United States Patent

McGrew et al.

[15] **3,675,809**

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[54] CAPILLARY INSULATION

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[52] **U.S. Cl.** ....220/9 LG, 220/9 B, 220/9 D

[51] **Int. Cl.** **B65d 25/18**

[58] **Field of Search** ....220/9 LG, 9 D, 10, 9 A, 9 B, 220/15; 52/249, 618

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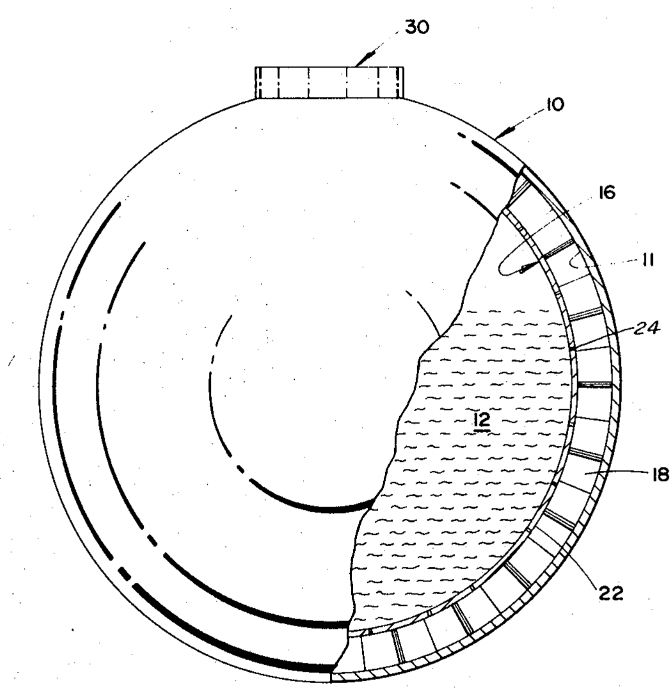
[57] **ABSTRACT**

The internal capillary insulation comprises cellular material secured to the internal wall of a vessel which is to contain liquid having a boiling temperature lower than the ambient temperature of the vessel. The cellular material disclosed provides a plurality of discrete cells. Each cell provides for establishing a column of gas therein between the tank wall and the liquid body. A capillary cover substantially closes the liquid side of the cells and has at least one capillary opening per cell designed to form a stable capillary gas-liquid interface or membrane at the capillary opening. The gas columns having a stable gas-liquid interface insulate the liquid from the vessel and in addition, support the liquid in the vessel thereby permitting fabrication of the insulation from materials which have low strength and weight and low thermal conductivity.

