Aug. 30, 1966 D. E. CHUBB ETAL 3,269,135

MULTI-STAGE HEAT EXCHANGE APPARATUS AND METHOD

Filed Oct. 7, 1963

3 Sheets-Sheet 1

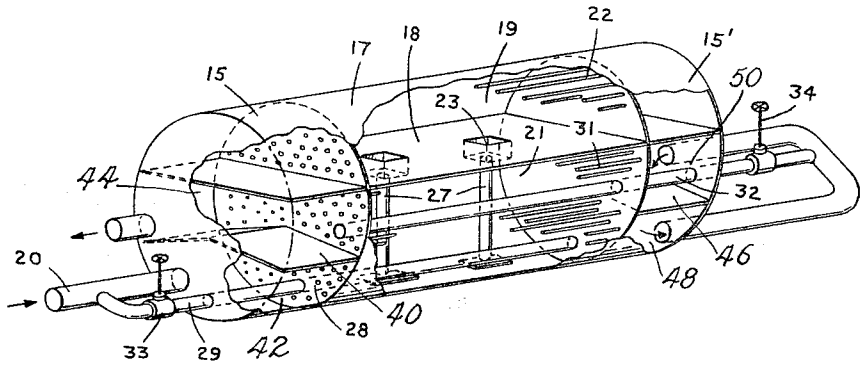


FIG. 1

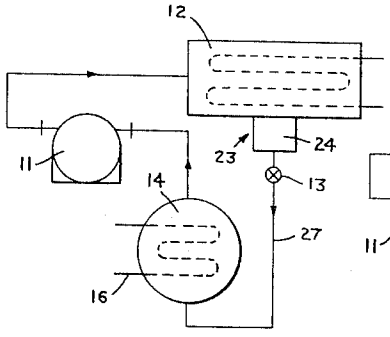


FIG. 2

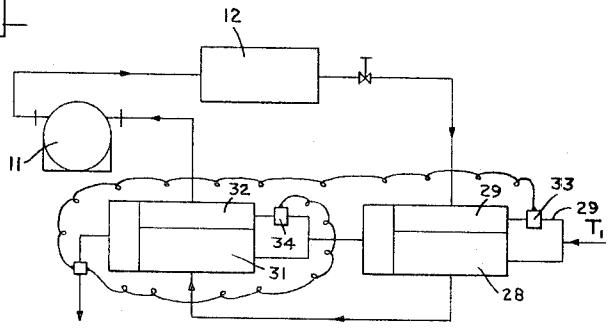


FIG. 3

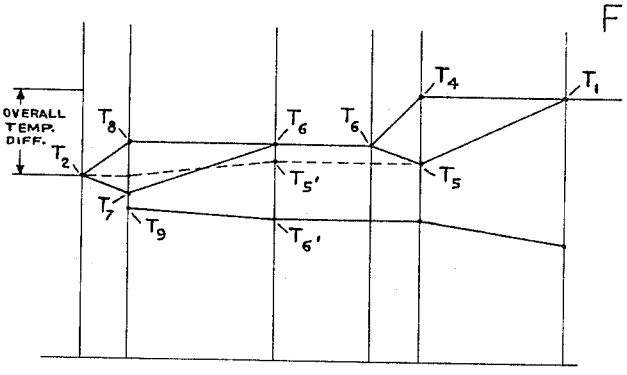


FIG. 4

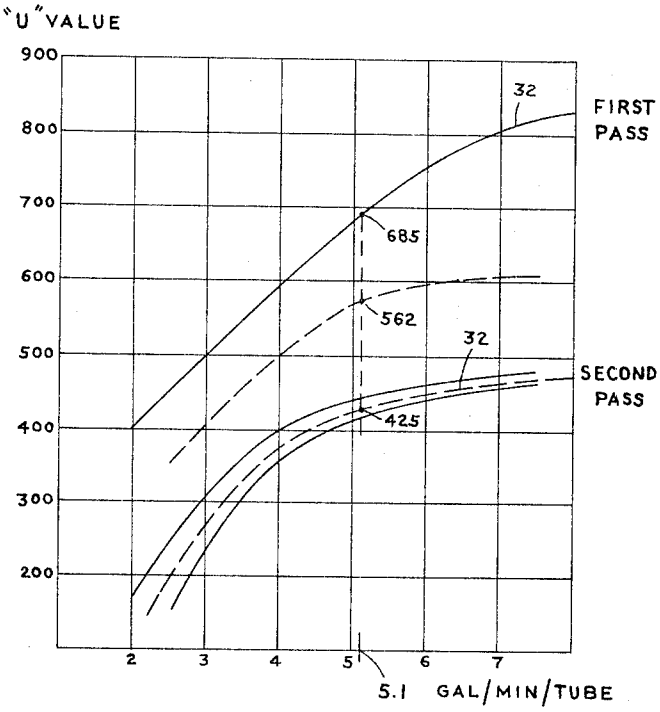
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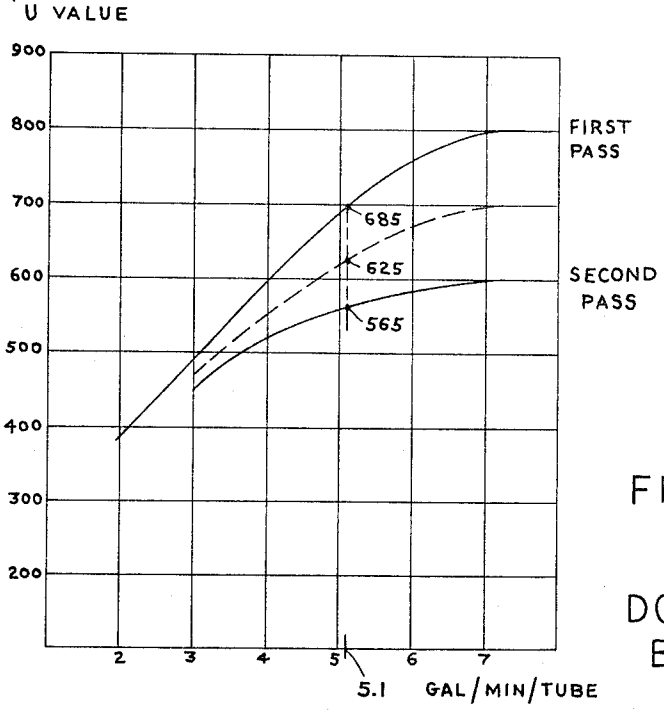
MULTI-STAGE HEAT EXCHANGE APPARATUS AND METHOD

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FIG. 5



FIRST PASS 120 TUBES
