HEAT PIPE SYSTEMS USING NEW WORKING FLUIDS

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Abstract

The performance of a heat pipe system is greatly improved by the use of a dilute aqueous solution of about 0.0005 and about 0.005 moles per liter of a long chain alcohol as the working fluid. The surface tension-temperature gradient of the long-chain alcohol solutions turns positive as the temperature exceeds a certain value, for example about 40°C for n-heptanol solutions. Consequently, the Marangoni effect does not impede, but rather aids in bubble departure from the heating surface. Thus, the bubble size at departure is substantially reduced at higher frequencies and, therefore, increases the boiling limit of heat pipes. This feature is useful in microgravity conditions. In addition to microgravity applications, the heat pipe system may be used for commercial, residential and vehicular air conditioning systems, micro heat pipes for electronic devices, refrigeration and heat exchangers, and chemistry and cryogenics.

ABSTRACT

The performance of a heat pipe system is greatly improved by the use of a dilute aqueous solution of about 0.0005 and about 0.005 moles per liter of a long chain alcohol as the working fluid. The surface tension-temperature gradient of the long-chain alcohol solutions turns positive as the temperature exceeds a certain value, for example about 40°C for n-heptanol solutions. Consequently, the Marangoni effect does not impede, but rather aids in bubble departure from the heating surface. Thus, the bubble size at departure is substantially reduced at higher frequencies and, therefore, increases the boiling limit of heat pipes. This feature is useful in microgravity conditions. In addition to microgravity applications, the heat pipe system may be used for commercial, residential and vehicular air conditioning systems, micro heat pipes for electronic devices, refrigeration and heat exchangers, and chemistry and cryogenics.

17 Claims, 2 Drawing Sheets
Figure 1
Figure 2
HEAT PIPE SYSTEMS USING NEW WORKING FLUIDS

ORIGIN OF THE INVENTION

The invention described herein was made by a civil servant employee of the United States Government, and a non-civil servant employee working under a NASA contract, and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 U.S.C. 2457).

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to the field of heat transfer. More particularly, it relates to the use of new heat transfer fluids in a heat transfer system, particularly for heat pipe systems both in terrestrial and microgravity environments.

2. Description of the Relevant Art

Heat pipes can be described as devices employing closed evaporating-condensing cycles for transporting heat from a locale of heat generation to a location of heat rejection, using a capillary structure or wick for return of the condensate. Whenever the surface of the pipe or tube has a negative surface tension against temperature, the Marangoni mechanism is strong enough to cause bubbles to form as a result of the temperature gradient that presses the bubbles onto the heat transfer pipe, as discussed by Ahmed and Carey in their article entitled “Effects of Gravity on the Boiling of Binary Fluid Mixtures” appearing in International Journal of Heat and Mass Transfer, Vol. 37, No. 16, 1998, pp. 2469-2483, conducted an experiment with water-2-propanol mixtures under reduced gravity. They concluded that the Marangoni effect arising from the reduced surface tension gradients due to concentration gradients is an active mechanism in the boiling of binary mixtures, and that the boiling mechanism in these mixtures is nearly independent of gravity.

The experimental results obtained by Abe et al. and by Ahmed and Carey clearly show that for so-called positive mixtures, in which the more volatile component has a lower value of surface tension, the Marangoni mechanism is strong enough in the mixtures to sustain stable nucleate boiling under microgravity conditions.

Besides the surface tension gradients due to concentration gradients, Marangoni effects are also induced by temperature gradients, which are more common and more important in heat transfer devices. Unfortunately, all working fluids used in existing heat transfer devices, including heat pipes, have a negative gradient of surface tension against temperature which is quite detrimental to boiling heat transfer, as mentioned above. In addition to the Marangoni flow around bubbles induced by the negative surface-tension-temperature gradient that presses the bubbles onto the heating surface resulting in an unfavorable situation for boiling performance, another Marangoni effect induced by the surface-tension-temperature gradient is the moving of a liquid body towards the region of lower temperature, thus preventing liquid spreading on a heated portion of the heating surface, such as the evaporator section of heat pipes.

