

United States Patent

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 [73] Assignee **The United States of America as**
 represented by the Secretary of the Interior

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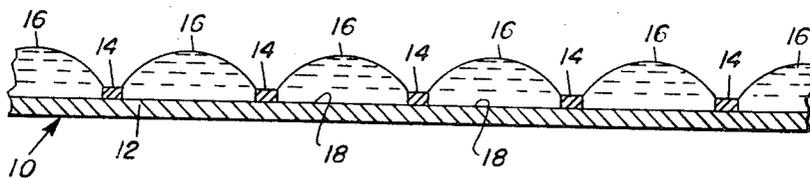
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[54] **APPARATUS FOR OBTAINING HIGH TRANSFER RATES IN FALLING WATER FILM EVAPORATORS AND CONDENSERS**
 13 Claims, 3 Drawing Figs.

[52] U.S. Cl..... **165/133, 165/133**
 [51] Int. Cl..... **F28f 13/18**
 [50] Field of Search..... **165/1, 133, 135**

ABSTRACT: Narrow strips of very thin hydrophobic material are arranged in parallel rows on a hydrophilic heat exchange substrate for use in fluid evaporation or condensation. Fluid rivulets of arcuate cross section form on the hydrophilic substrate between the hydrophobic strips, resulting in an improved heat transfer coefficient relative to systems employing a uniform fluid thickness. Increased fluid surface area and vertical motion of the rivulets account in part for the improved coefficient.



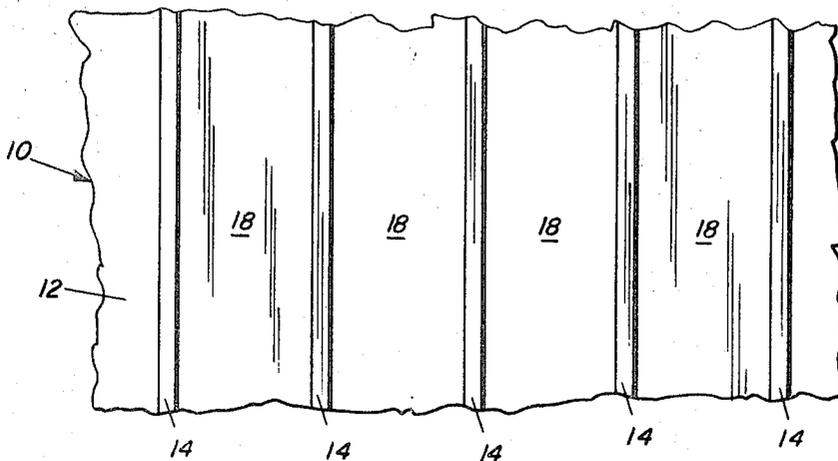


FIG. 1

FIG. 2

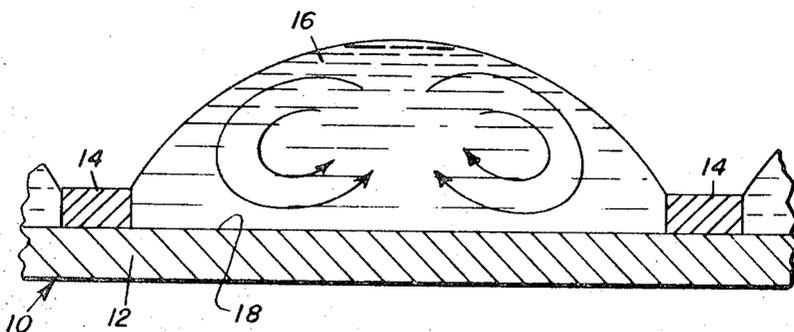
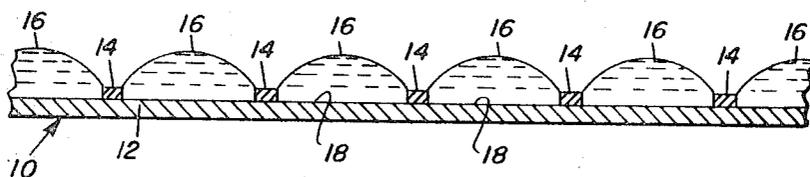


FIG. 3

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APPARATUS FOR OBTAINING HIGH TRANSFER RATES IN FALLING WATER FILM EVAPORATORS AND CONDENSERS

BACKGROUND OF THE INVENTION

Heat transfer in a fluid evaporation or condensation system is generally limited by the low thermal conductivity of the fluid relative to the conductivity of the heat exchange surfaces of the system. Because the heat flux of a heat exchange surface is inversely proportional to the thickness of fluid on the surface, the average thickness of the heat flow path through the fluid must be held to a minimum to obtain a maximum heat transfer rate. As a result of this inverse relationship, it is well known that a nonuniform distribution of fluid thickness provides a greater heat flux than a uniform thickness distribution when in each case the mean fluid thicknesses on heat exchange surfaces are the same. This phenomenon has been successfully employed in reducing the heat transfer coefficient of fluid evaporation and condensation systems employing fluted heat exchange surfaces and in systems employing dropwise condensation and evaporation.