SECOND PASS 120 TUBES
NO BYPASS



FIRST PASS 76 TUBES
SECOND PASS 100 TUBES
25% BYPASS

FIG. 6

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MULTI-STAGE HEAT EXCHANGE APPARATUS AND METHOD

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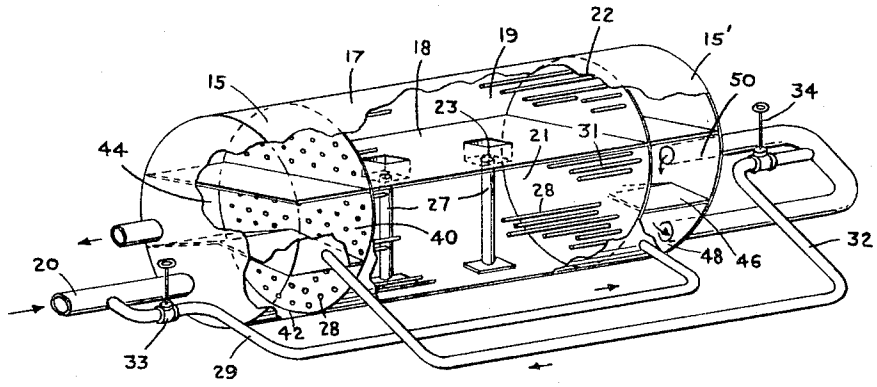


FIG. 7

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MULTI-STAGE HEAT EXCHANGE APPARATUS AND METHOD

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This invention relates to a heat exchange apparatus having a multi-stage arrangement of fluid carrying tubes for progressively chilling a circulating liquid.

