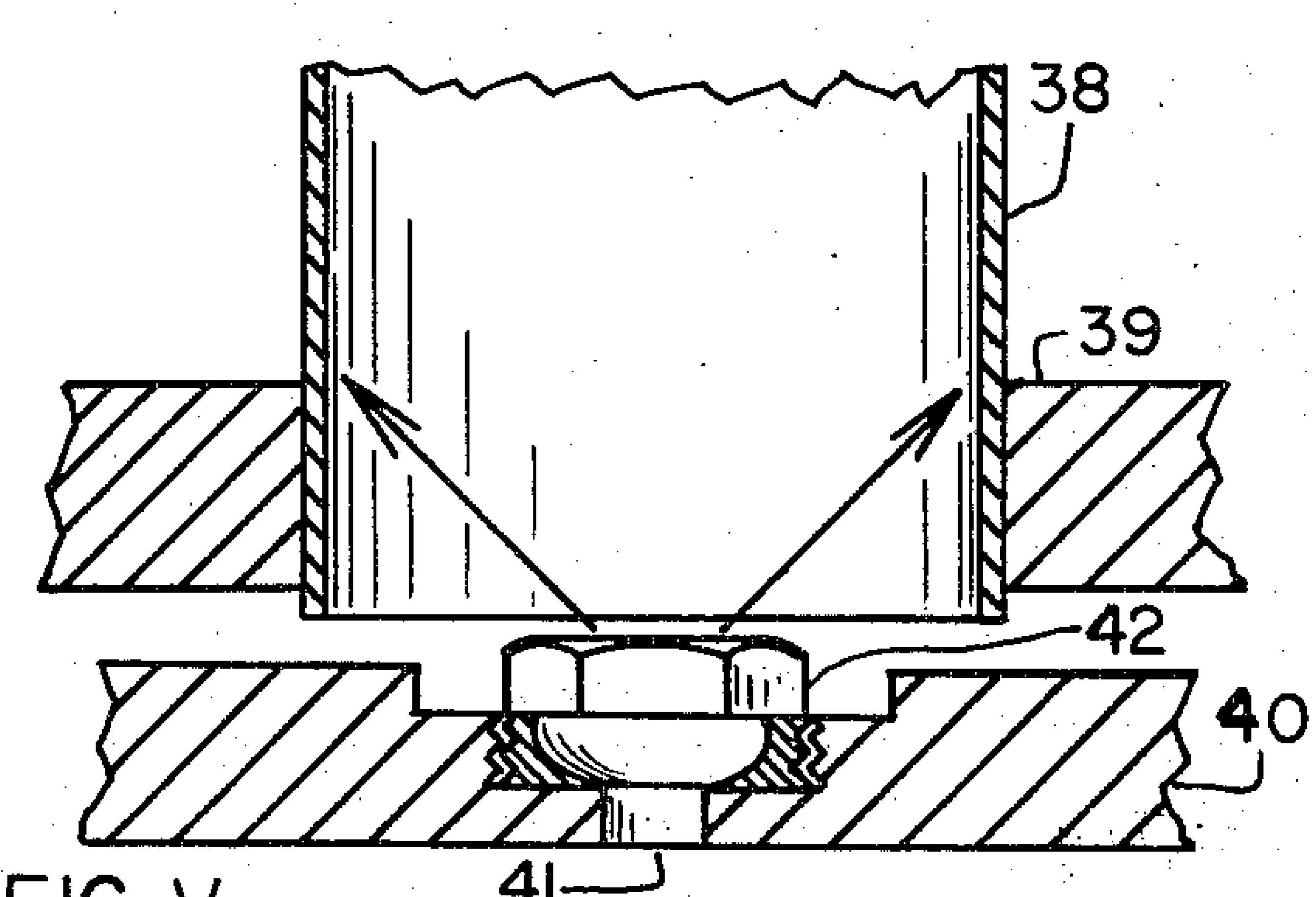

FIG. V

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FIG. VI

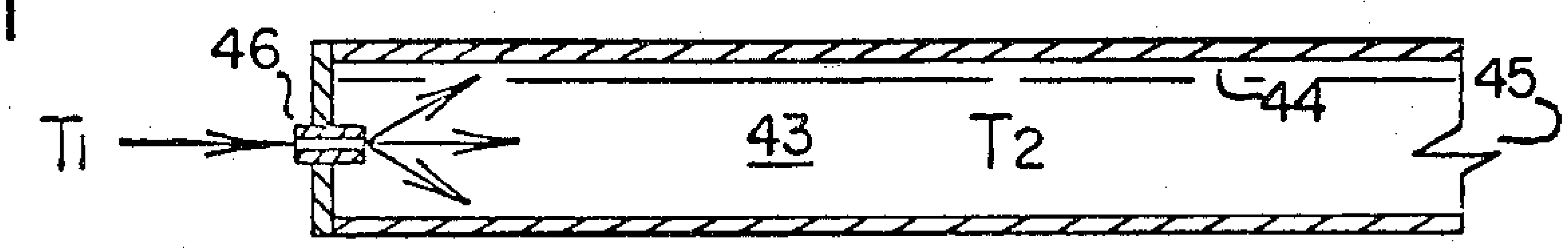

FIG. VII

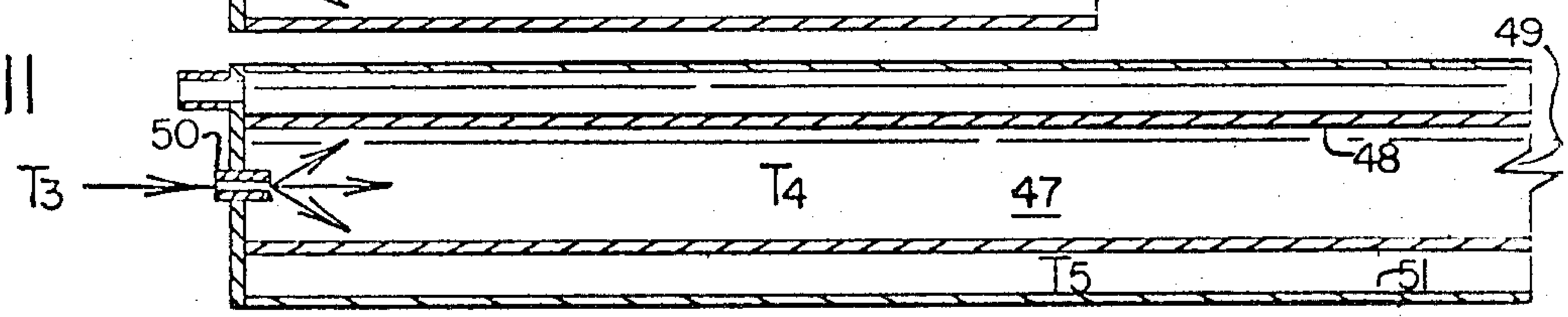

FIG. VIII

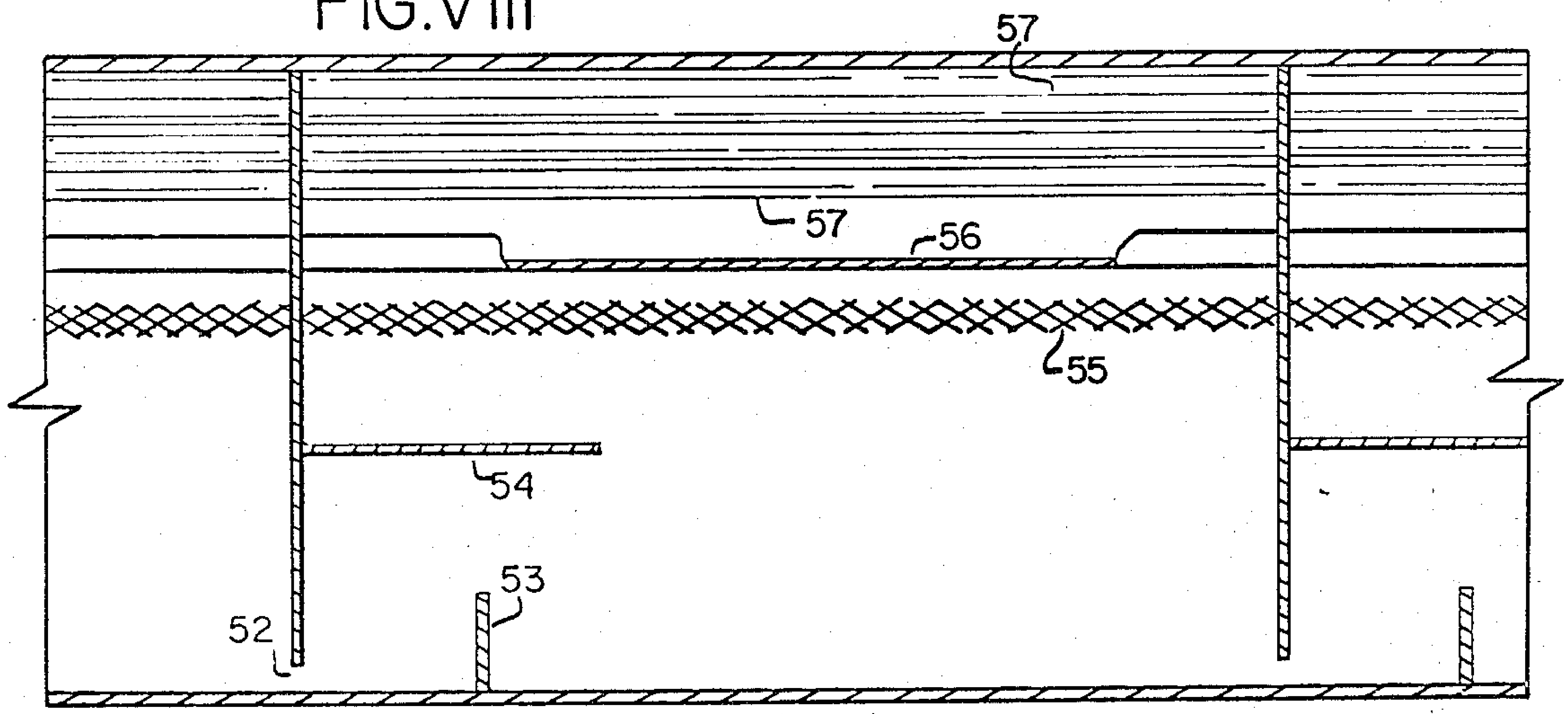

FIG. IX

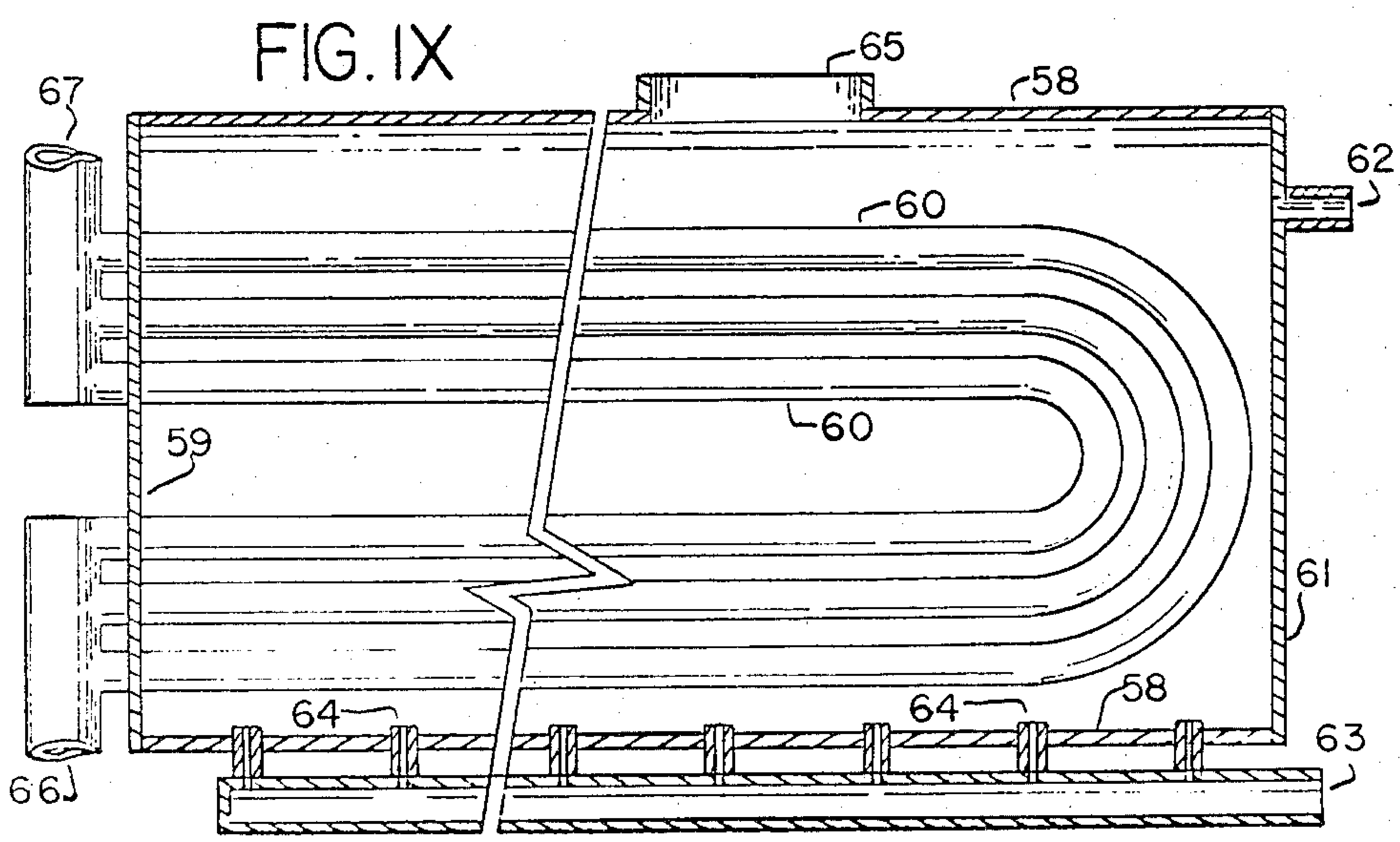

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FIG. X

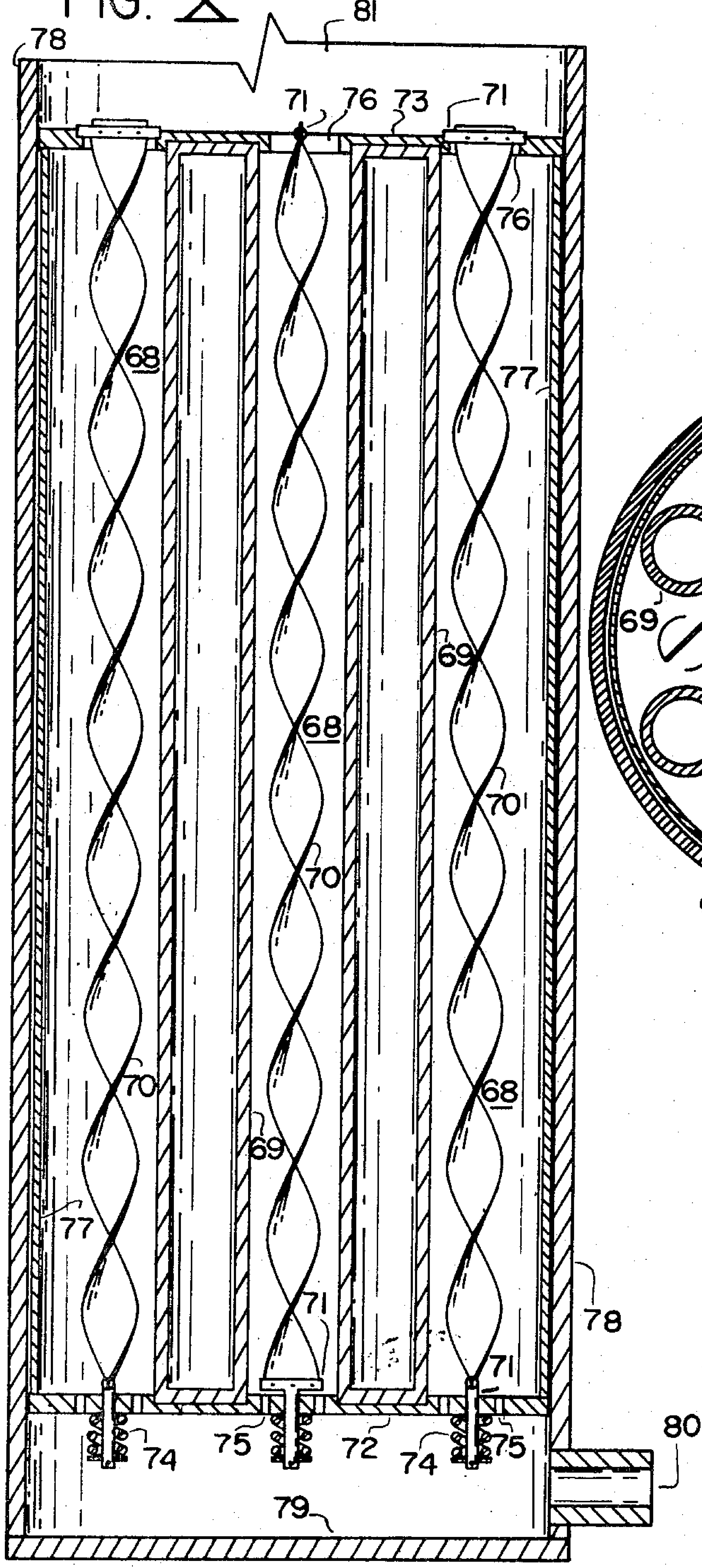
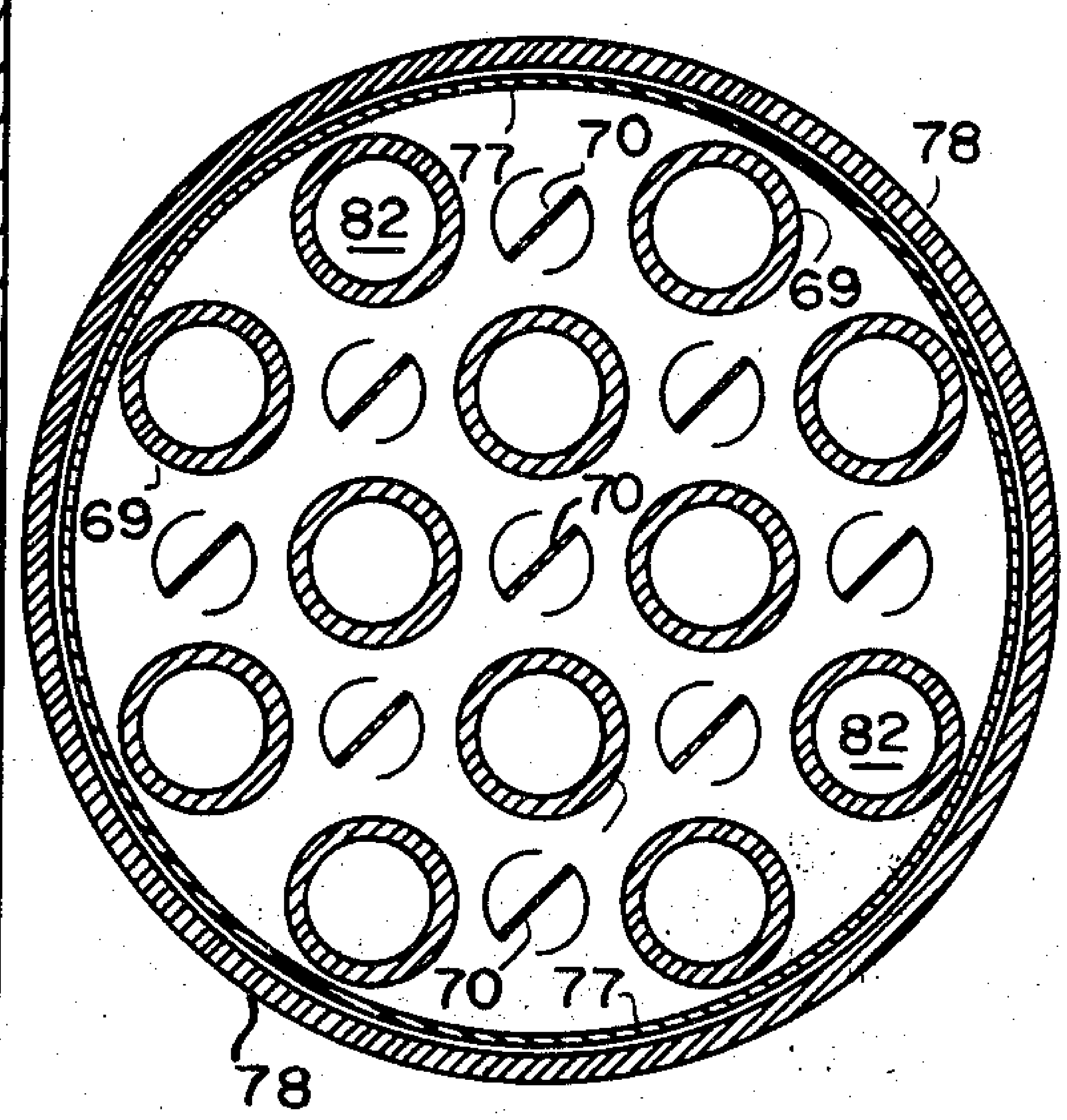


FIG. XI



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Patented Nov. 5, 1974

3,846,254

INTERFACE ENHANCEMENT APPLIED TO EVAPORATION OF LIQUIDS

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Continuation-in-part of applications Ser. No. 845,311, July 28, 1969, now Patent No. 3,648,754, Ser. No. 845,312, July 28, 1969, Ser. No. 845,313, July 28, 1969, Ser. No. 17,559, Mar. 9, 1970, and Ser. No. 52,658, July 6, 1970 all now abandoned. This application Jan. 31, 1972, Ser. No. 222,358
Int. Cl. B01d *1/22, 3/00, 3/08;* F25j *3/02*
U.S. Cl. 203—11 12 Claims

ABSTRACT OF THE DISCLOSURE

The rate of vaporization of a liquid is increased by imposing foamy two-phase flow thereon. This mode of imposed flow is dependent upon the addition of a foaming agent or a surfactant to the liquid and/or upon the process conditions applied to the liquid to create foaming, two-phase flow.