22 Claims, 5 Drawing Figures



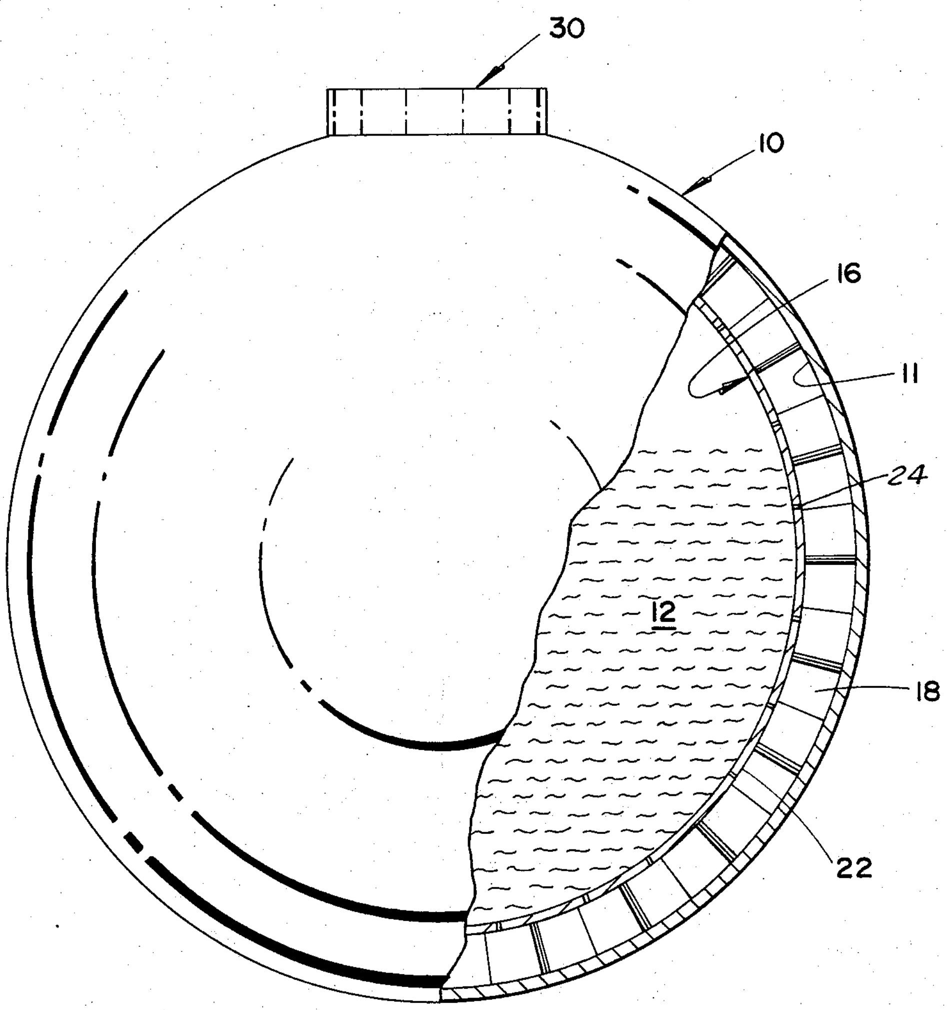


FIG. 1

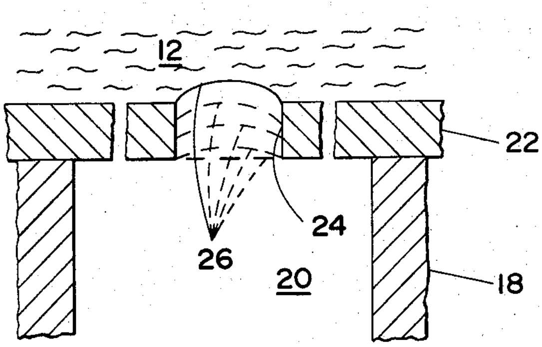


FIG. 3

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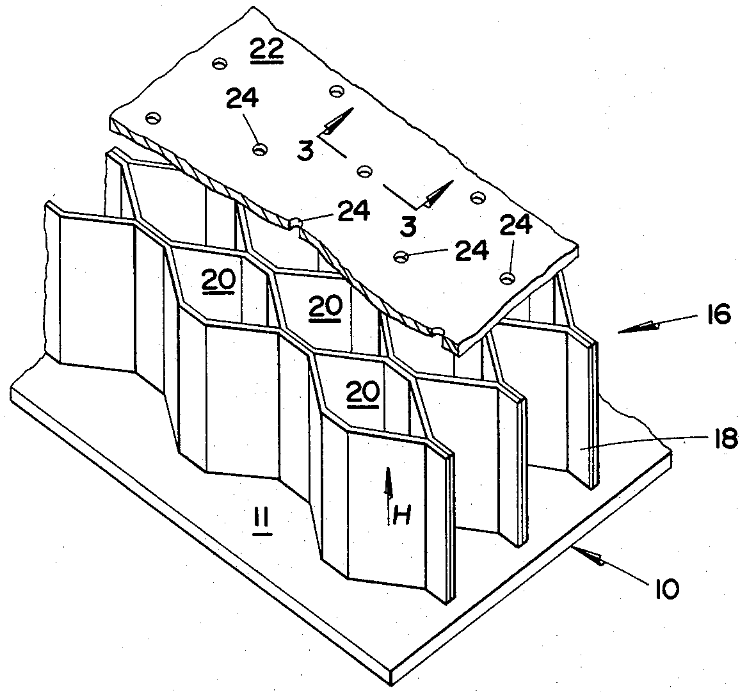