In heat exchange apparatus of the type contemplated, an exchange medium such as water is circulated through serially connected tube bundles to provide a plurality of heat exchange stages. The stages are so disposed in a shell or other enclosure to be contacted by a circulating second fluid for absorbing heat from, or imparting heat to the first mentioned medium.

In the instance of evaporative type coolers frequently employed in air conditioning systems and similar applications, in the chiller or evaporator portion of the apparatus a liquid such as process water is circulated and cooled to a predetermined temperature. The cooling medium generally in the form of a vaporizable refrigerant, circulates through the evaporator in two phases. The medium is first introduced as liquid, and by absorbing heat from the water at a reduced pressure, is caused to boil and vaporize. The vapors are then passed to a second stage of the cooler or alternatively passed to the compressor suction and recirculated through the refrigeration system.

Since one side of the evaporator, that is the tube side, carries only liquid, the cross-sectional area of liquid conducting passages is maintained substantially constant throughout the heat exchanger. More exactly, the respective tube bundles making up the liquid carrying portion of the system are designed having in mind the factors of available cross-sectional area of a tube and the aggregate of heat exchange surface provided by the tube bundle.

To achieve maximum efficiency in heat transfer between liquid and refrigerant, a certain optimum number of tubes or surface is required consistent with existing conditions. The minimum number of tubes which may be used however, is restricted in view of frictional resistance established at the inner wall of said tubes by flowing liquid.

In any heat exchange system, the efficiency or heat exchange rate across a particular fluid separating surface is a function of the temperature differential of the fluid at opposite sides of side surface. Thus, one means by which the rate of thermal conductivity across a thickness of heat transfer material may be improved is by increasing the temperature differential.

To achieve an improved heat transfer rate, and over all efficiency while minimizing the number and size of liquid carrying tubes, there is presently provided a heat exchange apparatus of the shell and tube type embodying a plurality of stages for passing a heat exchange medium in contact with a liquid to be cooled. The first cooling stage is formed by a chamber holding a supply of vaporizable refrigerant which at least partially submerges a tube bundle carrying a stream of the liquid to be cooled. A first portion of the liquid is thus cooled, while a second portion is passed through said first stage at a substantially constant temperature or at least at a minimum temperature differential. Thereafter, the two liquid flows at different

temperatures are combined at an intermediate temperature and introduced to a second cooling stage in which the liquid may be again divided into at least two streams for further cooling thus stabilizing an overall cooling rate through the respective stages.

It is therefore an object of the present invention to provide a novel heat exchange apparatus having improved thermoconductivity characteristics.

A further object is to provide a multi-stage heat exchanger having an array of fluid conducting tube bundles so arranged and proportioned in cross-sectional area to provide substantially equal loading of the respective stages.

A still further object is to provide a heat exchange apparatus of the tube and shell type embodying multiple stages through which heat exchanging fluids pass, the respective stages being proportioned in available tube surface area to provide maximum cooling rate efficiency throughout the apparatus.

Another object of the invention is to provide a heat exchanger of the type described including means for directing liquid to the respective multiple stages to provide a substantially equal rate of heat transfer at each stage.

Still another objective is to provide a liquid circulating heat exchanger of the evaporative type employing a vaporizable refrigerant as the cooling medium which passes in contact with liquid carrying tubes to absorb from the liquid a substantially equal amount of heat in the respective stages.

A still further object is to provide a novel multi-stage tube type heat exchange apparatus adapted to regulate the passage of fluid through the tube side in such manner to accurately control output fluid temperature.