This application is a continuation-in-part of my copending applications S.N. 845,311, filed July 28, 1969, now Pat. No. 3,643,754, entitled Vortex Flow Process and Apparatus for Enhancing Interfacial Surface and Heat and Mass Transfer; S.N. 845,312, filed July 28, 1969, entitled Interfacial Surface Enhancement for Heat and Mass Transfer Processes; and S.N. 845,313, filed July 28, 1969, entitled Interfacial Surface Enhancement for Heat and Mass Transfer Processes, application S.N. 17,559, filed Mar. 9, 1970, entitled Interfacial Surface Enhancement to Increase Heat Transfer in Vertical Tube Evaporation of Saline Water and S.N. 52,658, filed July 6, 1970, entitled Interface Enhancement Applied to Evaporation of Liquids, the four later abandoned.

BACKGROUND OF THE INVENTION

Desalination of sea water is becoming increasingly important as a source of potable water for domestic and industrial use in many parts of the world. Distillation has to date proved to be the most practical method for large scale desalination installations. Two types of distillation processes predominate in this field. The multistage flash process, hereinafter sometimes referred to as MSF, having consecutive stages wherein vapor flash-off from the brine stream occurs at gradually diminished vapor pressures through the series of stages that are usually horizontally arranged, has in the past been predominant. The second process, vertical tube evaporation, hereinafter sometimes referred to as VTE, has for many years been the dominant process in the evaporation field in general and is now gaining acceptance as the most promising distillation process for sea water conversion.

Industrial acceptance of vertical tube evaporation as the most economical method of producing fresh water from sea water hinges heavily upon demonstrating high heat transfer coefficients in the evaporator tubes and on maintaining such high heat fluxes over long periods of operation. The key to such high heat fluxes is to establish and maintain an enhanced liquid (or brine) evaporation coefficient. This specification discloses methods and means with which to accomplish that goal.

While the method disclosed here can obviously be applied in many other fields and in many types of mass or heat transfer equipment, this disclosure will primarily relate to the desalination of sea water by VTE, and all other relevant applications will be implied as being included in or covered by this disclosure.

The method of heat and mass transfer enhancement disclosed herein relies primarily upon the addition of a

selected foaming agent or surfactant to the feed liquid to provide for, or to enhance its tendency for, foamy two-phase liquid-vapor flow as the liquid is evaporated while being passed through a suitable flow channel or evaporator wherein the pressure on the liquid is reduced. In the case of VTE of sea water the feed brine is evaporated as it is caused to flow either downward as a falling film, or upward as a rising film through a multiplicity of parallel evaporator tubes while heat of evaporation is supplied through the tube walls by condensing steam on the outside surfaces thereof. In either case the method disclosed here provides that the rates of evaporation of the liquid, or the overall heat transfer coefficients, are substantially increased, by as much as 100–200 percent or more as indicated by the examples disclosed herein. Such enhancement of heat and mass transfer is obtained with different types of distillation tubes, including smooth surfaced tubes as well as the best available enhanced types of tubes having double-fluted or spiral-corrugated wall surface modifications designed to increase heat transfer.

SUMMARY OF THE INVENTION

The present invention resides in the discovery that by providing for the inclusion of small concentrations of foam-producing surfactants (surface-active agents), as hereinafter defined, in a liquid and thereafter reducing the pressure on the liquid to create a foam from the liquid and adjacent vapor phase, significant enhancement of the heat and/or mass transfer rate with respect to the liquid and vapor is obtained. More specifically, in the case of VTE of sea water where the feed brine is evaporated as it is caused to flow either downward as a falling film, or upward as a rising film through a multiplicity of parallel evaporator tubes while heat of evaporation is supplied through the tube walls by condensing steam on the outside surfaces thereof, the method disclosed herein substantially increases the rate of evaporation of the liquid (or the overall heat transfer coefficient) by as much as 100–200 percent or more. Such enhancement of heat and/or mass transfer does not depend on the types of distillation tubes employed and is effective with smooth surfaced tubes and with tubes having double-fluted or spiral-corrugated wall surface modifications designed to increase heat transfer.

Although concentrations of foaming agent as low as 2 p.p.m.* have been found to enhance heat and mass transfer, concentrations of 100 p.p.m. or even higher have advantages. In the method disclosed herein, the high heat and/or mass transfer enhancement for VTE of sea water is associated with the formation or stabilization of an annular web or network of foam that is sheared (passes) over the heat transfer surface (tube inside wall surface), thus providing for evaporation from an activated thin film of liquid on the heat transfer surface and from an enlarged liquid-vapor interface.

The term "interface enhancement" as used hereinafter is intended to describe several effects such as (a) enhancing the metal-to-liquid interface by rendering the metal surface more hydrophilic to improve its wettability to ensure a continuous contact between a film of liquid and this surface, (b) enhacing the liquid-to-vapor interface by enlarging its surface area (as a result of foam formation) and to thus increase mass transfer from liquid to vapor phase and (c) enhancing (or activating) the liquid layer (film) by thinning, wiping or agitating a thin film of liquid over the heat transfer surface by means of a web or network of foam sheared or blown over this surface. As a result, heat passed through a tube wall has only to be conducted through a thin film of liquid to be utilized at

* Parts per million (p.p.m.).

the liquid-film-to-vapor interface for the liberation of vapor into the vapor bubble being sheared over the tube wall inner surface. In addition to its heat transfer enhancing effect, the present method of two-phase evaporative flow control also provides for several additional beneficial effects as discussed below.

This specification discloses various modes of two-phase flow imposed within evaporator tubes each of which involves enhancing or enlarging the interfacial surface areas, thereby increasing the overall rate of heat and mass transfer such as for vertical tube evaporation of saline water. The present invention results from either the adjustment of the chemical composition of the feed liquid to include a surfactant capable of creating foam or in processing liquid already containing such foam-creating substances to produce foam. Thus, the present invention results from the treatment of a surfactant-containing liquid in such a way as to establish bubbly or foaming two-phase flow over a heat transfer surface so that the heat added can increase mass transfer from the liquid to vapor.

Applicant's invention can be accomplished with any organic or inorganic material that induces foam or bubble formation in a liquid when the pressure thereon is reduced. Any of the conventional wetting agents, soaps, detergents, metal or solid surface coating agents or interface active compounds that provide this foamy phase are intended to be included as foaming agents.

Within this broad concept of particular use are those surfactants (surface-active agents) i.e., substances that, even though present in small amounts, exert a marked effect on the surface behavior of a system. Such agents are essentially responsible for producing great changes in the surface energy of liquid surfaces and their ability to cause these changes is associated with their tendency to migrate to the interface between two phases. The mechanism by which such surface-active agents alter the surface energy of a solid or liquid is attributed to the dual nature of the molecules or ions of these substances. Thus, within a single molecule or ion of a surface-active agent, there is a group that is lyophilic toward the dispersing medium or solvent, and at a suitable distance within the same molecule or ion, there is another group that is lyophobic toward the dispersing medium.

This ability to embody within the same molecular particle two different groups whose properties are diametrically opposed is sometimes termed amphipathy. For example, the surface atcivity of sodium oleate $NaOOCC_{15}H_{31}$ is attributed to the combined effect of the hydrophylic ionic carboxyl salt group at one end of the molecule and the hydrophobic hydrocarbon group that constitutes the remainder of the molecule. In a dilute solution of sodium oleate, the solute migrates to the surface where the hydrophobic parts of the molecule can achieve their lowest energy positions as the result of the solvent striving to exclude the hydrocarbon group from the solution. Even though the external phase is gaseous, the hydrophobic groups find a sufficiently sympathetic environment at the surface of the liquid. As a result, bubbles of entrapped vapor phase are formed at the liquid surface.

Surface-active agents are usually classified in three groups, anionic, cationic and nonionic types. Anionic types include carboxylate ions such as occur in sodium oleate. The carboxyl group may be attached directly to the hydrophobic group, or there may be an intermediate ester, amide, or sulfonamide linkage. There are a large number of anionic agents derived from sulfuric and sulfonic acids in which the hydrophobic groups attached to them include aliphatic and aromatic groups that often contain substituents of varying polarity, such as halide, hydroxyl, ether, and ester groups.

Cationic surface-active agents are usually derived from the amino group where, through either primary, secondary, or tertiary amine salts, the hydrophilic character may be achieved by aliphatic and aromatic groups that may be altered by substituents of varying polarity. Other nitrogen compounds, such as quaternary ammonium compounds, guanidine, and thiuronium salts, are included in the cationic class.

The third class of surface-active agents, the nonionic type, are organic substances which contain groups of varying polarity and which render parts of the molecule lyophilic, whereas other parts of the molecule are lyophobic. Examples include polyethylene glycol, polyvinyl alcohol, polyethers, polyesters, and polyhalides. In this class are often included certain colloidal substances such as graphite, powdered metals, metallic oxides, clays, macromolecules, and polymers. For purposes of simplicity of discussion, the surfactants (surface-active agents) will hereinafter be referred to interchangeably as foaming agents or foam stabilizing agents.

Included in the preferred types of surface-active agents are soaps, i.e., an alkali metal or substituted ammonium salt of a straight-chain carboxylic acid containing 10 to 18 carbon atoms. Also possessing advantages in the present invention are synthetic organic materials (detergents) having similar molecular structures, for instance the ammonium salts of sulphated linear primary alcohols containing several ethylene oxide units, of which Neodol (Shell Chemical Co.) is one example. The marked imbalance of polarity within the molecule of soaps and detergents causes them to have unusual solubility and phase characteristics in both polar and non-polar solvents.

Conventional polar groups commonly used in detergents to replace the carboxylate of conventional soaps, are derived from sulfuric acid. Examples include alkyl sulfate, alkane sulfonates and alkyl aryl sulfonates. The broad class of soaps and detergents, all useful in this invention are more clearly set forth in the McGraw-Hill Encyclopedia of Science and Technology, Vol. 12, 1966, at page 393 et seq.

Some liquid distillands have a tendency to foamy evaporative flow and in such cases the specific addition of foaming agents can be omitted. Evaporative heat transfer enhancement can in such cases be obtained by the VTE operating procedures described in this specification. However, the addition of small quantities of selected foaming agents or foam stabilizing agents to such distillands also provides for substantial further enhancement of the evaporative heat transfer coefficients of such liquids and of all distillands.