FIG. 2

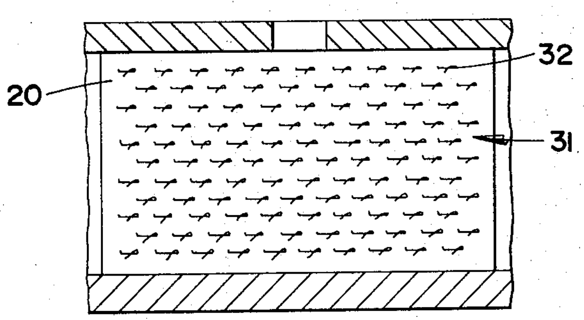

FIG. 4

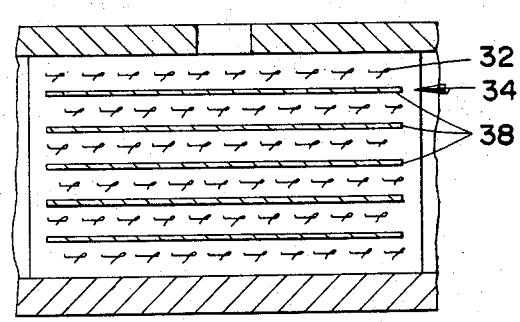

FIG. 5

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CAPILLARY INSULATION

BACKGROUND

Cryogenic and low temperature boiling point liquids have been used extensively by aerospace industries and are gaining in application in other industries. Examples of useful liquids are liquefied natural gas and liquid nitrogen, hydrogen, and oxygen. These liquids have several attractive features which contribute to their gain in application. However, the attractive features are offset by the problems associated with storing these fuels.

Insulation problems associated with storing low temperature liquid must be solved before widespread use can be made of these low temperature liquids. Specifically, the insulation must be thermally effective, relatively lightweight, inexpensive, and reliable over long periods, to mention a few. The present invention provides an insulation which provides the aforementioned features.

Vacuum jacket-type insulation is thermally the most effective insulation developed to date for insulating cryogenic and low temperature liquids. Basically, this insulation is provided by a container having inner and outer spaced walls and a vacuum is established between the walls. Such insulation has a very low thermal conductivity and consequently is a good insulator. However, the vacuum jacket-type insulation, even though effective as an insulator, has many problems, such as, making the walls air-tight so that a vacuum can be maintained without leakage, supporting the double wall tank, using special material for the inner tank to enable it to withstand the stress induced therein as a result of the large temperature differential on opposite sides thereof, and expending a large part of the liquid to be stored to cool down the inner tank wall. Hence, the vacuum jacket insulation has limited application because of the cost associated in overcoming these problems.

The present invention has for its objectives to provide an insulation which is lightweight, inexpensive, reliable, effective to insulate the liquid from the warmer environment it will experience during storage, which does not rely on vacuum and requires a minimum amount of stored liquid to cool down the insulation.

These objects are realized by the present invention by interposing and maintaining a plurality of discrete columns of gas between the wall of the tank to be insulated and the liquid stored therein. The gas columns are defined by lightweight cellular material having a low thermal conductivity and which can be of low strength because it is not required to support the liquid. The support function is assumed by the tank wall through the gas columns.

The discrete gas columns are established by gas trapped in voids in the cellular material and are maintained by utilizing surface tension herein referred to also as capillary forces which cooperate according to the present invention to establish a stable liquid-gas interface at the liquid end of the gas columns to prevent the liquid from penetrating the gas columns.

The stable capillary interface can be characterized as a membrane stretched across the top of the gas columns where the columns come into contact with the liquid and provide a physical barrier which prevents the liquid from penetrating the gas columns. Surface tension is that property that causes the interface to behave as a stretched membrane. A stable membrane permits the pressure of the gas to in effect push against the liquid to support the liquid independent of the cellular material and cover while insulating the liquid from the warmer tank wall.

Establishment of a stable membrane is dependent on a number of parameters such as the diameter of the opening which provides for communication between the gas column and liquid, the contact angle, surface tension and density of the liquid, and gravity. When the relationship between these parameters if controlled, it has been discovered that a stable membrane can be provided and maintained so that the gas columns can function to insulate and support the liquid from the tank wall. Furthermore, when the relationship between the parameters is so controlled, the stable membrane is independent of its orientation relative to the gravity vector.