Still another object is to provide a heat exchange apparatus including means to divert a flow of chilled liquid there through in response to varying heat exchange load conditions without deterring the rate of flow of cooling medium.

Other objects of the invention not particularly delineated will become clear to those skilled in the art from the accompanying description of the apparatus and its method of use.

In the drawings

FIGURE 1 is a view in partial cross-section of an apparatus of the type disclosed with portions of the outer shell broken away to show interior members.

FIGURE 2 is a diagrammatic sketch of a typical refrigeration system.

FIGURE 3 is a diagrammatic sketch indicating a flow diagram through a refrigeration system embodying the present invention, including a plurality of fluids through the evaporator section,

FIGURE 4 is a graphical representation illustrating fluid temperature at the various points in the heat exchange apparatus shown in FIGURE 3, and

FIGURES 5 and 6 illustrate graphically the results of comparative heat exchange tests made on the disclosed apparatus.

FIGURE 7 is a view in partial cross-section of another form embodying the present invention.

Referring to the drawings, an embodiment of the apparatus presently contemplated is illustrated in conjunction with a chiller or cooler unit. This type of apparatus is normally found in, although not peculiar to, a refrigerant circulating air conditioning system in which a com-

pressor delivers a stream of hot compressed refrigerant gas as the cooling medium. It should be borne in mind however, that while the apparatus is hereinafter described in terms of, and related to refrigeration equipment in a closed cycle, no such limitation is to be drawn since the apparatus and the novel method of operating the same might be applied to any number of systems embodying multi-stage heat exchange between fluids at different temperatures.

Referring to FIGURE 2 a typical system of the type mentioned is shown schematically and includes in general a closed refrigeration circuit defined by a compressor **11** having its discharge connected to the inlet side of condenser **12**. Liquified refrigerant in saturated condition at the downstream side of the condenser is passed through a control valve **13** adapted to meter the same into an evaporator **14**.

Evaporator **14** embodies generally a cooling coil or tube bundle **16** carrying a stream of water or other liquid medium to be chilled. Tube bundle **16** is immersed, or is in partial contact with a pool of liquid refrigerant which is caused to boil at the reduced evaporator pressure thus absorbing heat from water passed through cooling coil **16**. Thereafter, vaporized refrigerant is passed from the evaporator into the suction of compressor **11** for recirculation in the cycle.

Referring again to FIGURE 1, an embodiment of a condenser-evaporator arrangement operable in the circuit described, is shown incorporated as a unitary member within a single shell **17**. The ends of the shell enclosure are provided with removable heads defining manifolds **15** and **15'** in a manner well known in pressure vessel construction. The manifold **15** is divided as shown by a divider member **40** extending thereacross into a first chamber **42** and a second chamber **44**. Similarly, the manifold **15'** is divided as shown by a partition **46** extending thereacross into what may be termed a third chamber **48** and a fourth chamber **50**. Shell **17** embodies a fluid tight enclosure having an elongated partition **18** defining upper and lower pressure sealed chambers designated **19** and **21** respectively. Conduit means not presently shown is communicated with upper chamber **19** feeding a stream of hot compressed refrigerant to the latter from the system compressor. Upper chamber **19** together with tube bundle **22** positioned therein, define the condensing portion of the system. Cooling water or other medium circulates through tube bundle **22** for condensing vapor received from the discharge of compressor **11**.

Thereafter as shown in FIGURE 2, saturated liquid refrigerant gravitates to a sump or well **23** positioned at the lower side of the condenser and accumulates in the float chamber **24** having a float control valve **13** operable to vary flow from the sump in accordance with the level of contained liquid. A conduit **27** communicated with the downstream side of valve **26** carries a stream of liquid into lower chamber **21**.