On fluted heat exchange surfaces, surface tension forms a fluid into a thin film on the convex ridges of the flutes, between fluid streams which flow in the flute valleys. The major heat flux occurs on the ridges where the fluid film is thin, and little heat flux occurs in the region of the flute valleys. As an alternative to fluted heat exchange surfaces, which are difficult to fabricate, small radial projections of rectangular or circular cross section, fixed to a heat exchange surface made of similar material, have been proposed. The projections draw fluid from the relatively flat surfaces between them and reduce the mean fluid thickness on the surfaces, reducing the heat transfer coefficient of the system. Both the fluted and projection bearing heat exchange surfaces rely upon the hydrophilic affinity of the fluid to the raised metal areas to form the fluid thickness differentials which produce improved operating characteristics.

Dropwise condensation and evaporation are also employed in heat exchange systems to achieve the desirable effects of nonuniform fluid thickness. In a drop of fluid the water path for heat transfer goes to zero at the drop edge, and it is at the edge that greatest heat transfer takes place. Drop formation is enhanced by partial or complete coating of a heat exchange surface with a hydrophobic, or nonwetable, substance such as a fluorinated hydrocarbon polymer e.g. tetrafluoroethylene), gold, or palladium. In one application of hydrophobic coatings to a dropwise system, the microscopic pits or depressions in a hydrophilic heat exchange surface are filled with a hydrophobic material, yielding a heterogeneous heat transfer surface with an improved heat transfer coefficient. In another application, a plurality of spots of hydrophobic material are bonded to a hydrophilic substrate to the same effect. In these applications, optimum results are achieved when the hydrophobic coatings cover minute isolated areas of the heat exchange surface or, alternatively, completely cover the entire surface.

SUMMARY OF THE INVENTION

This invention is a heat exchange element for use in falling fluid film evaporators or condensers. It consists of a sheet of hydrophilic material of high thermal conductivity on which are bonded narrow strips of very thin, hydrophobic, or non-wetting, material such as fluorinated hydrocarbon polymers (e.g. tetrafluoroethylene), gold, or palladium. The strips are arranged parallel to one another on the heat exchange surface and are oriented along with the surface in a vertical direction. When a fluid contacts the heat exchange surface it is repelled by the hydrophobic strips, forming rivulets upon the intermediate hydrophilic surfaces. Surface tension forces form the outer surface of the fluid into an arcuate cross section between the strips, which lie on opposite edges of the rivulets. In this way the rivulets are constrained to flow downward on the heat exchange surface.

The fluid rivulets formed by this invention improve the heat transfer characteristics of an evaporation or condensation surface in several respects. At the edges of the rivulets near the hydrophobic strips the fluid layer is very thin, and heat transmission is, therefore, increased. Temperature gradients within the rivulets themselves result from the difference in heat transmission across the rivulet cross section, causing internal mixing of the fluid. This mixing enhances heat transfer by continually renewing the fluid in the most effective edge area of the rivulet. In the case of evaporation of a solution such as salt water, vortical motion within the rivulets is caused by surface tension gradients which result from variations in concentration between the edges and center of the rivulets. In addition to the above effects, the convective heat transfer characteristics of the system are improved by the increase in effective fluid surface area which results from the wavelike cross section of the rivulets.

Therefore, an object of this invention is a heat exchange surface having a high heat transfer coefficient.

A further object of this invention is a heat exchange surface on which alternate, contiguous parallel rows of hydrophobic and hydrophilic surfaces interact to channel an evaporating or condensing fluid into spaced rivulets of arcuate cross section. These and other objects of the invention will be apparent in the following specification and drawing which describe the preferred embodiment of the invention.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a plan view of a heat exchange surface including alternate, contiguous, parallel rows of hydrophobic and hydrophilic surfaces.

FIG. 2 is a cross section of the heat exchange surface shown in FIG. 1, including fluid rivulets formed between the hydrophobic surfaces.