To better understand the effect the above mentioned parameters have on establishing and maintaining the stable capillary membrane at each gas column, consider the following example. It can be observed that when a finger closes one end of a soda straw immersed in liquid and the straw is removed, the liquid is suspended in the straw. This is due to the fact that a stable membrane is established so that the atmospheric pressure can act on the exposed end of the liquid and exert sufficient force on the liquid to support the liquid. Atmospheric pressure is sufficient in this example to support the liquid column because a partial vacuum is established in the straw by closing off one end which contributes to the support of the liquid.

When the finger is removed, the partial vacuum is replaced by atmospheric pressure which acts along with gravity to overcome the atmospheric pressure supporting the liquid in the straw causing the liquid to drain from the straw. Notwithstanding the fact that a pressure differential contributed to the support of the liquid in the example, no quantity of air pressure will support the liquid in the absence of a stable membrane because there is nothing for the pressure to act against.

To demonstrate this latter statement, consider a second example where the same procedures of the first example are followed except that the straw selected has a diameter several magnitudes greater than the ordinary soda straw. The same pressures are acting on the liquid but the liquid drains from the larger straw even with one end closed.

The reason for the different result is that a stable membrane does not form in the second example so that the atmospheric pressure has nothing to act against. The larger straw diameter limited the membrane to a small rate of curvature in order to span the diameter. The smaller the rate of curvature of the membrane, the weaker the membrane. Conversely, the greater the rate of curvature of the membrane, the stronger the membrane. When the rate of curvature of the membrane is small as in the second example, the membrane is not stable and gas flows up the tube while liquid flows down until the tube is drained.

The parameters controlling the maximum diameter across which a stable membrane can form are the surface tension and density of the liquid, magnitude of the gravitation field, and the contact angle of the liquid. The contact angle of the liquid is the angle formed through the liquid at the line of intersection of liquid, gas and solid. The contact angle depends on the particular liquid, gas and the material of the solid surface involved.

PREFERRED EMBODIMENT OF THE INVENTION

Having described the background of the invention, a preferred embodiment of the invention will be described in conjunction with the drawing in which:

FIG. 1 is a side elevational view of a tank having a portion cut away to expose the insulation according to the present invention;

FIG. 2 is a perspective view of the insulation of FIG. 1 with parts broken away to more clearly illustrate details of construction of the insulation;

FIG. 3 is a cross sectional view taken approximately along the line 3—3 of FIG. 2 but on a larger scale showing the stable capillary interface of the liquid and gas;

FIG. 4 is a cross sectional view of one cell of the insulation illustrating packing means for the cell to reduce gas convection and radiation within the cell; and

FIG. 5 is a view similar to FIG. 4 but illustrating still another packing means for the cell for reducing convection and more effectively reducing radiation through the gas column.

Referring to the drawings and initially to FIG. 1, a tank indicated generally as **10** is disclosed for storing low temperature boiling point liquids **12**. The liquid **12** may be liquefied natural gas or liquid nitrogen, oxygen, hydrogen, etc. The tank **10** has internal insulation **16** applied to the interior surface **11** of the tank **10**, in any appropriate manner such as by bonding, etc. The bonding agent must be effective to bond the particular material selected for the insulation and tank and be compatible with the liquid to be stored.

The insulation **16** includes a cellular structure **18** best illustrated in FIG. **2** which may be fabricated of any lightweight material which is compatible with the liquid being insulated and has a low thermal conductivity, such as plastic. It has been discovered that materials having thermal conductivity of 1(Btu -ft)/(ft^2 -°F-Hr) or less are suitable. Examples of some plastic materials which comply with this criteria for use as the cellular structure **18** are polyimide, Mylar, Nomex, nylon, and plastic impregnated Kraft paper. Studies to date indicate polyimide is a preferred material for high tank temperature applications (up to 700° F) and Mylar is a preferred material for lower temperature applications. Both have excellent low temperature compatibility, low thermal conductivity, high shear strength, ductility at low temperature, and commercial availability.

The cellular material **18** can be of various geometric forms but the illustrated embodiment comprises a honeycomb structure defining a plurality of hexagonal cells **20** therein.

In the illustrated embodiment, the cells **20** are closed on one side by the inner surface **11** of the tank wall. However, in certain instances it may be desirable to bond the cellular material to another member which in turn is secured to the tank wall.