Furthermore, this specification anticipates that the foaming agent or foam stabilizing agent or agents that are either present in or specifically added to the liquid to be evaporated may be concentrated in the liquid by the prior partial evaporation of the liquid, and that the further evaporation of the partially concentrated liquid, having the foaming agent proportionately concentrated therein, is covered by the interface enhancement method of this specification. In addition, the recovery of such foaming agents from the concentrated liquid and their recycling in the liquid to be evaporated according to the interface enhancement method, is likewise covered.

The following modes of flow control and examples of practising this invention are discussed to disclose the method thereof:

A. Foamy flow condition imposed by means of foaming agent additives and/or by the process conditions applied. See FIG. I.

B. Combination of foamy two-phase flow, and vortex flow control within an elongate channel by means of a vortex-inducing helical insert. See FIG. II. The vortex flow control method and apparatus therefor were disclosed in U.S. Pats. Nos. 3,423,294 and 3,457,982.

C. VTE of sea water feed as a falling film (down-flow mode) with surfactant added to the feed. See FIG. III.

D. VTE of sea water feed as a rising film (up-flow mode) with surfactant added to the feed. See FIG. IV and FIG. V.

E. Vortex-inducing helical inserts in combination with C.

F. Vortex-inducing helical inserts in combination with D.

G. Several examples of up-flow VTE data obtained with fresh water and sea water feed having surfactant added thereto to provide for enhancement of the overall heat transfer coefficient by up to 200 percent are quoted.

H. Flash evaporation flow channel for mass transfer. See FIG. VI.
I. Flash evaporation and evaporative heat transfer flow channel (mass and heat transfer). See FIG. VII.
J. Flash evaporation of sea water. See FIG. VIII.
K. Enhancement of steam production in a boiler. See FIG. IX.
L. Enhancement of steam production in a nuclear reactor core. See FIG. X and FIG. XI.

Additional examples of the application of this invention are the following:

M. Use of high rates of vapor flow over the foamy liquid-vapor layer on a heat transfer surface to thereby increase shear and to further enhance evaporative heat transfer rates.
N. Bubbly or foaming evaporative liquid-vapor flow in various modes of flow, over heat transfer surfaces of different types, for instance fluted, scratched or indented surfaces.
O. Flat plate evaporator use of induced foamy two-phase flow.
P. Horizontally surfaced evaporators, for instance spinning disc types, used with induced foaming two-phase evaporative flow.
Q. Horizontally oriented tubular evaporators, used with foaming flow of a distilland either on the outside or on the inside tube surface.
R. Evaporation from the outside surface of tubes, with foaming distilland in a down-flow mode.
S. Wiped film evaporators having mechanical wiping means of various constructions.

LIST OF DRAWINGS

The methods of operation, and examples of evaporation and distillation apparatus that can be utilized to practice this invention are discussed with the aid of several drawings listed below. Up-flow, down-flow or horizontal-flow of liquids are included. This interface enhancement method can be applied to a wide variety of processes, operations and fluids.

DISCUSSION OF FIGURES AND METHODS OF OPERATION

Vertical tube evaporators usually comprises a multiplicity of heat transfer tubes extending in parallel orientation through a heating vessel or a steam jacket, and communicating with a liquid distilland distributor or inlet vessel at their inlet ends and with a vapor and liquid disengagement vessel at their opposite ends. Evaporation of the distilland usually occurs inside the heat transfer tubes as it is passed through these tubes, either in down-flow mode as a falling film or layer on the tube walls or in an up-flow mode whereby the liquid phase is subjected to vapor lift upward through the tubes. Heat for evaporating the liquid distilland is usually provided by steam or vapor condensing on the outer surfaces of the heat transfer tubes whence it passes through the tube wall by conduction and is utilized on the distilland side as heat of vaporization. The overall rate of heat flux, or the overall heat transfer coefficient, is composed of three elemental coefficients: The condensing coefficient, the wall material coefficient and the evaporating coefficient. Enhancement of any one of these coefficients will increase the overall coefficient or rate of heat flux. However, since the wall coefficient is usually relatively high, especially for copper or the copper alloys usually preferred in VTE applications, the overall heat flux is most effectively increased by enhancing the vapor condensation and the liquid evaporation coefficients. Several effective means for enhancing the vapor condensation coefficient are known, for instance by vertical flutes cut or indented longitudinally into the condensing surface, by double-fluting the entire wall to produce complementary flutes longitudinally on both the outside and the inside surfaces or by spiral-corrugating to form both surfaces into spiralled flutes or grooves.

The latter two types of tube wall modifications produce some enhancement of the liquid evaporation coefficient on the inside wall as well. Such wall modifications by fluting can provide for a 100 percent enhancement of the overall heat transfer coefficients in VTE. The methods disclosed in this specification have been found to further enhance the overall heat flux and heat transfer coefficients of such fluted types of tubes (as well as smooth tubes) by a further 100 to 200 percent, depending upon the concentration and the type of foaming agent added to the distilland. It was for instance found that the overall heat transfer coefficient under typical up-flow VTE process conditions can be doubled when five parts per million of a selected commercial surfactant was used, and similarly, a threefold enhancement was demonstrated when 50 parts per million of such a surfactant was used in sea water feed or fresh water feed evaporated in a VTE utilizing spiral-corrugated or double-fluted tubes in the up-flow mode, as indicated in examples quoted herein.

One of the purposes of this specification is to disclose and claim a method or mode of operation as applied to VTE in general. It includes the use of surfactant additives or foaming agents to the feed liquid to provide for a mode of two-phase liquid-vapor flow that is conductive to enhanced rates of evaporating heat or mass transfer. Another purpose is to provide and claim a method for enhancing interfacial surfaces (interfaces) for increased heat or mass transfer at a metal-liquid and at a liquid-vapor interface. Another purpose is to disclose and claim combinations of VTE modes of operation that depend upon the adjustment of the physico-chemical properties, or the composition, of the liquid-vapor system so that it will be conducive to foamy or bubbly two-phase evaporative flow through a flow channel, and ways to utilize this for heat and mass transfer enhancement. The means employed comprises the addition of a selected foaming agent, for instance a surfactant or detergent, to the feed liquid in a suitable concentration, introducing the feed into a distillation tube as a foamy layer on the inner wall thereof in the presence of its vapor phase, and evaporating it under two-phase flow conditions and evaporative heat flux rates that tend to maintain the foamy distilland flow condition over the heat transfer surface. One purpose of the surfactant additive is to maintain liquid film contact with the tube wall by rendering the wall surface more hydrophilic and to improve metal-to-liquid-phase heat transfer. This is especially advantageous if the tube surface should become covered during prolonged use, for instance by a porous oxide layer. The surfactant additive helps maintain liquid film continuity therethrough and film contact to the metal surface below such a porous layer. Another purpose of the additive is to enhance evaporative heat transfer by maintaining the liquid layer on the tube wall as a thinned and agitated film. Another purpose of the additive is to extend the liquid-vapor interface to provide an increased surface area for mass transfer. A further purpose of this specification is to disclose and claim a few specific examples of heat flux enhancement by combinations of the addition to the feed brine of surfactant and the imposition of shear-flow at the metal-liquid and at the liquid-vapor interfaces, and by imposed vortex shear-flow by means of a helical ribbon mounted co-axially within the VTE distillation tubes. Another purpose is to disclose and claim several beneficial effects of the use of surfactant additives to liquids in VTE use, added either continuously, intermittently or occasionally.

The preferred mode of two-phase flow of this specification is illustrated and discussed with reference to FIG. I, showing a section view of a portion of a flow channel and depicting bubbly evaporating flow on opposite heat transfer surfaces of a flow channel. It is intended that the heat transfer surfaces **1** and **2** shown can be curved, for instance in the case of a tube wall, or they may be flat, for instance in flat plate evaporators. Vapor flow through the channel **3** over the foamy layer **4** shown may be up or down and the foamy layer **4** may be in down-flow or in up-flow over th eheat transfer surfaces **1**, **2** and subject to interfacial shear at the vapor-liquid interface. Enhancement of evaporative heat transfer by interface enhancement and by induced foamy two-phase flow depends upon several factors: One of these is the greatly increased vapor-liquid interfacial surface area provided, to increase mass transfer from the liquid phase to the vapor phase. Another is the thinning of the liquid layer in contact with the heat transfer surface by means of the vapor bubbles enmeshed in the liquid layer to provide a thin film for an increased rate of heat transfer therethrough. Another factor is agitation of this thinned liquid layer (film) by the vapor bubbles being sheared thereover and the continuous renewal of this liquid film by this vapor bubble movement. This is comparable to a wiping action on the thin film by means of the web of foam. Another factor is that the metal-to-liquid interface is enhanced, for instance by providing for better wetting of the heat transfer surface by the liquid film and by preventing dry-out at this surface. Another factor that is especially important in up-flow operation is that the greatly increased abundance of vapor bubbles, resulting from the adjustment of the liquid feed for foamy flow, reduces the volume of liquid that is at any time retained in the evaporative flow channel to thereby reduce the hydrodynamic pressure gradient through the flow channel which in turn increases the effective ΔT, or temperature difference available for vaporization. This increased ΔT provides for an increased heat flux and this in turn provides for an increased abundance of vapor bubbles and an increased vapor-liquid interfacial shear effect—all of these tending to further enhance the heat flux and rate of vaporization. Vapor bubbles are initiated at the inlet to the distillation tubes and some of them will collapse as they become enlarged by vapor from the evaporation of the liquid film. New vapor bubbles are continuously initiated by nucleation on the heat transfer surface, especially under conditions of relatively high heat flux rates.

FIG. II shows, in section, a helical insert **5** mounted axially in a fluid flow channel or tube **6**, for instance by tensioning it. The purpose of the helical insert is to impose vortex flow within the vapor flow channel so as to effect phase separation and increased vapor-liquid interfacial shear. The vortex flow induced also provides for

the separation of liquid phase entrained therein from the vapor phase flow channel and to return this liquid to the wall layer where it can be vaporized further. The vortex flow control method and apparatus therefor are disclosed and claimed in my U.S. Pats. Nos. 3,423,294 and 3,457,982 respectively. Such helical inserts and such vortex flow imposed within VTE channels can be very effective for increasing heat transfer in conjunction with the foamy flow conditions of this specification. This is especially effective in the down-flow mode because it reduces entrainment which can be a problem in the down-flow VTE use of foaming agents. When used in up-flow VTE in conjunction with foamy two-phase flow, the helical inserts provide a central vortexing flow vapor phase channel which allows a vapor escape channel from the lower end of the tube. It also stabilizes the hydrodynamic flow through the channel by reducing oscillations in the axial direction of the flow channel. The conjunctive use of the helical insert of FIG. II with foamy two-phase flow shown in FIG. I is thus to impose vortex flow within the vapor phase channel **3** so as to control fluid flow, and to further enhance the heat flux.

With reference to FIG. III and the down-flow mode of operation, the invention of this specification can be practiced with most existing VTE apparatus after chemically adjusting or conditioning the feed liquid so that it is conducive to foaming two-phase flow, for instance by the addition thereto of a surfactant or a foaming agent.