FIG. 3 is a cross section of a single fluid rivulet of FIG. 2, illustrating the effect of vortical fluid motion.

DESCRIPTION OF THE PREFERRED EMBODIMENT

FIG. 1 shows a representative portion of a heat exchange plate 10 for use in a falling fluid film evaporator or condenser. The plate 10 includes a hydrophilic, or wettable, metallic substrate 12, such as titanium, having a high thermal conductivity. On the plate 10 there are bonded narrow, parallel strips 14 of very thin hydrophobic, or nonwetable, material such as a fluorinated hydrocarbon polymer (e.g. tetrafluoroethylene), gold or palladium. An operational heat exchange plate 10 is longer and wider than the portion shown, in accord with well-known construction principles of falling fluid film heat exchangers.

In operation in an evaporator or condenser, the plate 10 is oriented in a vertical plane with the parallel strips 14 aligned to divide the plate into a series of alternating, vertical, hydrophobic and hydrophilic surfaces. When a fluid 16 contacts the surface of plate 10, rivulets are formed on the wettable metal surfaces 18 between the strips 14 of nonwetable material, as shown in FIGS. 2 and 3. Surface tension forces form the outer surface of the fluid 16 into an arcuate cross section between the strips 14, increasing the exposed fluid surface area over that of a uniform thickness, two-dimensional fluid film. The increased fluid surface area enhances the convective heat transfer characteristics of the plate 10 in comparison with the plain metallic substrate 12 acting alone.

While the heat exchange plate 10 and the strips 14 are shown in FIGS. 1-3 with exaggerated thickness for descriptive clarity, in actual practice both the plate and the strips are very thin. For effective operation, the plate thickness is on the order of several mils, and the strip thickness is on the order of a fraction of a mil. Of course, deviations from these exemplary values are warranted where dictated by experimental results with the many fluid systems to which this invention is applicable.

The desirability of minimizing the thickness of the hydrophobic strips 14 on the metallic substrate 12 is evident from an operational analysis of the heat exchange plate 10. In a fluid film heat exchanger, the rate of heat transfer is limited by the low thermal conductivity of the fluid relative to the metallic heat exchange plate. An increase of heat transfer results when the fluid path for heat flow is minimized. It follows that the greatest heat transfer through the plate 10 will occur where the fluid thickness is smallest. For the rivulet cross section resulting between the hydrophobic strips 14, the thinnest fluid surface is adjacent to the strips. By minimizing the thickness of the strips 14, the fluid surface adjacent to the strips is drawn close to the metallic surface 12, and the heat transfer through the plate 10 is increased. For saline solutions, a strip thickness on the order of one-quarter mil or less has been found to be effective.

The optimum spacing between the hydrophobic strips 14 on the substrate 12, and the width of the strips, themselves, are variable design parameters dependent upon the construction materials of the plate 10 and upon the fluid 16 which is operated upon. Surface tension forces within the fluid govern the tendency of the fluid to form rivulets between the strips; the construction materials of the substrate 12 and the strips 14 govern the relative rates of heat transfer as the size and spacing of the strips is varied. When the spacing between the strips 14 is too great, the surface tension is insufficient to conform the fluid surface to a semiarcuate shape. When the spacing is too small the fluid thickness differential is minimized, and the effective surface area of the substrate 12 is also minimized, so that the evaporation or condensation rate is decreased. Similarly, the width of the hydrophobic strips 14 is a compromise between opposing effects. For maximum heat transfer through the metallic substrate 12, the width of the low thermal conductivity strips should be held to a minimum. However, for effective rivulet formation the strip width should exceed the value at which flooding between adjacent rivulets occurs. Each of these optimum values of strip width and spacing is readily determined by experimentation with a given operating fluid. For saline solutions, strip widths on the order of 2 mils, and spacings in the range of 10-20 mils are desirable.

In addition to enhancing convective heat transfer through increased film surface area and enhancing conductive heat transfer by reducing the effective film thickness, the heat exchange plate 10 improves convective and conductive heat transfer efficiency in several other respects. Because maximum heat transfer occurs at the rivulet edges near the strips 14, temperature gradients arise across the rivulets, promoting mixing of the fluid within the rivulets. In this way the operating fluid at the most efficient edge area of the rivulet is continually renewed.