The cells **20** are substantially closed on the liquid side by a capillary cover **22**. Cover **22** may be made from material such as 1-mil Mylar film, plastic impregnated fiberglas cloth, or 1-mil Kapton film. However, Mylar film is preferred because of its strength, ductility, and flexibility at very low temperatures. The cover **22** is secured to the liquid side of the cellular material **18** in any suitable manner consistent with the intended use such as by adhesive bonding.

The cellular material **18** cooperates with cover **22** and the inner surface **11** of tank **10** to define substantially confined areas or voids designated herein as cells **20** within which gas can accumulate and form a plurality of discrete gas columns extending between the surface **11** of tank wall **10** and the liquid **12** being insulated. It is very important to the present invention to avoid communication between cells because such communication would destroy the integrity of the gas columns.

Each cell **20** communicates with the liquid **12** through at least one capillary opening or hole **24** provided in cover **22**. The opening **24** is generally smaller than the width of its associated cell and is sized to permit a stable capillary interface or membrane **26**, best illustrated in FIG. **3**, to form at the interface of the gas columns and liquid **12**. Membrane **26** prevents liquid **12** from penetrating the gas columns in cells **20** so that the gas columns remain intact to function as insulators for the liquid. Also membranes **26** provide surfaces against which the pressure of the gas columns can act to support the liquid **12** apart from the insulation **16**. Ultimately, the liquid **12** is supported by tank **10** through the gas columns. Hence, the insulation **16** can be constructed of relatively low strength material since it is not required to bear substantial loads.

Holes **24** can be provided by selecting material for cover **22** which has openings therein of the required size and distribution. Woven filter cloth and screen are examples of this type of material. Care must be taken when using this type of cover to assure proper distribution of the openings relative to the cells as will be more fully described hereafter. For this reason, it is preferable to select a material such as Mylar which is not porous and physically make the appropriate sized holes therein after the cover **22** has been bonded to the cellular material **18**. This assures that the proper number of openings are provided at the proper location relative to the cells. The holes can be formed through the cover approximately at the cell centers by use of an appropriate tool.

The location of the hole **24** relative to the cells **20** and the shape and diameter of the holes are parameters which are critical to establishing the stable membrane **26**. Each hole **24** must be located relative to its associated cell so that it is not adjacent to one of the cell's corners. If a hole is located over a corner there is a danger that a wicking condition will develop causing the liquid to be drawn or wicked along the corner into the cell and gas column. When liquid enters the cell the thermal conductivity of the cell increases.

Holes **24** preferably are circular or have a continuous curvature. A sharp angle in the surface of the material defining the hole is permissible, but will require a smaller maximum hole size.

The size of holes **24** is very important in establishing the stable membranes **26**. It has been discovered that the largest permissible circular hole diameter (*d*) which will establish and maintain stable membranes is the lesser diameter derived by the following relationships:

$$d_{ft} = (K_1\, S/RG)^{1/2} \qquad \text{(a)}$$

where

$K_1 = 3.36$ (a dimensionless, empirical constant for circular holes)

S = surface tension of the liquid gas interface under operating conditions (lb_{force}/ft)

R = difference between density of the liquid and the density of the gas (lb_{mass}/ft^3)

G = magnitude of the gravitational vector imposed by gravitational attraction and/or acceleration of the container wall (no. of std. earth gravity units with dimensions of lb_{force}/lb_{mass})

and

$$d_{ft} = K_2\, S/RGH \qquad \text{(b)}$$

where

$K_2 = 4$ (a dimensionless constant for circular holes)

H = maximum distance between any two openings in the same cell in the direction of the gravitational vector (ft)

The smaller diameter obtained from these relationships defines the ideal maximum hole size for the cells. In practice a hole diameter is selected which is smaller than the hole diameter provided by the above relationship to provide a safety factor.

Consider a typical example for determining the maximum diameter hole which would provide a stable capillary gas-liquid interface according to the foregoing relationship. Liquid nitrogen is to be stored at local atmospheric pressure (14.7 psia) in a stationary storage vessel. The saturated or boiling temperature of the liquid nitrogen under the foregoing conditions will be approximately −320° F. At this temperature and pressure, the liquid density is approximately 50.4 lb_{mass}/ft^3, the density of the nitrogen vapor is approximately 0.28 lb_{mass}/ft^3 and the liquid-gas surface tension is approximately 0.000597 lb_{force}/ft.