All heat pipes have a boiling limit, which is directly related to bubble formation in the liquid. If the number and
size of vapor bubbles generated at the wall and/or the fin-wick interface are small, these bubbles may migrate from the solid surfaces to the liquid-vapor interface and vent into the vapor groove without destroying the capillary menisci. However, as the heat flux is increased further, bubbles may coalesce, form a vapor blanket at the wall and/or the fin-wick interface, and eliminate the capillary force that circulates the liquid condensate. Vapor bubbles that are coalesced at the evaporator section may block the liquid return from the condenser section and the boiling limit can be reached. For the heat pipes with a wick structure, the critical temperature difference across the liquid layer at the evaporator section, which reflects the boiling limit, is given as:

\[ \Delta T_{cr} = T_w - T_e = \frac{2 \sigma T_e}{h_{fg} \rho_v} \left( \frac{1}{R_{pb}} - \frac{1}{r_{ev}} \right) \]

where \( T_w \) and \( T_e \) are the wall temperature and the vapor temperature at the evaporator section, respectively; \( \sigma \) is the surface tension of the working fluid; \( h_{fg} \) is the enthalpy of vaporization of the working fluid; \( \rho_v \) is the vapor density; \( R_{pb} \) is the radius of vapor bubble at the liquid-wall interface, and \( r_{ev} \) is the effective pore radius of the wick or the effective curvature radius of the liquid film on the wall. It is obvious that the critical temperature difference closely relates to the characteristics of the surface tension of the working fluid. Based on this relation, ignoring the changes of \( R_{pb} \) and \( r_{ev} \) with the wall temperature, the following equation can be derived:

\[ \Delta T_{cr} = \frac{2 \sigma T_e}{h_{fg} \rho_v} \left( \frac{1}{R_{pb}} - \frac{1}{r_{ev}} \right) \]

It can be seen that the negative surface-tension gradient with temperature will reduce the critical temperature difference when the operating temperature at the evaporator section is increased.

On the other hand, the available capillary-pressure pumping-head decreases as the evaporating temperature of the heat pipes increases, and the operation becomes unstable. The varying of the available capillary-pressure pumping-head \( P_r \) with temperature can be expressed as:

\[ \frac{\partial P_r}{\partial T_e} = \frac{2}{r_{ev}} \frac{\partial \sigma}{\partial T_e} + \frac{2 \sigma}{r_{ev}} \frac{\partial T_e}{T_e} \]

where \( \theta \) is the contact angle of the working fluid on the wall or the wick surface. It is obvious that because of a negative value of

\[ \frac{\partial \sigma}{\partial T_e} \]

and a positive value of

\[ \frac{\partial \theta}{\partial T_e} \]

the left side of the equation,

\[ \frac{\partial P_r}{\partial T_e} \]

is negative, meaning a decrease of the available capillary-pressure pumping-head when the temperature at the evaporation section is increased.

The increase of the operative temperature also leads to the increase of liquid pressure drop. As a result, the heat load of the heat pipe system is limited. Additionally, it has been demonstrated that capillary-pumped device instabilities are caused by thermocapillary instabilities of the contact line region of evaporating menisci. The cause of the instabilities is disintegration of the liquid film, caused by the relation of negative surface tension gradient with temperature.

Water has widely been used in heat pipes for all kinds of systems, both in terrestrial and microgravity environments, by virtue of its availability, cost, safety, and especially its high surface tension. Surface tension \( \sigma \) of water can be formulated as:

\[ \sigma = 75.64 - 0.1673t \]

where \( t \) is the temperature in degrees Celsius. As can be seen from this equation, the surface tension of water largely decreases as temperature increases, and, therefore, the heat load and the performance of the heat pipe systems with water are limited. As contrasted to the existing working fluids used in the heat pipes, the new working fluids introduced by the present invention have positive gradient of surface tension with temperature. All the shortcomings induced by the negative surface-tension-temperature gradient are eliminated. The heat load of heat pipes will be significantly increased for the results of increase of both boiling and capillary limits and the operation of heat pipes will be more stable.