In the down-flow VTE apparatus shown in FIG. III a multiplicity of evaporator tube **7** extend vertically through a suitable heat exchanger or steam vessel **8** or jacket having a steam inlet conduit **9** and a condensate outlet conduit **10** and a noncondensable outlet or vacuum conduit **11** connected therewith. The top inlet ends of the evaporator tubes **12** communicate with a liquid inlet vessel **13** having a liquid inlet conduit **14** connected therewith. Liquid flow or liquid and vapor flow into the evaporator tubes **7** may be distributed by means of a flat plate **15** having suitably spaced holes **16** drilled therethrough or it may have suitably spaced nozzles or holes for either direct or indirect distribution of liquid to the individual tubes **7**, or the tubes may be individually capped with suitable liquid or liquid and vapor distributing devices, for instance nozzles or swirl flow devices of any kind, or the individual tubes may be provided with liquid overflow weirs to distribute the liquid as a film onto the tube inner walls for down-flow as a thin layer or a falling film. Liquid and vapor flow within the tubes may be manipulated or controlled by means of helically twisted inserts **17** mounted under moderate tension axially within the tubes and imposing vortex flow within the two-phase system passing therethrough. The outlet ends of the tubes **18** communicate with a vapor and liquid blowdown vessel **19** wherein the vapor phase produced is disengaged from the liquid phase residue. The blowdown vessel **19** is provided with a vapor outlet conduit **20** and a residual liquid outlet conduit **21**. In practice the VTE can be operated as a single effect or as two or more effects coupled in a multi-effect series so that vapor produced in the first effect can serve as the heating fluid (or steam) for the second effect and so on down the series. In such an arrangement only the evaporator tubes of the first effect receive heat from an outside source, for instance steam from a boiler, and the condensate collected in that effect is usually returned to the boiler. All condensate collected from the steam vessels **8** of the remaining effects as well as those obtained in the heat reject condenser coupled with the last effect and from feed preheater condensers or heat exchangers are collected and pooled as the distillate produced by the VTE plant. Alternatively the heat of vaporization of the feed liquid can be provided by means of vapor compression, for instance by compressing vapor from the vapor outlet conduit **20** with a suitable compressor to a pressure and temperature sufficiently higher than the evaporation temperature of the feed liquid in the tubes 7 and to pass it through the steam inlet conduit 9 for condensation on the outside walls of the tubes 7 of the same effect (or evaporator) or to the tubes of another effect operating at a higher temperature in a multi-effect series. Thus mechanical energy can be converted into heat of vaporization of the liquid feed. Alternatively another form of energy, for instance pressurized steam or another pressurized fluid, may be utilized to compress the vapor from the vapor conduit 20.

One of the purposes of this specification is to disclose and claim the use of surfactant addition to the feed liquid for down-flow evaporation in a variety of apparatus of which the above is one. Other evaporators to which this specification apply are vertical or horizontal tube evaporators especially where the evaporating liquid is sprayed onto the tube outside surfaces or is allowed to cascade over a multiplicity of horizontal tubes, also plate type evaporators having flat evaporation surfaces for down-flow, up-flow or horizontal-flow of the liquid feed.

The effect of the addition of surfactant to the feed liquid in down-flow VTE operation is that it enhances the tendency for, or provides for bubbly or foaming two-phase evaporative flow thereof. Foamy flow may be initiated by the method of introduction of the distilland into the distillation tube (by turbulence, flash-down or hydrodynamic shock) or it can be initiated or augmented further downstream by nucleation on the heat transfer surface. This foamy flow condition is very beneficial for evaporative heat flux enhancement, in part because it provides for thin, activated layers of liquid on the heat transfer surface because of vapor bubbles being sheared or blown over this surface. Both the liquid layer or film on this surface and the bubbles enmeshed therein are thus continuously being renewed over a site on the evaporator surface to enhance the rate of evaporation, and the liqiud film is thinned and agitated by the vapor bubbles where they occur close to the surface, thus providing for activated thin-film evaporation. In addition, numerous such flowing bubbles are provided for and are sheared or blown over the surface to agitate and continuously renew the thin liquid layer, thus enhancing the rate of evaporation greatly. Furthermore the foaming flow condition thus created or maintained provides a greatly increased liquid-vapor interfacial surface area for enhanced rates of evaporation (mass transfer). In addition the metal-liquid interface is enhanced in that dry-out of the film on the heat transfer surface is reduced and a more intimate liquid-to-metal contact is provided for by the wetting action of the additive. Similarly, the use of surfactant in the up-flow mode of VTE operation, in a variety of apparatus including multi-effect and vapor compression applications, is covered though only one specific example is extensively discussed below.

With reference to FIG. IV and the up-flow mode of operation, this invention can be practiced with most existing VTE apparatus (and with other evaporators or steam generators) after adjusting the chemical composition of the feed liquid so as to provide for bubbly or foaming two-phase flow over the heat transfer surface. Also of importance, especially in the up-flow mode, is the mode of liquid distribution to, or its introduction into the evaporator tube or channel, in combination with the foaming additive, to establish a two-phase liquid-vapor flow condition at or near the entrance to the distillation tubes or flow channels.

In the up-flow VTE apparatus shown in FIG. IV a multiplicity of evaporator tubes 22, of which only three are shown, extend in parallel orientation through a suitable heat exchanger vessel or steam jacket 23 having a heating fluid inlet conduit 24, a heating fluid or condensate outlet conduit 25 and a noncondensable outlet conduit or vacuum conduit 26 connected therewith. The lower, inlet ends 27 of the evaporator tubes 22 communicate with a liquid distilland inlet conduit 28 via an inlet vessel 29 provided with feed liquid distribution devices, for instance a flat plate 30 having holes or nozzles 31 therethrough for distributing feed liquid to all the tubes 22 at the desired rate of flow. Provision can be made for lateral-flow redistribution of feed liquid so as to prevent starvation of some tubes resulting from malfunction or blockage of distribution devices, by providing a gap between the flat plate 30 and the inlet end of the tubes 27. Thus provision is made for mutually communicating inlet nozzles spaced from the inlet ends of a bundle of evaporation tubes or channels for equalizing fluid flow to the tubes. An important function of the holes or nozzles 31 is to provide a pressure drop or hydrodynamic shock, or turbulence, or flashdown in the feed liquid as it passes therethrough into the evaporator tubes 22 so as to initiate a bubbly two-phase liquid-vapor flow at or near the inlet ends of the tubes 27. Further vaporization of the feed liquid then ensues, because of heat transferred to it through the tube walls, resulting in a vapor lift or vapor shear to sweep the liquid phase up through the tubes 22, for instance as a rising film, and out through their outlet ends 32. Disengagement of the vapor from the residual liquid is provided for in a suitable vessel 33 into which the tube bundle outlet ends 32 extend. This vessel 33 is provided with a vapor outlet 34 and a liquid outlet 35 conduit. Provision is made to prevent the liquid from flowing back into the tube outlet ends 32, for instance by extending the tubes through the upper tube sheet 36 and by providing a channel 37 for drainage of liquid from the upper surface of this tube sheet 36.

Up-flow VTE can be accomplished with a single effect or evaporator, or by two or more evaporators operated in series or in multi-effect coupling with either compressed vapor or steam as the external source of heat, as described earlier for the down-flow mode of VTE operation. One of the purposes of this specification is to disclose and claim the interface enhancement method whereby bubbly or foaming two-phase flow is specifically imposed upon the distilland as it passes through the evaporator tubes for the purpose of greatly enhancing the evaporative heat flux and the distillate production capacity over those obtained by conventional operating procedures. Means for imposing, enhancing or maintaining bubbly two-phase evaporative flow are the addition of small quantities (order of about 1 to 100 p.p.m.) of selected foaming agents or surfactants to the distilland, and the method of introducing the distilland into the tube in such a manner that a liquid-vapor interface is provided at the inlet end of the evaporator tube or close thereto.

In the up-flow mode of VTE operation with interface enhancement it is preferred to introduce the distilland through a suitable nozzle or valve, or an orifice comprising a port of flow diameter less than that of the evaporator tube or flow channel into which the feed is introduced. It is especially beneficial if a foamy consistency in the feed is established immediately after passing through the port, and if the temperature of the foamy feed at this location is lower than the temperature of the heating fluid or steam on the outside of the evaporator tube. To establish such a condition it is sometimes required that the temperature of the feed liquid before entering the port to the evaporator tube be higher than the temperature of the heating fluid or steam on the outside of the evaporator tube (superheated feed) and to cause the feed to flash down (to produce liquid-vapor foam) upon entering the tube through the port, preferably to a temperature below the steam side temperature. FIG. V illustrates the preferred inlet for up-flow VTE in combination with foamy two-phase flow. It shows, in section view, portions of an evaporator tube 38 extending through the lower tube sheet 39 of a steam vessel or jacket, and a distributor plate 40 with an orifice 41 drilled therethrough, and a nozzle 42 for distributing the feed on to the tube surface. A gap is provided between the lower end of the tube 38 and the distributor plate 40 to provide for lateral-flow redistribution of feed to tubes that may be deficient in feed flow rate because of blocked or malfunctioning feed inlet orifices. This gap can be varied anywhere from zero to a substantial size, depending on circumstances. For instance, a gap of up to several inches can be useful to provide for maximal turbulence immediately above a multiplicity of close-spaced nozzles to thereby induce maximal foaming, yet allow sufficient space for dissipation of this turbulence before the feed enters the tubes. In addition to serving as a feed flow equalizer to parallel flow channels the spaced relationship between the lower tube sheet **39** and the distributor plate **40** thus also serves to provide the desired foamy two-phase condition of the feed at the inlet ends of all the tubes. Excessive turbulence in the tube inlet can produce undesirable erosion of the tube wall. The preferred nozzle shown is of the swirl-flow type commonly used in lawn sprinkler systems, and distributes the feed by swirling flow, projecting it as an inverted cone towards the tube wall. This inlet device is designed to initiate foamy two-phase flow by means of turbulence, hydrodynamic shock or flashdown of feed liquid. The foamy two-phase system then flows up the tubes **22, 38,** subject to further vaporization of the distilland by heat passing through the tube walls, and an increasing vapor phase volume and flow rate is thus provided to transport the residual liquid phase up through the tubes **22, 38,** by vaopr lift or by a shear effect between the vapor phase flow, the annular web of foam and the film of liquid in contact with the inside wall of the tube.

Because of the increased vapor phase flow rate of foamy liquid-vapor layer is thus blown or sheared upward over the heat transfer surface, especially in the upper half of the evaporator tubes, providing an agitated thin liquid film in contact with this surface, for a greatly enhanced evaporative heat transfer coefficient. In addition, the upflow mode provide for agitation of the liquid-vapor mixture which can fill part of the lower half of the evaporator tubes, by means of larger bubbles or aggregates of vapor breaking through the foamy liquid-vapor mixture and agitating it. This agitation and mixing is transferred to the liquid layer in contact with the tube wall is the lower reaches of the evaporator tubes, thus contributing to the greatly enhanced evaporative heat transfer coefficient. A condition of activated or sheared vapor bubbles enmeshed in a liquid and an activated or constantly renewed thin film of liquid on the heat transfer surface is thus prevalent throughout most of the evaporator tubes and this flow condition is largely responsible for greatly enhanced VTE heat transfer coefficients over the prior art.