The maximum permissible diameter of a circular hole at which the capillary interface is established, is as follows:

$$dia_{ft} = (K_1 S/RG)^{1/2}$$

where

$K_1 = 3.36$

$S = 0.000597$ lb/ft

$R = 50.4 - 0.28 = 50.12\ lb_{mass}/ft^3$, the difference in density between liquid and gaseous nitrogen at the operating conditions (Note: for many cases, including this one, the gas density can be considered to be negligible without significant consequence)

G = 1 standard earth gravity unit, since the vessel is stationary and not subject to significant vibration or acceleration.

Thus,

$$dia_{ft} = (3.36 \times 0.000597/50.12 \times 1)^{1/2} = 0.00632_{ft}$$

or 0.0758 in.,

which is the maximum hole diameter if only a single opening is provided for each cell.

If, as a second example, two holes per cell are to be used for the possible purpose of providing redundancy in case one of the holes in any cell should become plugged, a further calculation is required. Assume that the maximum vertical separation between the two holes in any cell is controlled to one-half inch, or 0.0208 ft., then the maximum hole diameter is also limited by the condition of Equation (b):

$$dia_{ft} = K_2S/RGH$$

where

$K_2 = 4$

$H = 0.0208$ ft. the maximum separation between any two openings in the same cell in the direction of the gravity vector, i.e., in the vertical direction for a stationary vessel.

thus

$$dia_{ft} = (4 \times 0.000597/50.12 \times 1 \times 0.028) = 0.0023 \text{ ft or } 0.0263 \text{ in}$$

Since the smaller diameter obtained from the two equations establishes the maximum hole size, the hole diameters must be 0.0023 ft or smaller.

It should be apparent from the foregoing description that the insulation **16** is effective to insulate the liquid **12** from the tank wall **11**. The heat gradient which is indicated by the arrow marked H on FIG. **2** is from the tank wall **11** to the liquid **12**, and consequently, the insulation is effective for maintaining the liquid **12** at a temperature below the ambient temperature of the tank **10**.

It should also be apparent due to the nature of the cellular material **18** and cover **22**, that the weight of the insulation for a given surface to be insulated is very small. The disclosed cellular material **18** is of a honeycomb configuration which is available commercially in sizes as small as 35 cells per foot weighing approximately from 1.9 to 2.5 pounds per cubic foot to nine cells per foot weighing less than 1.5 pounds per cubic foot. At the present time, honeycomb having nine cells per foot has been found to be satisfactory for purposes of the present invention. However, it should be understood that various materials and cell configurations could be used for the cellular material as long as they satisfy the criteria required of the cellular material.

The cellular material selected should be strong enough to withstand the shear loading, thermal stresses, and the small loads due to the pressure acting on the cover. However, these loads are very small and the structural requirements imposed during fabrication and installation of the insulation may be more significant and may ultimately dictate the structural requirements.

It has been discovered that the low structural requirements imposed on the cellular material permit it to be constructed from a material having a ratio of the area of the solid material taken in a plane through the cellular material parallel to surface area **11** being insulated to the surface area **11** insulated thereby of 0.09 or smaller ratio. The small amount of material required also reduces the thermal conduction through the solid material and consequently reduces the thermal conductivity of the insulation. Further, the small thermal mass of the cellular material and cover requires a minimum of liquid boil-off to cool the insulation to the operating temperatures. Liquid boil-off cools the insulation by a process similar to the evaporative refrigeration process. From the foregoing, it should be apparent that the insulation is lightweight, has thermal conductivity approaching that of the gas columns in the cell, and requires small boil-off losses to cool down.

A tank **10** having the insulation **16** applied thereto as disclosed in FIG. **1** will be filled through a conventional cryogenic opening or inlet **30** disclosed on the top of tank **10**. The tank **10** can be prepared prior to filling by purging with a suitable gas compatible with the liquid **12** such as nitrogen or helium. The purging gas assures that all undesirable elements such as water vapor are displaced by the purging gas. It has been discovered that the gas in cells **20** will be replaced by the purging gas due to diffusion through openings **24**. Hence the cells **20** will be initially filled with the purging gas.