A number of other water mixtures have also been used as working fluids, as in, for example, U.S. Pat. No. 3,777,811. This patent specifies that desirable working fluids for heat pipe devices include properties such as high surface tension and a freezing point above the lowest temperatures that may be encountered. It states that lower freezing point fluids such as “the alcohols ...” are less effective and less desirable than liquid metals and water for use in heat pipe-type devices to heat transport in space. U.S. Pat. No. 4,664,181 relates to heat pipe working fluids containing water and between about 1% and 7.5% by volume of low molecular weight alcohols, such as ethanol, propanol and butanol. The mixture serves to protect the heat pipe from damage due to freezing. The patent does not deal with enhancements of heat transfer of these working fluids through changing surface tension characteristics for increase of heat pipes’ heat load and stabilities, especially under microgravity conditions. In fact, as solutions, the properties of the dilute aqueous solutions of long-chain alcohols are quite different from the one of the water-alcohol mixtures, especially the surface tension characteristics with temperature.

BRIEF DESCRIPTION OF THE INVENTION

One object of the present invention is to greatly increase the heat transfer performance of heat pipes, including conventional heat pipes, micro heat pipes, capillary pumped loops (CPLs) and loop heat pipes (LHPs), for such uses as electronics cooling, air conditioning, engine cooling, power generation and energy recuperation, by using the new working fluids that have a positive surface tension gradient with temperature. The operational instabilities are also eliminated.
A second objective is to use dilute aqueous solutions of long-chain alcohols as working fluids of heat pipes for space applications within the operating regimes of these working fluids.

Yet another object is to extend the limit of the pumping capability of the capillary structure in providing enough liquid return to the evaporator, including an increase in the maximum heat flow rate at operating temperature.

Still another object is to obtain higher pumping capability over long distances at any orientation in a gravitational or microgravitational field.

Finally, it is an object to provide a means to reduce costs and increase the reliability and performance of finished products that utilize heat pipes for thermal management.

These and other objects and advantages, that will become apparent upon a reading of the detailed description described below, are achieved in the following manner.

A heat pipe system is described which utilizes a working fluid that has a positive gradient of surface tension with temperature. The working fluid comprises a dilute aqueous solution of a straight or a branched chain alcohol containing 4 or more carbon atoms. The candidate alcohols are, n-butanol, n-pentanol, n-hexanol, n-heptanol, n-octanol, n-nonanol, n-decanol, 2 or 3 or 4 or 5 nonanol, or 2,6-Dimethyl-4-heptanol, 3,5-Dimethyl-4-heptanol, 2,2-Diethyl-1-pentanol, and 7-Methyl-1-octanol. The alcohols are present below their saturated concentration, generally in a very small amount, preferably between about 0.0005 moles per liter and about 0.0005 moles per liter of water.

The invention also relates to a heat pipe system comprising a closed evaporating-condensing cycle and the method of its use. The system includes a working fluid having a positive gradient of surface tension with temperature. The working fluid comprises an aqueous solution of a straight or branched chain alcohol containing more than 4 carbon atoms.

The invention also relates to the method of achieving heat exchange under conditions of microgravity comprising the use of a working fluid in a heat exchanger wherein the fluid comprises an aqueous solution and an effective amount of a long-chain alcohol to provide the fluid with a positive gradient of surface tension with temperature. The fluid comprises an aqueous solution of an alcohol containing at least 4 carbon atoms. The alcohol is selected from the group consisting of C₆ to C₁₀ straight and branched chain alcohols, and is used in a concentration below its saturated concentration, which is between about 0.0005 and about 0.005 moles per liter of water. The heat exchanger typically comprises a heat pipe selected from a conventional heat pipe, a capillary pumped loop (CPL), a loop heat pipe (LHP) and a micro heat pipe.

Still further, the present invention relates to a method of increasing the heat transfer rate of an aqueous working fluid in a heat pipe. The method involves adding to the working fluid of water an effective amount of an alcohol to provide the fluid with a positive gradient of surface tension with temperature in the range of operating temperatures of the fluid. Typically, the alcohol is a C₆ to C₁₀ straight or branched chain and is present in the fluid in an amount of between about 0.0005 and about 0.005 moles per liter.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a graph showing the surface tension versus temperature for a series of dilute aqueous solutions of n-alcohols; and

FIG. 2 is a graph showing the surface tension of different concentrations of n-heptanol in water at various temperatures.