One of the purposes of establishing a foamy or bubbly flow condition is to provide for a reduction in the hydrodynamic pressure gradient through the tubes (sometimes referred to as the hydrostatic head or back pressure or pressure drop) to approximately one quarter or one third of this gradient without the sustained foamy flow condition through the tubes. This has a distinct advantage over the prior art because it provides for an increase in the actual available ΔT or the temperature difference available to provide vaporization, summated along the length of the tube. This also provides that one can operate with a much reduced overall ΔT and still maintain upflow stability. Another such advantage is that the mode of two-phase flow described here provides a greatly enhanced hydrodynamic stability, or a reduction in the magnitude of fluid oscillation within the evaporation tubes. Another advantage of this method of VTE operation is that it provides for the use of longer evaporation tubes as compared to the prior art, because of the reduction of the hydrodynamic pressure gradient, and this can result in further economies in material. Another advantage of this mode of operation is that process stability of the upflow VTE process is extended into a range of operating conditions that are not practical without the benefit of induced foamy two-phase flow, for instance to low overall ΔT values, low feed flow rates, low feed temperatures (superheat), etc.

The major advantage of interface enhancement applied

to VTE is that it results in greatly enhanced overall heat transfer coefficients and evaporator productivity rates. Such enhancements to 100 and 200 percent over typical prior art conditions are readily obtained, dependent upon the type and concentration of surfactant added to the feed, for instance fresh water, brine or sea water, and upon operating the up-flow VTE as detailed in this specification, as shown in specific examples below.

Another advantage of this interface enhancement method of operation is that dirt or particulate matter, for instance scale and rust, tend to become or to remain suspended in the residual liquid phase and it is thus removed from the VTE installation with the residual feed liquid discharged rather than be accumulated on the heat transfer surfaces to the detriment of heat flux. This results in extending the effective periods of productive operation between interruptions for reconditioning the heat transfer surfaces. Another advantage to the use of surfactant additives in up-flow VTE results from their effectiveness in clearing or blowing off water-logged evaporator tubes by the foaming action, especially during start-up of a VTE plant from cold. In such use the surfactant can be added to the feed liquid occasionally in a single application or intermittently, in relatively higher concentrations than proposed above. It has also been observed that during intermittent addition of surfactant to the feed liquid, the enhancement effect tapers off rather gradually, probably because of adherence of surfactant to the heat transfer surfaces. On this basis it is advantageous in some cases to add surfactant intermittently to the feed stream, or at regular intervals rather than continuously.

EXAMPLES

To further illustrate the invention several examples are summarized below comprising test data obtained with fresh water and brine feeds before and after addition thereto of selected surfactants. These data were obtained under typical up-flow VTE process conditions, relevant to a multi-effect large desalination plant, including pretreatment of the feed for the purpose of scale control by the addition of sulphuric acid, and the usual deaeration or de-gassing of the feed and adjusting the pH of the feed to about pH 7.

Example 1: Up-Flow VTE Data; Double-Fluted Distillation Tubes

Overall Heat Transfer Coefficient, U, in B.t.u. per hr.-ft.^{2}-° F., Obtained with Surfactant Additive to Fresh Water Feed in Increased Concentration (Procter and Gamble's Joy, in p.p.m.).

P&G Joy, p.p.m. in fresh water feed:	U
0	1050
5	1600
10	1750
20	1900
30	1970
40	1990
50	2000

Double-fluted copper-iron tubes (CDA 194), 3-inch diam. x 11-foot long; $\Delta T = 10°$ F.; Feed flow rate 2 g.p.m. per tube; Evaporation temperature 210° F.; Steam side Temp. 220° F.

Example 2: Up-Flow VTE Data; Double-Fluted Distillation Tubes

Overall Heat Transfer Coefficient, U, in B.t.u. per hr.-ft.^{2}-° F., Obtained Through a Range of Evaporation Temperatures with Fresh Water Feed Before and After Having 50 p.p.m. Surfactant (Procter and Gamble's Joy) Added Thereto.

Evaporation Temperature, ° F.	112	135	160	190	210
U, fresh water feed without surfactant	[1] ±500	650	900	1,150	1,200
U, fresh water with surfactant, 50 p.p.m.	1,100	1,300	2,000	2,250	2,400

[1] Unstable.

Double-fluted copper-iron tubes (CDA 194), 3-inch diam. x 11-foot long; ΔT=10° F.; Feed flow rate 2 g.p.m. per tube. Flashdown of the feed was maintained at the tube inlet ends.

Example 3: Up-Flow VTE Data; Spiral-Corrugated Distillation Tubes

Overall Heat Transfer Coefficient U, in B.t.u. per hr.-ft.^{2}-° F., Obtained with Fresh Water and Sea Water Feeds having Surfactant Additive (Neodol, Shell Chemical Co.) in Increased Concentrations (p.p.m.).

Neodol additive, p.p.m.	0	2	4	6	10	20	30	50
U, fresh water feed	1,250	1,500	2,050	2,400	2,920	3,270	3,450	3,800
U, sea water feed	1,300	1,800	2,450	2,750	2,920	3,150	3,300	3,700

Spiral-corrugated copper tubes, 2-inch diam. x 11-foot long; ΔT=10° F.; Feed flow rate 1 g.p.m. per tube; Evaporation temperature 210° F.; Steam side temperature 220° F.; feed temp. 221° (±1°) F.; flashdown temp. of feed passing through the inlet nozzle about 5° F.

Example 4: Up-Flow VTE Data; Spiral-Corrugated Distillation Tubes

Overall Heat Transfer Coefficient U, in B.t.u. per hr.-ft.^{2}-° F., Obtained through a Range of Evaporation Temperatures with Fresh Water and Brine (3.5% NaCl) Feeds Before and After Having 50 p.p.m. of Surfactant (Procter & Gamble's Joy) Added Thereto.

Evaporation temperature, ° F.	135	145	175	210	235
U, fresh water feed	550	650	900	1,150	1,350
U, fresh water plus 50 p.p.m. surfactant	1,300	1,700	2,650	3,400	3,600
U, 3.5% NaCl feed		800	2,200	1,300	1,500
U, 3.5% NaCl feed plus 50 p.p.m. surfactant		1,550	2,550	3,300	3,600

Spiral-corrugated copper tubes, 2-inch diam. x 11-foot long; ΔT=10° F.; Feed flow rate 1 g.p.m. per tube. Flashdown of the feed was maintained at the tube inlet ends.

Example 5: Up-Flow VTE Data; Spiral-Corrugated Distillation Tubes

Overall Heat Transfer Coefficient U, in B.t.u. per hr.-ft.^{22}-° F. Obtained through a Range of Evaporation Temperatures with Sea Water Feed Before and After Having 7.5 p.p.m. of Surfactant (Neodol, Shell Chemical Co.) Added Thereto.

Evaporation temperature, ° F.	212	225	240
U, sea water feed	1,100 (for ΔT range 5.3–6.5° F.)	1,170 (for ΔT range 5.1–5.2° F)	1,500 (for ΔT range 4.5–5.0° F.)
U, sea water plus 7.5 p.p.m. surfactant	3,100 (for ΔT range 3.2–4.9° F.)	3,050 (for ΔT range 3.4–5.1° F.)	3,100 (for ΔT range 4.5– 5.0° F.)

Spiral-corrugated copper tubes, 2-inch diam. x 11-foot long; ΔT as indicated in table; Feed Flow at 0.5 to 1 g.p.m. per tube. The ΔT applied was in each case in minimal ΔT required to maintain up-flow hydrodynamic stability; the data show that interface enhancement increases up-flow stability to provide for stable operation at reduced ΔT; feed temp. ranged from 3° F., below to 5° F., above the steam side temp.; the hydrodynamic pressure gradients through the distillation tubes were equal to about 40 inches water pressure for the U-data obtained without a surfactant added to the feed, and equal to about 14 inches of water pressure when 7.5 p.p.m. of surfactants were added to the sea water feed.

Example 6: Up-Flow VTE Data; Double-Fluted Distillation Tubes

Overall Heat Transfer Coefficient U, in B.t.u. per hr-ft.^{2}-° F., Obtained through a Range of Evaporation Temperatures with Sea Water Feed Before and After Having 6 p.p.m. Surfactant (Neodol), Shell Chemical Co.) Added Thereto, Under Process Conditions Simulating Those of a Large Multi-Effect Up-Flow VTE Plant Producing Distilled Water and an Effluent of Three-fold Concentrated Brine from Sea Water Feed.

Evaporation temperature, ° F.	140	150	160	175	190	210	235
U, sea water feed	500	625	700	750	850	950	1,075
U, sea water plus surfactant	900	1,150	1,300	1,600	1,750	2,000	2,200

Double-fluted 90–10 copper-nickel tubes (CDA 706), 2-inch diam. x 14-foot long; ΔT Range 8–10° F.; Feed flow rate 1 g.p.m. per tube. Flashdown of the feed as it passed through the inlet nozzles was maintained; the steam temp. was 8 to 10° F. above the evaporation temp. and the feed temp. was maintained at 0 to 2° F. above the steam temp. for this series of U-data.

Having discussed the use of this method of enhancing VTE heat transfer for two specific modes of operation it will be understood that much wider applications are implied as thereby covered, as will become apparent to those skilled in the art. For instance, since the rate of evaporation is in part dependent upon interfacial shear between the vapor phase flow and the foamy layer of liquid-vapor on the heat transfer surface it is beneficial to operate under VTE process conditions that provide for increased vapor phase flow, for instance a relatively high ΔT or a longer, narrower evaporator tube, or vortex inducing helical inserts in tubes, or tubes having enhanced heat flux capabilities provided by different means, for instance fluted or scratched or porous or dented surfaces, or enhanced steam side condensation coefficients, for instance by dropwise condensation promotion by non-wetting surfaces. The use of vortex inducing helical inserts in conjunction with interface enhancement is particularly attractive, especially in the downflow mode of VTE operation because it can provide added interfacial shear, and phase separation to prevent removal of liquid phase from the tube wall and to provide for further heat transfer enhancement when surfactants are added to the distilland. In the up-flow mode, relatively narrow helical baffles mounted under tension centrally within the tubes can provide a vortex flow escape channel for vapor centrally up through the tube, to thus prevent hydrodynamic instabilities and to prevent flooding of the lower ends of the tubes with liquid phase. Such helical inserts are shown in FIG. II at 5 and in FIG. III at 17. The preferred helical inserts are narrower in width than the tube internal dimension and are mounted therein under moderate tension by anchoring or securing them non-rotatably at the ends thereof. In most of these cases where enhanced shear-flow is imposed it is of importance to recognize that increased shear-flow can result in prohibitively large pressure drops through tubes, which in turn can reduce the effective ΔT available for evaporation of the distilland as it passes through the tube. One therefore has to consider what the most effective combination of ΔT and pressure drop is in utilizing shear-flow for added heat flux enhancement by the methods described in this specification.