In the case of evaporating solutions, vortical fluid motion arises within the rivulets. A saline solution provides an appropriate example. As the water evaporates from the solution near the rivulet edges, the concentration of the solution near the edges increases. Due to this increased concentration, the edges of the rivulet exhibit a higher surface tension than the peak of the rivulet. The surface tension gradient from the edges to the peak causes vortical flow, as shown by arrows in FIG. 3, promoting heat transfer by convection as well as conduction, and increasing the heat transfer coefficient of the system. Because their concentration remains constant in evaporation or condensation, pure fluids do not exhibit this surface tension effect, or the resulting vortical motion.

Fabrication of the heat exchange plate 10 can be accomplished by any of the known processes for selectively coating one material upon the surface of another. A photoetch process, for example, is suitable for coating tetrafluoroethylene strips upon a titanium heat exchange substrate. In this process a clean titanium surface is coated with a light-sensitive polyester coating a few mils thick. After drying, a photographic negative made by reducing a ruled set of parallel lines is placed over the coating and the polymer is exposed

to ultraviolet light in the 3,600 A. region. The coating is then developed, leaving a polymerized resin on the exposed areas and a bare etched metal surface on the areas which were shielded by the opaque lines of the negative. Finally, the entire plate surface is sprayed with a tetrafluoroethylene suspension, allowed to dry and baked in an oven at 725° F. to adhere and coalesce the tetrafluoroethylene particles. During the heating the tetrafluoroethylene adheres to the bare etched metal, but on regions covered with resin the bond is poor. Final brushing removes the resin, while the bonded tetrafluoroethylene remains to form the spaced parallel strips 14.

While the preferred embodiment of the invention has been shown and described, modifications within the scope of this disclosure are to be expected for adapting the invention to diverse heat exchange environments. Other bonding processes can be employed with equal facility. The hydrophobic strips can be recessed into channels cut into the metallic substrate to achieve a smooth outer surface. Alternate strips of hydrophobic and hydrophilic substances can be joined at their edges or bonded to a single substrate to insure optimum properties for both heat transfer and rivulet formation. The heat exchange element can be designed in shapes other than a plane surface with equal operational effectiveness. Fluids other than water can be used with the heat exchange element. In this regard the terms hydrophobic, "hydrophilic," "wetttable," and "non-wetttable" are used to define the corresponding properties with reference to any fluid. These and other modifications of the invention within the scope of the following claims will be apparent to those of ordinary skill in the art.

What is claimed is:

1. A heat exchange element comprising: alternate, contiguous, parallel rows of hydrophobic and hydrophilic surfaces, the rows of hydrophobic surfaces being wide enough to prevent flooding of them when fluid rivulets are caused to flow on the rows of hydrophilic surfaces yet narrow enough to maximize heat transfer through the heat exchange element, and the rows of hydrophilic surfaces being narrow enough to enable surface tension forces in fluid rivulets, which are caused to flow on the hydrophilic surfaces, to form the rivulets into an arcuate cross section between the rows of hydrophobic surfaces, yet wide enough to maximize heat transfer through the heat exchange element.
2. A heat exchange element is claimed in claim 1 in which: the rows of hydrophilic surfaces are spaced portions of a substrate having a continuous hydrophilic surface, and the rows of hydrophobic surfaces are a series of thin, spaced strips of hydrophobic material arranged parallel to one another and bonded to the hydrophilic surface of the substrate.
3. A heat exchange element as claimed in claim 2 in which: the substrate is metallic and has a high coefficient of thermal conductivity, and the hydrophobic material is metallic.
4. A heat exchange element as claimed in claim 2 in which: the substrate is metallic and has a high coefficient of thermal conductivity, and the hydrophobic material is nonmetallic.
5. A heat exchange element as claimed in claim 3 in which: the hydrophobic material is gold.
6. A heat exchange element as claimed in claim 3 in which: the hydrophobic material is palladium.
7. A heat exchange element as claimed in claim 4 in which: the hydrophobic material is a fluorinated hydrocarbon polymer.
8. A heat exchange element is claimed in claim 2 in which: the substrate is in the form of a plane surface plate.
9. A heat exchange element as claimed in claim 3 in which: the substrate is in the form of a plane surfaced plate.
10. A heat exchange element as claimed in claim 4 in which: the substrate is in the form of a plane surfaced plate.
11. A heat exchange element as claimed in claim 5, in which: the substrate is in the form of a plane surfaced plate.

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12. A heat exchange element as claimed in claim 6, in which:
the substrate is in the form of a plane surfaced plate.

13. A heat exchange element as claimed in claim 7, in which:
the substrate is in the form of a plane surfaced plate.

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