Chamber **21** forms an evaporator section, which as shown in FIGURE 1 may be so arranged to define two or more serially connected stages for achieving progressive cooling of liquid. Any number of stages may theoretically be embodied in the evaporator depending on the degree of heat exchange or cooling to be achieved. For the purpose of illustrating the invention however, the instant arrangement embodies two cooling or chilling stages. A pool of liquid refrigerant accumulated at the base of chamber **21** at least partially immerses a tube bundle **28** having an inlet **20** connected to a source of process water to be chilled thus defining the first stage.

At the reduced pressure maintained in the lower side of the evaporator first stage, the refrigerant pool is caused to boil and absorb heat from liquid circulating tube bundle **28**. Refrigerant in vapor form then rises from the first stage as a vaporous cooling medium.

A second, controlled stream of cooling water introduced to the first stage, is directed into conduit **29** which may be so disposed to pass through the first stage, or may be positioned external to the shell **17**. Conduit **29** defines in effect a liquid by-pass circumventing the entire first stage. As shown in FIGURE 1, conduit **29** may be substantially submerged in the boiling liquid refrigerant and will consequently be subjected to a temperature decrease. When by-pass conduit **29** is disposed externally of the shell **17** and out of contact with the cooling medium, there will be little or no temperature gradient from the inlet to the outlet thereof so that the temperature in conduit **29** remains substantially constant.

Conduit **29** carrying the secondary flow of water may be formed of a tube or pipe having a relatively large diameter as compared to the diameter of the liquid carrying tubes making up the tube bundle. This conduit, in order to minimize temperature decrease across the thermally conductive wall thereof may also be insulated or formed of a multi-wall conduit construction. Still another embodiment of the by-pass conduit includes a plurality of liquid carry tubes disposed inversely of and coextensively with an outer liquid tight shell.

FIGURE 7 is substantially identical in operation and structure as that described hereinbefore under FIGURE 1, except that lines **29** and **32** have been disposed outside of shell **17**.

Schematically, the division of liquid flowing through the first stage is indicated in FIGURES 3 and 4 which depict on a graphical basis the proportioning of water entering at temperature T1, the heat exchange section of the first stage as compared with the flow through the by-pass section. This proportioning of cooling water may vary in quantity between about 20 to 35% of the total flow passed through the first stage.

Regulating the flow rate through by-pass **29** is accomplished with the aid of valving **33** and **34** as shown in FIGURE 3, or by means normally provided for adjusting and controlling liquid flow. Further, this regulation of flow through one or both control valves may be made in response to the load on the system, by use of a suitable sensing means having a sensing element disposed at the chilled water outlet and operable to adjust the setting on the control valves to vary the rate of water there through. Although valves **33** and **34** may be disposed external to the chiller unit and operable to control flow to respective manifold heads. Referring to FIGURE 4, water entering the first stage at temperature T1 is divided into two streams, one of which contacts the refrigerant and leaves the first stage at T5. Downstream of the first stage, for example in head **15'**, water at temperatures T4 and T5 is intermixed in a manifold or accumulator to an intermediate temperature T6. Thereafter, chilled water at temperature T6 is introduced to the second stage of the multi-stage evaporator where the stream is again bifurcated into a main stream passing through tube bundle **31**, and a secondary regulated stream passing through by-pass conduit **32**. Again, as in the first stage, the proportioning of this liquid is regulated by valve **34** dependent on the degree of efficiency desired in the overall system and upon the ultimate temperature desired in the cooled liquid.

In the second cooling stage, liquid entering the upstream side at temperature T6 is further cooled to temperature T7. This cooling is achieved by the upward passage of vaporized refrigerant rising from the first stage of the evaporator into contact with tube bundle **31** in the second stage. By-passed liquid will circumvent the second stage at temperature T6 or at a slightly decreased temperature T8.

Referring to FIGURE 4, it is seen by the comparative slope of the curve T1–T5, as compared with the slope of curve T6–T7, that the temperature drop realized in the first stage is substantially sharper than the temperature drop realized in the second stage.