It is to be understood that this specification covers existing evaporation apparatus of both up-flow and down-flow types when used with interface enhancement and other evaporators that are specifically designed to utilize the high evaporative heat transfer coefficients provided for by the methods and modes of operation described in this specification. It also is to be understood that the flow channel may be other than tubular, for instance a rectangular vessel, and the heat transfer and evaporation surface may be flat, concave or convex and that additional means of liquid flow control and distribution or manipulation may be employed, for instance evaporation from a spinning disc, cone or tube or from a liquid film wiped on to a heat transfer surface of any dimension, contour or disposition. One of the purposes of this specification is to provide for heat transfer enhancement by a method of imposing, maintaining or enhancing bubbly or foamy two-phase flow over any and all types of evaporator heat transfer surfaces, however these are constituted, modified or operated. For instance, the use of foaming agents or of surfactant additives to the distilland or feed liquid for evaporators utilizing smooth-surfaced tubes, fluted tubes, double fluted tubes, spirally indented or spiral-corrugated tubes or tubes having other surface modifications, for instance scratches, indentations, protuberances or sintered or porous layers overlaying or attached to or integral with such tube surfaces, are all intended to be covered by this specification and claims. This specification also applies to combination plants and apparatus utilizing VTE in a portion only of the overall installation, for instance in combination VTE and multistage flash evaporation plants for desalination of sea water.

Having disclosed specific methods of VTE operation and modes of evaporative two-phase flow to enhance heat transfer, it is to be understood that this specification has much broader applications and that all such applications are intended to be covered thereby. For instance, several additional applications of interface enhancement are briefly discussed below with the aid of the drawings.

The interface enhancement method of this specification can be utilized for the purpose of increased mass and/or heat transfer between components of a fluid within a flow channel or a vessel or betwen the fluid and the channel wall or a fluid passed in heat exchange relationship therewith. Evaporative flow of the fluid can be horizontal, up-flow or down-flow or cascading through the channel, and heat of vaporization can be derived from the sensible heat in the fluid or it can be added thereto through the wall of the channel or vessel. The flow channel can be tubular or open (as in a trough) and its wall can be rectangular or irregular, for instance the interstitial channels formed between parallel rods, plates, tubes or heat transfer bodies providing heat of vaporization of a liquid. Such modes of flow and such flow channels are represented in the above discussion on VTE applicatons and by the following illustrations and discussion.

The flow channels represented by FIG. VI and FIG. VII can be operated in any orientation from vertical up-flow to vertical down-flow and can assume any shape and dimension other than the tubular representation shown. The fluid inlet ends of the channels are defined as a means to provide or initiate two-phase flow or to provide a liquid-vapor interface. The outlet ends of these schematic fluid flow channels can serve a variety of process needs thus requiring a variety of embodiments and these fluid outlet ends are therefore not narrowly defined in this specification.

FIG. VI represents a liquid flashdown channel **43** (or a vessel) comprising a tubular wall **44** having an open outlet end **45** and an inlet end including an inlet orifice **46** or nozzle of suitable flow diameter and pressure drop characteristics determined by the process application intended. A liquid to be partially vaporized is conditioned regarding its physio-chemical properties by adding thereto in low concentration a suitable foaming or surface active agent (surfactant). The temperature (T_1) of the liquid to be vaporized is adjusted to within a few degrees of the temperature at which it is to be vaporized, for instance to about 10° F., above the evaporation temperature (T_2) within the flow channel **43**. The liquid is then introduced into the flow channel **43** through the orifice **46** wherein it is subject to a pressure drop and turbulence (hydrodynamic shock) sufficient to initiate vaporization or the formation of many small vapor bubbles as the fluid enters the channel **43**. One of the purposes of the surfactant is to stabilize these small vapor bubbles many of which would otherwise be transient. Another is to form or stabilize a large number of vapor bubbles thus to provide a greatly enlarged vapor-liquid interfacial surface area that provides for increased overall rates of evaporation. Another purpose is to activate the vapor-liquid interface by means of concentration gradient activation of the liquid layer adjacent to each bubble surface. When used in vertical up-flow orientation the surfactant also provides for a lowering of the hydrodynamic pressure gradient within the flow channel by reducing the residence volume of the liquid phase within the channel. This results in an increased flashdown temperature at the inlet end of the channel thus providing for a more complete flashdown within the channel or for increased thermal efficiency. This also applies to an extent if the flow channel orientation changes from vertical up-flow to vertical down-flow. These flow considerations also apply with some modifications to the flow channel of FIG. VII.

FIG. VII represents a liquid evaporation channel that provides for the formation of a two-phase liquid-vapor interfacial surface and a liquid-solid interfacial surface and for the addition of heat of vaporization to the liquid phase through the channel wall. This flow channel **47** (or vessel) comprises a tubular wall **48** having an open fluid outlet end **49** and an inlet end including an inlet orifice **50** or nozzle or another suitable liquid, or liquid and vapor distributor for initiating a liquid-vapor interface or for directing a liquid layer (in the presence of a vapor phase) onto the tube wall. Around the tube wall **48** provision is made for a source of heat in contact therewith or for passing a fluid in heat exchange relationship therewith, for instance heat of vaporization of the liquid in the channel can be provided by passing a hot fluid through an annular space around the channel wall **48** and bounded by the outer tubular wall **51**. A liquid to be vaporized is conditioned regarding its physical-chemical characteristics by the addition thereto of a small quantity of a suitable surfactant. The temperature (T_3) of the liquid to be vaporized is adjusted to within a few degrees of the temperature at which it is to be vaporized, for instance to about 10° F. above the evaporation temperature (T_4) within the flow channel **47**. The liquid is then introduced into the flow channel through the orifice **50** whereby it is subjected to a pressure drop and turbulence sufficient to initiate vaporization or the formation of many small vapor bubbles or for initiating a liquid-vapor interface or the directing of a liquid layer on to the tube wall for flow as a layer in interfacial contact with its vapor. One of the purposes of the surfactant additive is to stabilize the many small vapor bubbles formed at the orifice, some of which would otherwise be transient. Another purpose is to form or stabilize a large number of vapor bubbles, thus to greatly increase the liquid-vapor surface area available at the site at which vaporization takes place, and to enhance the overall rate of vaporization. Another purpose is to activate the vapor-liquid surface area in a hydrodynamic sense by the relaxation of concentration gradients set up below this surface as a result of vaporization at the surface. Another purpose is to provide for activation or enhancement of the interface between the liquid being evaporated and the heat transfer surface (channel wall **48**) by means of vapor bubbles being sheared or blown across this surface by the vapor phase flow to thereby agitate the thin liquid layer contacting this surface. Another purpose of the surfactant additive is to provide for a more intimate contact between the liquid and the heat transfer surface, for instance to assure that the wall remains wet under high heat flux conditions and to provide for a liquid layer remaining in contact with a metal surface that has a layer of scale or metal oxide or dirt on it, i.e. to provide for wetting clear through a porous layer that would otherwise be detrimental to high evaporative heat transfer coefficients. These effects of the surfactant are collectively referred to as interfacial surface (interface) enhancement in this specification. When used in vertical up-flow orientation, the surfactant also provides for a reduction of the hydrodynamic pressure gradient through the flow channel by reducing the residence volume of the liquid phase within the channel **47**. This results in an increased flashdown temperature at the inlet end of the channel which means that the effective ΔT available for vaporization (T_5–T_4 summated along the channel length) is increased. This also applies to an extent when the channel orientation is changed from the vertical up-flow to the vertical down-flow use, at intermediate orientations. It is to be understood that the source of heat can be the inner tube **48** or the inner channel **47**, and the liquid to be evaporated can be passed through the outer channel or the annular channel between tubes **48** and **51**, and still fall within this specification and claims.

FIG. VIII illustrates one use of some of the principles discussed above, to enhance the flashing efficiency, or to reduce the liquid residence time required or the flow channel length required to attain a satisfactory brine-vapor equilibrium, in one complete stage intermediate of a multi-stage flash (MSF) evaporator for sea water conversion to fresh water. The temperature difference of the brine from stage to stage is usually about 3° F., so that brine entering the stage at the submerged orifice **52** will flash down through about 3° F. to the brine saturation (or equilibrium) temperature in that stage and so on down the line of stages used from left to right. Vapor lift will carry the brine over a barrier **53**; and a splash plate **54** is usually provided to project the spray horizontally into the stage. A large part of the vapor is released in this initial rather turbulent entrance to the stage but significant further vaporization and brine-vapor equilibration usually require a considerable length of flow channel downstream from the barrier **53**. A demister mesh screen **55** is usually provided to reduce brine carried as fine droplets in the vapor stream. The vapor is usually condensed on the outside of a tube bundle and the product distillate collected in a suitable trough **56** located underneath the condenser bundle **57**. The heat of condensation of the vapor is collected as sensible heat by cold brine passed through the condenser tube bundle **57** and is later in the cycle re-utilized as flashdown heat of vaporization of brine.

Application of the interface enhancement method to MSF of sea water involves the addition of surfactant at low concentrations to the brine to be evaporated, for instance at concentrations ranging well below 100 p.p.m. to provide for significant enhancement in the flashdown efficiency. One of the purposes of the surfactant added to the brine is to reduce the hydrodynamic pressure at the inlet orifice by providing for an abundance of vapor bubbles that carriers the brine over the barrier **53**. This, together with the enhanced liquid-vapor surface area provided by the surfactant allows vaporization to proceed faster, and to reach liquid-vapor equilibrium sooner after entry of the brine through the orifice. Another purpose of the surfactant addition is to allow a reduction in the length of the stage required downstream from the inlet orifice, thus saving in material and construction costs.

FIG. IX illustrates another use of the flow and heat transfer principles of the interface enhancement method disclosed above, in the operation of a vapor generator or boiler that can for instance be utilized to generate steam, for instance with heat derived from the coolant fluid of a nuclear reactor. A horizontally oriented tubular heat exchanger is shown comprising a tubular shell **58** having one end plate **59** serving as a tube sheet for heat exchanger U-tubes **60** and another end plate **63** providing a liquid outlet **62**. A liquid inlet distributor tube **63** having a multiplicity of liquid inlet orifices or nozzles **64** extending through the tubular shell **58** is located below the vaporizer, and a steam outlet **65** is provided in the upper side of the shell **58**. Provision is made for passing a source of heat, for instance hot liquid metal coolant from a nuclear reactor, through the heat exchanger tube **60**, passing through these tubes from an inlet distributer tube **66** to an outlet tube **67**.