After the purging process has been completed, liquid is directed into the vessel **10** through inlet **30**. The liquid **12** contacts the capillary cover **22** which cools and contracts the gas columns in cells **20** and permits in most instances a small amount of liquid to enter the cells. The liquid in cells **20** vaporizes and increases the pressure in the gas columns until sufficient liquid vaporizes to equalize the pressure of the gas columns with the pressure of the liquid which permits the establishment of the stable capillary membrane **26**. The membrane **26** can form at various locations relative to the openings **24** which positions are illustrated in dotted lines in FIG. **3**. As long as the conditions remain relatively constant, the gas columns will insulate and support the liquid **12**. If the tanks were to be depressurized after the stable membranes **26** are established, gas would bubble from the cells **20** to establish a new state of pressure equilibrium. A pressure increase in the tank results in a sequence of events similar to those described during initial cool-down of the system. At no time during normal operation does the pressure difference across the cover **22** exceed that due to flow loses through the capillary opening **24**, which can be sized to limit this pressure difference to a small value. Thus, the cells can be characterized as being self-restoring when liquid enters them which contributes to the insulation being reliable over long durations.

Immediately following filling of the tank with a liquid, the cells **20** will be filled with a mixture of the purged gas and vapor of the contained liquid. The purge gas will ultimately dissipate and the cells **20** will be totally filled with the vapor of the contained liquid.

The present invention contemplates providing packing means in each cell **20** to reduce the convection and radiation within cell **20**. This means is illustrated in FIGS. **4** and **5**. In FIG. **4** packing means **31** comprises a filler **32** which is loaded into the cell to fill the cell prior to placing the cover **22** thereon. The filler **32** must be such that it will not prevent pressure equalization to occur throughout the cell, be lightweight, inexpensive, and have low thermal conductivity. Examples of suitable fillers would be loose polystyrafoam chips, rock wool batting, Fiberglas, ceramic felt, shredded paper, and expanded perlite.

FIG. **5** discloses a modified cell packing **34** which includes a combination of filler **32** sandwiched by a reflective foil material **38** such as aluminum foil, aluminized Mylar, or aluminized Kapton. The filler **32** reduces the convection while the foil **38** reduces radiation through the cells.

Another means effective to reduce convection and radiation in cell **20** is to making the dimension across the cell very small in relation to the length of the cell. However, this approach increases the weight and thermal conduction through the cellular material.

It should be apparent that the present invention provides an effective insulation which satisfies the objects set forth heretofore namely light in weight, reliable due to the self-restoring feature provided thereby, easily applied and utilizes minimum amounts of stored liquid to cool down the insulation, all of which contribute to an economical insulation for low temperature liquid.

What is claimed is:

1. Insulation for reducing heat transfer from the surface of a container for liquid to liquid being contained therein, comprising first means adapted to be attached to an internal surface of the container and providing a plurality of discrete cells adapted to contain insulating gas, means closing the ends of said cells adjacent the container surface, and second means for providing a stabilized capillary gas-liquid interface closing the opposite ends of said cells when in contact with the contained liquid with none of the liquid penetrating the cells during steady state conditions.

2. Insulation as defined in claim **1**, wherein said first means comprises structural material having thermal conductivity of 1 (Btu - ft)/(ft^2 -°F-Hr) or less when measured at 70° F.

3. Insulation as defined in claim **1**, wherein said first means comprises a structure such that the ratio of cross sectional area of the solid portion of the structure to the total area of the surface being insulated is equal to or less than 0.09.

4. Insulation as defined in claim 1, further including means associated with each cell for reducing free convection within each cell.

5. Insulation as defined in claim 1, further including means associated with each cell for reducing radiation in each cell.

6. Insulation as defined in claim 1 wherein the contained liquid has a boiling temperature corresponding to pressure imposed on the liquid below the container surface temperature.

7. Insulation as defined in claim 1 wherein the bulk of the contained liquid is at a temperature below the boiling temperature corresponding to the pressure imposed on the liquid and wherein the cell is partially filled with a gas other than the vapor of the contained liquid, so as to permit a stable liquid gas capillary interface to be maintained at a temperature lower than the boiling temperature corresponding to the pressure imposed on the liquid.