This is attributed to two reasons: one reason is that the cooling capacity of liquid refrigerant in the first stage is substantially greater than the cooling capacity of vaporized refrigerant in the second stage. More simply stated, the heat of vaporization available in the first stage for cooling liquid as the refrigerant vaporizes, permits more work to be achieved in terms of the amount of heat absorbed from circulating water.

Secondly, at the primary stage of heat exchange, the temperature differential between process water, and the cooling medium is at a maximum as compared with the temperature differential at the inlet side of subsequent stages.

To induce a more favorable heat exchange at the second stage, without substantially altering the physical characteristics of the cooling medium, the temperature differential between cooling medium and cooled water entering the second stage is increased. Thus, process water at temperature T6 and refrigerant at T8 are brought into heat exchange contact to bring the cooled water to temperature T7 and the cooling medium to T9.

If a third or fourth stage of cooling is required the water received at each of said stages is divided into first and second flow, at least one flow by-passing the heat exchange area and being intermixed with water discharged from said stage at the downstream side thereof.

While not presently shown in the figures, in by-passing a certain quantity of process water about the first stage, the liquid stream rather than being introduced to the second stage may be passed directly from the downstream side of the first stage to the inlet of a third or subsequent stage. It is to be understood further that other arrangements together with suitable piping and valving means may be incorporated into the evaporator flow stream to effect mixing and by-passing of stated proportions of the cooling fluid.

Test data

FIGURES 5 and 6 of the drawings depict graphical representations of data obtained on a series of runs made on test equipment embodying the multi-stage construction herein described, interconnected in a refrigeration system. Data shown in FIGURE 5 illustrates tests made on an evaporator having two passes, the first pass, comprising approximately 120 copper tubes carrying water. The second pass connected down stream of the first pass and comprising 120 tubes also carrying water. This series of tests included passing the water sequentially across first and second stages with no by-passing whatsoever. The vaporizable refrigerant circulated as the cooling medium was R–11 refrigerant.

In the following discussion, the term heat transfer or "U" value will be employed as the standard by which an effective comparison is made. This term may be designated in a number of ways depending on the terminology of the factors effecting said value.

While one of the objectives of the present invention is to provide an overall increase in the heat transfer rate across all stages in a multi-stage unit, it should be remembered that said rate is determined by several factors. For example, the theoretical heat transfer rate is established as being the reciprocal of several factors as shown in the following formula:

$$U=\frac{1}{R_0}+\frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}$$

In the formula, R_0=refrigerant film resistance; R_1=water film resistance; R_2=tube wall resistance and R_3=scale resistance.

Referring to the FIGURE 5, a datum line of 5.1 gallons per minute of water was used in this first run as well as in the test shown on FIGURE 6 in which a certain percentage of the water was by-passed.

Referring again to FIGURE 5, the test run graph line designated 32, includes first and second passes in which cooled water was passed at a rate of approximately 5.1 gallons per minute. In the first pass the heat transfer rate was calculated to be approximately 685. In the second pass, the heat transfer rate was calculated to be approximately 425. To determine the overall heat transfer across both stages, an average of the above figures was calculated to be approximately 562.

Referring to FIGURE 6, a test pass was made, again using refrigerant R–11 as the chilling medium, and a water flow rate of 5.1 passed through both stages of the apparatus. As noted in FIGURE 6, the first pass included 76 copper tubes instead of the 120 used in the original test. The second stage included 100 tubes rather than 120 as in the first test. Further, in FIGURE 6, the distribution of water through the heat exchange portion of the first stage was such that approximately 25% of the water flow was by-passed, directly to the second stage.

In analyzing the results tabulated on the graphs, it is seen that in the first stage or pass, for a flow of 5.1 gallons per minute per tube, a heat exchange rate of 685 was realized. This figure was substantially the equivalent of the value realized in the first test even though the amount of water passed through the first stage has been reduced by 25%. It should be remembered however, that the first stage was modified such that only 76 tubes, or a little more than half the tubes originally used were now used as the heat exchange surface.