In operation the liquid to be vaporized, for instance water having a small quantity of surfactant added thereto, and preheated to a temperature close to that at which it is to be vaporized, is passed through the inlet orifices **64** so as to partially vaporize it and initiate the formation of very small vapor bubbles in the liquid just above the orifices. Stabilized by the surfactant, these vapor bubbles serve as the initial interfacial surface to promote further vaporization of the liquid, sustained by the heat passed thereto from the heat exchanger tubes **60**. Steam generation thus occurs throughout the liquid in the vessel rather than from the surface layers only as in conventional steam generators. The hydrodynamic pressure in the lower part of the vessel **58** is reduced by the bubbly two-phase condition maintained therein, thus providing for passage of heat of vaporization to the liquid in the lower area of the vessel at an increased effective ΔT and with enhanced thermal efficiency and heat transfer rate because of this two-phase condition initiated and sustained in the lower area of the vaporizer. A disengagement area above the tubes **60** or a demister screen or a cyclone separator may be provided to separate entrained liquid droplets from the steam produced before using it, for instance to drive a turbine. Unevaporated liquid is drawn off through the outlet **62** for recycling after addition thereto of condensate recycled from a condenser wherein the steam is recovered by condensation after its passage through the turbine, and after preheating this combined liquid to be vaporized. This preheating requires a relatively small amount of heat as compared to the heat required to vaporize the liquid in the vaporizer or boiler, and can be accomplished in a relatively small auxiliary heat exchanger through which this combined liquid is passed in heat exchange relationship with the hot reactor coolant or part thereof.

Another example of the use of the interface enhancement method of this specification is described below with reference to FIG. X and FIG. XI representing the flow channels **68** interstitial to nuclear fuel rod **69** heat sources in a nuclear reactor core. In the case of a boiling water (or other liquid) reactor the preferred mode of fluid flow through these interstitial channels **68** is similar to the up-flow mode of VTE discussed above and illustrated with FIG. IV and FIG. V. Tensioned helical inserts **70** can be utilized for the purpose of fluid flow control by means of the vortex flow thereby imposed within the interstitial channels **68**. Such helical inserts and vortex flow control were disclosed and claimed in my U.S. Pats. 3,457,982 and 3,423,294 respectively; their conjunctive use with interface enhancement is disclosed in this specification.

FIG. X and FIG. XI illustrate a side view section and a top view section respectively of multiple vertical flow channels between spaced rods or tubes **69** (or heat transfer bodies **69**) from which heat is to be passed to a fluid flowing in these interstitial flow channels. Helical baffles **70** are disposed axially within these flow channels and supported under moderate tension applied at the end supports **71** of the baffles mounted in spaced relationship with the rods or tubes **69**, for instance by means of suitable perforated plates or spiders **72, 73** that permit flow of fluid therethrough, so that the baffle edges are generally spaced from the surface of the rods or tubes **69**. The baffles can be tensioned by means of compression springs **74** supported by the perforated plate **72**. It is to be understood that occasional spacer tabs or connectors may be used to prevent lateral vibration of either the baffles **70** or the rods or tubes **69** by serving as braces or stays. One of the perforated plates **72** may be provided with relatively small orifices **75** through which a coolant liquid can be passed so as to provide for turbulence and a pressure drop suitable to initiate foamy flow through the flow channels. Relatively larger orifices or coolant ports can be provided in the perforated plates when required, for instance the ports **76** shown in the other support plate **73**. The perforated plates **72** and **73** supporting the helical baffles can also be utilized to support the heat transfer bodies **69** and can in turn be supported on a cylindrical flow channel **77**. This entire assembly can be inserted into an outer vessel, for instance a pressure vessel having cylindrical sides **78**, a cover plate **79**, a coolant inlet **80** and a coolant outlet **81**. The heat transfer bodies **69** shown provide tubular space **82** (FIG. XI) for inserting the nuclear fuel therein or for passing a source of heat in the form of a fluid therethrough.

The purpose of the helical baffles **70** disposed axially within the parallel flow channels is to impose vortex flow on the fluid passed through each of these channels and to thereby enhance the rate of heat transfer from the rod or tube **69** surfaces to the fluid. In the case of boiling heat transfer the helical baffles may also serve to channel vapor upward in contact with the helical baffle and thus provide for improved hydrodynamic stability, for instance in boiling water power reactors. This channeling effect also can be used to reduce the hydrodynamic pressure especially at the lower end of such a boiling flow channel and to thereby improve heat transfer by increasing the effective temperature difference, ΔT, available for heat transfer. Reducing the hydrodynamic pressure gradient through the flow channels in boiling heat transfer, for instance in a boiling water reactor, will reduce the magnitude of the instability that can set in within such flow channels. The rotary component of flow imposed upon the fluid will also contribute toward stability by reducing the tendency for hydrodynamic oscillation in the axial direction. The rotary component of flow imposed serves to control two-phase flow through vaporizer channels, concentrating a less dense fluid component centered upon the baffle and directing a denser fluid component toward the heat transfer surfaces. Foamy flow can thus be controlled, and whereas this mode of flow may otherwise be a source of trouble, because of entrainment of liquid and carry-over with the vapor, poor heat transfer and burnout, such troubles can be prevented by the vortex-inducing helical insert.

Interface enhancement applied to a boiling liquid (or boiling water) reactor includes introducing the liquid having a surfactant added thereto into the flow channels **68** through an orifice **75** or nozzle that induces turbulence, a pressure drop or a temperature drop that initiates foamy liquid-vapor flow. Thus a web of foam is sheared over the heat transfer surfaces to provide for shallow, agitated liquid layers (films) through which heat can be passed rapidly from those surfaces to produce vapor that is released into the vapor bubbles. The vapor bubbles provide an increased vapor-liquid surface area (interface) to enhance the overall evaporation rate (mass transfer). Surfactant addition also provides for improved wetting of the heat transfer surface and to prevent dry-out, thus increasing heat flux. An additional favorable effect is the reduction of the total liquid residence volume within the flow channels to thereby reduce the hydrostatic head or the hydrodynamic pressure gradient through the channels so as to increase the effective ΔT available for evaporative heat transfer.

This specification is intended to illustrate and be applicable to forced convection vaporizers or vertical tube vaporizers, heat exchangers and boilers, for instance the tubes **69** may be used for passing a hot fluid, such as sodium metal or pressurized water used as nuclear reactor

core coolants, to generate vapor or steam from another fluid in the interstitial channels; or hot gas may similarly be passed through the tubes **69**, (**82**), for instance hot combustion products, or pressurized gas used as nuclear reactor core coolant may be passed in heat exchange relationship with a secondary coolant that is passed through the interstitial flow channels **68**. The interface enhancement method of this specification can be applied with apparatus such as in FIG. X and FIG. XI without vortex-inducing helical inserts (**70**).

Having disclosed the principles of interface enhancement and discussed several examples of its application for fluid flow control and to increase heat and mass transfer and to enhance up-flow VTE stability and extend the range of practical process conditions for multi-effect VTE, and having briefly summarized additional fields and processes wherein interface enhancement can be utilized, it is to be understood that this specification implies inclusion of a wider range and scope than the applications disclosed herein.

What is claimed is:

1. A method for increasing the interfacial surface between a liquid phase and a vapor phase, and the rate of evaporation of said liquid phase, to enhance heat and mass transfer therebetween, comprising: selecting a liquid to be evaporated; incorporating a surfactant into said liquid, wherein said surfactant, having within the molecule a lyophilic and lyophobic grouping is a member selected from the group comprising synthetic anionic, cationic and nonionic surfactants consisting of sulphonated ethoxylated linear alcohols, quaternary ammonium compounds, and polyvinyl alcohols; passing said surfactant-containing liquid substantially as a single phase into a flow channel while simultaneously reducing the pressure on said liquid by an amount sufficient to thereby convert a portion of said surfactant-containing liquid to a foamy mixture consisting substantially of liquid phase and vapor phase; partially vaporizing said liquid phase while flowing said liquid and vapor phases through said flow channel; and thereafter separating and condensing said partially vaporized liquid phase.

2. In the partial evaporation of a liquid in a vertical tube evaporator, to produce vapor and residual liquid by passing said liquid over a heat transfer surface having a temperature substantially higher than the temperature of said liquid, the method of improving evaporative heat transfer rates and the rate of evaporation of said liquid by interfacial surface enhancement, comprising; incorporating a surfactant into said liquid, said surfactant being a salt of a sulphonated linear primary alcohol containing several ethylene oxide units; passing said surfactant-containing liquid substantially as a single phase into a flow channel comprising said heat transfer surface, while simultaneously reducing the pressure on said surfactant-containing liquid by an amount sufficient to convert a portion thereof into a foamy mixture consisting substantially of liquid phase and vapor phase; and flowing said foamy mixture over said heat transfer surface associated with said channel to thereby provide for wiping a liquid phase film over said heat transfer surface.

3. In the partial evaporation of a liquid to produce vapor and residual liquid by passing said liquid over a heat transfer surface having a temperature substantially higher than the temperature of said liquid, the method of improving evaporative heat transfer rates by interfacial surface enhancement, comprising: incorporating a surfactant into said liquid, wherein said surfactant, having within the molecule a hydrophilic and hydrophobic grouping, is a member selected from the group consisting of salts of sulphonated ethoxylated linear alcohols, quaternary ammonium compounds, and polyvinyl alcohols; passing said surfactant-containing liquid substantially as a single phase into a flow channel comprising the heat transfer surface while simultaneously reducing the pressure on said surfactant-containing liquid by an amount sufficient to convert a portion thereof into a foamy mixture composed substantially of liquid phase and vapor phase; and flowing said foamy mixture over said heat transfer surface associated with said channel to provide for wiping a liquid phase film over said heat transfer surface; whereby the rate of heat transfer from said surface to said liquid phase is increased significantly, thereby accomplishing a corresponding increase in the rate of evaporation of said liquid phase.

4. A method in accordance with Claim 3 wherein said liquid comprises non-fresh water and wherein said vapor is subsequently separated from said residual liquid and condensed into fresh water.

5. A method in accordance with Claim 3 applied to the multi-effect operation of a series of evaporators wherein said partially evaporated residual liquid is further partially evaporated in subsequent evaporators.

6. A method in accordance with Claim 3 wherein said heat transfer surface is of the enhanced surface type having a modified surface shape designed to enhance evaporative and condensing heat transfer coefficients.

7. A method in accordance with Claim 3 applied to steam generation and wherein said liquid is water and said vapor is steam.

8. A method in accordance with claim 3 wherein the flow within said channel is substantially vertically upward and whereby the hydrodynamic presure drop through said channel is reduced by more than 25 percent and the overall heat transfer coefficient is increased by at least 20 percent.

9. A method in accordance with Claim 3 wherein the flow within said channel is vertically downward.

10. A method in accordance with claim 3 wherein said foamy mixture is caused to flow within a tubular channel as an annular layer of foam, to enhance the overall heat transfer coefficient obtained when said liquid is evaporated by the vertical tube evaporation process.

11. A method in accordance with claim 3 applied to multi-channel operation wherein said channel is one of a multiplicity of parallel flow channels and wherein said foamy mixture is expanded into a restricted zone comprising said channels through an intermediate free zone.

12. A method in accordance with claim 3 wherein said foamy mixture is manipulated to flow over said heat transfer surface by means other than gravitational force.

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