DETAILED DESCRIPTION OF THE INVENTION

Capillary pressure is the driving force for the circulation of the working fluid in heat pipe systems, and is considered as an operating limit with respect to total pressure drop within the system. For a wick-structured heat pipe system including conventional heat pipes, CPLs and LHPs, stable working fluid circulation is achieved through the capillary pressure head developed by the wick structure. The available capillary pressure pumping head is a function of the surface tension of the working fluid. Thus, the surface tension is a key factor in determining the capillary limit of the heat pipe system.

One of the performance indexes of a heat pipe is its maximum heat load value. To ensure a large heat load without reaching the boiling limit at the evaporator, the most significant factor is the ability of the working fluid to wet the heated wall. In accordance with the teachings of the present invention, dilute aqueous solutions of alcohols with a chain length of at least four carbon atoms develop a positive surface-tension-temperature gradient when the fluid temperature exceeds a certain value, for example about 40°C for the aqueous solutions of n-heptanol. This is shown in FIG. 1 which plots the surface tension vs. temperature for seven aqueous solutions from C₆ to C₁₀. It is noted that, as the chain length of the alcohol increases, the temperature inversion point of the surface tension gradient (i.e. the temperature at which the surface tension gradient changes from a negative value to a positive one with temperature) decreases. All of this data is determined at Earth’s gravity.

Turning now to FIG. 2, the effect of concentration of n-heptanol in the aqueous solution on the surface tension with various temperatures is shown. These results are reported in an article by R. Vochten et al entitled “Study of the Heat of Reversible Adsorption at the Air-Solution Interface” in the Journal of Colloid and Interface Science, Vol. 42, No. 2 (1973), pp. 320-327. Pure water and eight different dilute aqueous concentrations of n-heptanol were tested with the surface tension measured at various temperatures between 0°C and 70°C and at 760 mm Hg. These concentrations are noted as follows:

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pure water</td>
</tr>
<tr>
<td>2</td>
<td>6.31 x 10⁻⁴</td>
</tr>
<tr>
<td>3</td>
<td>8.00 x 10⁻⁴</td>
</tr>
<tr>
<td>4</td>
<td>1.00 x 10⁻³</td>
</tr>
<tr>
<td>5</td>
<td>1.50 x 10⁻³</td>
</tr>
<tr>
<td>6</td>
<td>1.89 x 10⁻³</td>
</tr>
<tr>
<td>7</td>
<td>2.00 x 10⁻³</td>
</tr>
<tr>
<td>8</td>
<td>5.00 x 10⁻³</td>
</tr>
<tr>
<td>9</td>
<td>7.60 x 10⁻³</td>
</tr>
</tbody>
</table>

The surface tension of pure water is 75.64 dynes at 0°C and 58.91 dynes at 100°C. (see Vargaftik et al, entitled “International Tables of the Surface Tension of Water” in J. Phys. Chem. Ref. Data, Vol. 12, 1983, p. 817). It is readily apparent from FIG. 2 that the surface tension gradient of dilute aqueous solutions of n-heptanol alcohol shows a positive value near the boiling point while having almost same value of surface tension as water. It is noted that
solutions having concentrations of 0.005 mole per liter and higher have a substantially larger surface tension gradient near the boiling point than those solutions of 0.002 mole per liter and less. Furthermore, the effect of temperature on surface tension on samples 8 and 9 is more than the effect on samples 1–7.

This surface tension force is assisted by the buoyant force in nucleate boiling on earth, whereas it would become the principal driving force for bubble departure from the heating surface microgravity environment. Consequently, bubble departure size is smaller in these aqueous solutions than in water, with a higher departure frequency.

Note that it requires the addition of only a small quantity of the long-chain alcohols, on the order of 10^−2 mole/l, to alter surface tension characteristics of water without affecting other bulk properties of the water, such as the boiling point. Another important feature of these aqueous solutions is a very high value of the positive surface tension-temperature gradient when the working fluid temperature is near its saturation point, thus producing considerable driving force for bubble departure and moving of the fluid towards the hot areas in the evaporator section of heat pipes. Recognizably, this factor greatly enhances heat transfer.