In the second stage where only 100 tubes were used rather than the original 120, with the 25% by-pass of chilled water the overall heat transfer rate was found to be approximately 565. In calculating an average between the first and second stage heat rates to arrive at an overall heat rate, it is found that the intermediary figure comes to a value of approximately 625.

In comparing this figure of 625 with the corresponding figure of 562 achieved in the first set of runs wherein no by-pass was used, it is seen that there is a substantial difference of approximately 63 units. It may be readily appreciated then that the method of by-passing a portion of the cooled water being heat exchanged is considerable. Not only is the unit in the second test operated more efficiently to achieve a particular temperature drop in chilled water, but the desired temperature drop is achieved with much less tube surface in the heat transfer portion than has been heretofore used.

Referring again to FIGURE 6, in the first stage the heat transfer surface in terms of number of tubes is reduced from 120 to approximately 76. In the second stage it is reduced from 120 to approximately 100. Thus, these figures when extrapolated to consider original and unkeep costs, indicate a substantial saving in both labor and material not to mention the great reduction in size which also affects the ultimate cost of a piece of equipment.

From the foregoing description it is readily seen that the disclosed method and apparatus constitute a decided economic advantage in the art of heat transfer particularly when related to, although not restricted to the field of refrigeration. It should be appreciated however, that modifications and changes may be made in the apparatus described without departing from the spirit and scope of the invention as defined in the appended claims.

What is claimed is:

1. In a multistage evaporator which includes an evaporator shell adapted to contain a liquid and vaporous cooling medium therein, and first and second, serially connected cooling stages extending therethrough the improvement comprising means for dividing a stream of liquid at entry temperature into first and second streams, means for passing said first liquid stream through said first cooling stage of said evaporator in heat exchange relationship with said liquid cooling medium with resultant lowering of the temperature of said first liquid

stream below said entry temperature, means for maintaining the temperature of said second liquid stream at substantially entry temperature and mixing said second liquid stream with said first liquid stream after the latter has been passed through said first cooling stage to provide an intermixed stream of liquid at an intermediate temperature which is lower than said entry temperature, means for dividing said intermixed stream of liquid into third and fourth streams, means for passing said third stream through said second cooling stage in heat exchange relationship with said vaporous cooling medium with resultant lowering of the temperature thereof to a temperature below said intermediate temperature, means for maintaining the temperature of said fourth liquid stream at substantially intermediate temperature and mixing said fourth liquid stream with said third liquid stream after the latter has been passed through said second cooling stage to provide a mixed liquid stream at a temperature below said intermediate temperature.

2. In a multistage evaporator as in claim 1 wherein, the means for maintaining the temperature of at least one of said second and fourth liquid streams substantially equal to said entry or intermediate temperature, respectively, comprises conduit means for passing said liquid stream through said evaporator shell in substantially non-heat exchange relationship with said cooling medium.

3. In a multistage evaporator as in claim 1 wherein, the means for maintaining the temperature of at least one of said second or fourth liquid stream substantially equal to said entry or intermediate temperature, respectively, comprise conduit means for bypassing said liquid stream around said evaporator shell.