8. Insulation as defined in claim 1, wherein said second means includes a member capping said opposite ends of said cells and having a capillary opening in communication with each cell.

9. Insulation as defined in claim 8, wherein the projections of the edges of said member defining said openings includes angles.

10. Insulation as defined in claim 8, wherein said openings are located relative to the portion of said first means that define said cells, so that capillary ducting of the liquid into the cell is prevented.

11. Insulation as defined in claim 8, wherein each portion of said member defining said openings has a continuous curvature.

12. Insulation as defined in claim 11, wherein the maximum dimension of said openings is determined by the smaller dimension (d) provided by the following relationships:

$$d_{ft} = (K_1\ S/RG)^{1/2} \qquad \text{(a)}$$

where

$K_1 = 3.36$ (a dimensionless, empirical constant for circular holes)

S = surface tension of the liquid gas interface under operating conditions ($1b_{force}$ / ft)

R = difference between density of the liquid and the density of the gas (lb_{mass} / ft^3)

G = magnitude of the gravitational vector imposed by gravitational attraction and/or acceleration of the container wall (no. of std. earth gravity units with dimensions of lb_{force}/lb_{mass})

and

$$d_{ft} = K_2\ S/RGH \qquad \text{(b)}$$

where

$K_2 = 4$ (a dimensionless constant for circular holes)

H = maximum distance between any two openings in the same cell in the direction of the gravitational vector (ft)

13. Insulation for reducing heat transfer from the surface of a container to liquid contained therein, comprising means for providing a plurality of discrete columns of gas between the liquid and the container surface and second means for providing a stable capillary interface between said gas columns and the liquid when said gas columns are in contact with the liquid to support the liquid away from the container while preventing the liquid from penetrating the gas columns during steady state conditions.

14. Insulation as defined in claim 13, further including means associated with each cell for reducing free convection within each cell.

15. Insulation as defined in claim 13, further including means associated with each cell for reducing radiation in each cell.

16. Insulation as defined in claim 13, wherein said means for providing a plurality of discrete columns of gas includes cellular material having a plurality of discrete cells or voids therein within which the gas columns are provided.

17. Insulation as defined in claim 16, wherein said cellular material has thermal conductivity of 1 (Btu - ft)/(ft^2 - °F-Hr) or less when measured at 70° F.

18. Insulation as defined in claim 16, wherein said cellular material has a ratio of cross sectional area of the solid portion thereof to the total area of the surface being insulated equal to or less than 0.09.

19. Insulation as defined in claim 13, wherein second means comprises a capillary cover which substantially closes the liquid side of each cell, and capillary openings in said cover above each cell to provide communication between the gas columns and liquid to permit the stable capillary interface to be established.

20. Insulation as defined in claim 19, wherein said openings are configured of a continuous curvature.

21. Insulation as defined in claim 20, wherein the maximum dimension of said openings is determined by the smaller dimension (d) provided by the following relationships:

$$d_{ft} = (K_1\ S/RG)^{1/2} \qquad \text{(a)}$$

where

$K_1 = 3.36$ (a dimensionless, empirical constant for circular holes)

S = surface tension of the liquid gas interface under operating conditions (ob_{force}/ ft)

R = difference between density of the liquid and the density of the gas (lb_{mass}/ft^3)

G = magnitude of the gravitional vector imposed by gravitational attraction and/or acceleration of the container wall (no. of std. earth gravity units with dimensions of lb_{force}/lb_{mass})

and

$$d_{ft} = K_2\ S/RGH \qquad \text{(b)}$$

where

$K_2 = 4$ (a dimensionless constant for circular holes)

H = maximum distance between any two openings in the same cell in the direction of the gravitational vector (ft)

22. A method for thermally insulating contained liquid to reduce heat transfer from the container to the liquid comprising the steps of providing a plurality of discrete columns of gas interposed between the liquid and the container and providing the ends of the gas columns in contact with the liquid with a stable capillary interface with the liquid to support the liquid away from the container while preventing the liquid from penetrating the gas columns during steady state conditions.

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