Because the surface tension of aqueous solutions of alcohols with chain lengths of four carbon atoms and longer have a positive gradient with temperature when the temperature exceeds a certain value, the operating temperature of the evaporator can be increased. Consequently, the pumping pressure load and the heat load increase. In addition, the instability problems previously mentioned are overcome as well. The performances of heat pipes with water, including conventional heat pipes, CPLs and LHPs, and the micro heat pipes, are improved significantly by using the dilute aqueous solutions of these alcohols. The temperature at which the gradient becomes positive may be, for example, about 20 °C for aqueous solutions of n-decanol, about 40 °C for the aqueous solutions of n-heptanol, and about 70 °C for butanol solutions. Generally, the performance of all kinds of heat pipes can be greatly increased by changing the surface tension characteristics of their working fluids from the negative gradient to the positive gradient with temperature. Accordingly, the Wick permeability in the operating temperature range of the system.

The specific details of the aqueous alcohol solutions and their method of preparation are well known to persons of ordinary skill in the art and do not comprise a part of the present invention, except to the extent that these details and uses have been modified to become useful therein. While the invention has been described in combination with embodiments thereof, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art in light of the foregoing teachings. Accordingly, the invention is intended to embrace all such alternatives, modifications and variations as fall within the spirit and scope of the appended claims.

What is claimed is:

1. A heat pipe system comprising a closed evaporating-condensing cycle and including a working fluid having a positive gradient of surface tension with temperature at operating temperature range of the system.

2. The system according to claim 1 wherein working fluid comprises an aqueous solution of an alcohol containing at least four carbon atoms.

3. The system according to claim 2 wherein the alcohol is selected from the group consisting of C4 to C10 straight and branched chain aliphatic alcohols.

4. The system according to claim 1 wherein the heat pipe is selected from a conventional heat pipe, a capillary pumped loop, a loop heat pipe and a micro heat pipe.

5. The system according to claim 2 wherein the concentration of the alcohol in the aqueous solution is between about 0.0005 and about 0.005 moles per liter of water.

6. A working fluid for a heat pipe system wherein the fluid comprises an aqueous solution of an alcohol containing more than four carbon atoms.

7. A working fluid according to claim 6 wherein the alcohol is selected from the group consisting of C4 to C10 straight and branched chain aliphatic alcohols and mixtures thereof.

8. The working fluid according to claim 6 wherein the alcohol is selected from the group consisting of C4 to C10 straight and branched chain aliphatic alcohols and mixtures thereof.

9. The working fluid according to claim 7 wherein the concentration of the alcohol in the aqueous solution is between about 0.0005 and about 0.005 moles per liter of water.

10. A method of achieving heat exchange under conditions of microgravity comprising the use of a working fluid in a heat exchanger wherein the fluid comprises an aqueous solution and an effective amount of a long-chain alcohol to provide the fluid with a positive gradient of surface tension with temperatures above about 40 °C, at atmospheric pressure.

11. The method according to claim 10 wherein the fluid comprises an aqueous mixture of an alcohol containing at least four carbon atoms.

12. The method according to claim 11 wherein the alcohol is selected from the group consisting of C4 to C10 straight and branched chain aliphatic alcohols and mixtures thereof.
13. The method according to claim 10 wherein the concentration of the alcohol is between about 0.0005 and about 0.005 moles per liter of water.

14. The method according to claim 10 wherein the heat tension with temperature in the range of operating temperatures of the fluid in the heat pipe.

15. A method of increasing the heat transfer rate of an aqueous working fluid in a heat pipe comprising adding an effective amount of an alcohol to the working fluid to provide a solution having a positive gradient of surface tension with temperature in the range of operating temperatures of the fluid in the heat pipe.

16. The method according to claim 15 wherein the alcohol is a C₂ to a C₂₀ straight or branched chain alcohol.

17. The method according to claim 16 wherein the alcohol is an aliphatic alcohol and is added in an amount of between about 0.0005 and about 0.005 moles per liter of water.