4. In a multistage evaporator, an evaporator shell adapted to contain a cooling medium therein, first and second chamber means formed at one extremity of said evaporator shell, third and fourth chamber means formed at the other extremity of said evaporator shell, a first plurality of liquid carrying conduits extending through said evaporator shell in heat exchange relationship with said cooling medium, said first plurality of liquid carrying conduits connecting said first and third chamber means for liquid flow therebetween from said first chamber means to said third chamber means, a second plurality of liquid carrying conduits extending through said evaporator shell in heat exchange relaitionship with said cooling medium, said second plurality of liquid carrying conduits connecting said fourth and second chamber means for liquid flow therebetween from said fourth chamber means to said second chamber means, means to introduce a stream of liquid to said first chamber means for flow therefrom to said third chamber means through said first plurality of liquid carrying conduits, means connecting said third chamber means and said fourth chamber means for liquid flow from said third chamber means to said fourth chamber means and therefrom to said second chamber means through said second plurality of liquid carrying conduits, first bypass means connecting said liquid introduction means with said third chamber means for the flow of liquid from said first chamber means to said third chamber means without said first plurality of liquid carrying conduits, second bypass means connecting said connecting means with said second chamber means for the flow of liquid from said connecting means to said second chamber means without said second plurality of liquid carrying conduits, first control means cooperatively associated with said liquid introduction means to control the amounts of liquid flowing through said first plurality of liquid carrying conduits and said first bypass means, and second control means cooperatively associated with said connecting means for controlling the amounts of liquid flowing through said second plurality of liquid carrying conduits and said second bypass means whereby, a liquid to be cooled may be divided into first and second streams by said first control means with said first stream thereof flowing from said liquid introduction means to said first chamber means and therefrom to said third chamber means through said first plurality of liquid carrying conduits and being cooled thereby, and said second stream thereof flowing from said liquid introduction means to said third chamber means through said first bypass means without said first plurality of liquid carrying conduits, said first and second streams of said liquid may be mixed in said third chamber means and flow therefrom to said connecting means, with said second control means dividing said liquid into third and fourth streams with said third stream flowing from said connecting means to said fourth chamber means and therefrom to said second chamber means through said second plurality of liquid carrying conduits and being cooled thereby, and said fourth stream being flowed from said connecting means to said second chamber means through said bypass means for mixing with said third stream in said second chamber means.

5. In a multistage evaporator as in claim 4 wherein, at least one of said first and second bypass means comprise conduit means which extend externally of said evaporator shell, whereby, the liquid flowing therethrough will not be in heat exchange relationship with said cooling medium.

6. In a multistage evaporator as in claim 4 wherein, at least one of said first and second bypass means comprise conduit means which extend internally of said evaporator shell but are of significantly larger diameter than the liquid carrying conduits of said first and second pluralities thereof whereby, the liquid flowing through said bypass means conduit means is in significantly less of a heat exchange relationship with said cooling medium than the liquid flowing through said liquid carrying conduit means of said first and second pluralities thereof.

7. In a multistage evaporator as in claim 4 wherein, at least one of said first and second bypass means comprise conduit means which extend internally of said evaporator shell but are thermally insulated from said cooling medium whereby, the liquid flowing through said bypass means conduit means will be in only limited heat exchange relationship with said cooling medium.

8. In a method for progressively cooling a liquid by passage thereof through first and second, serially connected cooling stages of a multistage evaporator which is adapted to contain a liquid and vaporous cooling medium therein, the steps of, dividing a stream of said liquid at entry temperature into first and second streams, passing said first liquid stream through said first cooling stage of said evaporator in heat exchange relationship with said liquid cooling medium with resultant lowering of the temperature of said first liquid stream below said entry temperature, maintaining the temperature of said second liquid stream at substantially entry temperature and mixing said second liquid stream with said first liquid stream after the latter has been passed through said first cooling stage to provide an intermixed stream of liquid at an intermediate temperature which is lower than said entry temperature, dividing said intermixed stream of liquid into third and fourth streams, passing said third liquid stream through said second cooling stage in heat exchange relationship with said vaporous cooling medium with resultant lowering of the temperature thereof to a temperature below said intermediate temperature, maintaining the temperature of said fourth liquid stream at substantially intermediate temperature and mixing said fourth liquid stream with said third liquid stream after the latter has passed through said second cooling stage to provide a mixed liquid stream at a temperature below said intermediate temperature.

9. In a method as in claim 8 wherein, the temperature of at least one of said second and fourth liquid streams is maintained substantially equal to said entry or intermediate temperature, respectively, by passing said liquid stream through said evaporator in substantially non-heat exchange relationship with said cooling medium.

10. In a method as in claim 8 wherein, the temperature of at least one of said second or fourth liquid streams is maintained substantially equal to said entry or intermediate temperature, respectively, by bypassing said liquid stream around said evaporator.

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