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HEAT TRANSFER PERFORMANCE OF AN INCLINED TWO-PHASE CLOSED THERMOSYPHON

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Abstract—An experimental study on the heat transfer performance of an inclined two-phase closed thermosyphon is described. Water and ethanol have been used as the working fluids. The amount of working fluid and the inclination angle have been used as the experimental parameters. A visualization of the movement of liquid with boiling, the scattering of liquid drops and the condensation of vapor has made clear the heat transfer mechanism in the thermosyphon. In addition, the overall heat transfer coefficients and the thermal diode characteristics have been obtained.

NOMENCLATURE

A	area [m^2]
Q	heat transfer rate [W]
q	heat flux [W m^{-2}]
T	temperature [°C]
U	overall heat transfer coefficient [W m^{-2} K^{-1}]

Greek symbols

ζ	fill ratio of working fluid [%]
Φ	inclination angle (degrees)
Φ_D	thermal diode angle (degrees)

Subscripts

C	condenser
E	evaporator
H	heating
L	cooling
op	operating

1. INTRODUCTION

THE DEVELOPMENT of the heat pipe was originally directed towards space applications. The recent emphasis on energy conservation has promoted the use of the heat pipe as a component in terrestrial heat recovery units and solar energy utilizations. The other interesting development in the heat pipe field has been the increasing emphasis on its use as an effective device for the cooling of electronic equipment.

A two-phase closed thermosyphon must be used instead of a capillary heat pipe when the heating region is located below the cooling region of an external force, such as gravity and centrifugal force. This is due to the fact that the construction of the two-phase closed thermosyphon is simpler, the thermal resistance is smaller, the operating limits are wider, and the fabrication cost is lower than that of the capillary heat pipe. The two-phase closed thermosyphon may be also used for the cooling of gas turbine blades.

The basic experiment of the two-phase closed thermosyphon was carried out by Lee and Mital [1]. They studied it in a vertical situation only. Recently, there have been some investigations [2–5] on the vertical thermosyphon. Imura *et al.* [2] and Shiraishi *et al.* [3] obtained the heat transfer coefficient and the thermal resistance of a vertical thermosyphon. Ho and Tien [4] investigated the reflux condensation characteristics in a vertical thermosyphon. The boiling in a vertical thermosyphon was studied by Savchenkov *et al.* [5].

There have been very few investigations in inclined thermosyphons. Nguyen-Chi and Groll [6] and Hahne and Gross [7] studied the influence of the inclination on the entrainment limit and the maximum heat flow. The design information and the operating technique of this device are neither understood sufficiently nor available. Furthermore, the inclined thermosyphon has the unique property in that it can function as a thermal diode or a thermal switch.

The object of the present work is to obtain experimentally information on the interactive influence of the inclination angle and the amount of working fluid upon the heat transfer performance of an inclined two-phase closed thermosyphon and to observe the detailed phenomena concerned with the heat transfer mechanism of this device. In addition, it is to obtain the overall heat transfer coefficients and the characteristics as a thermal diode for the practical applications.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic diagram of the experimental set-up is shown in Fig. 1. The thermosyphon was made of a 15 mm standard copper tube. The tube was 330 mm long and had a 13 mm I.D., with a wall thickness of 1.0 mm. Two 150 mm long water jackets were set on the tube. One was used as a heating jacket for an evaporator and the other was used as a cooling jacket for a condenser. An inlet small tube for heating or cooling water flow into each jacket was directed at a tangent to the inside surface of the jacket so as to prevent the thermosyphon from direct exposure to the water flow.

Two glass windows, one fitted in each end of the thermosyphon, made possible the observation of the

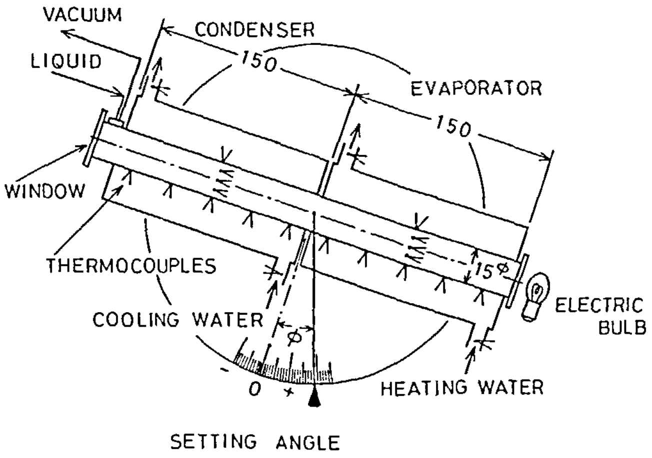

FIG. 1. Experimental apparatus.

phenomena of boiling, liquid movement and condensation of vapor by the light of an electric bulb. In addition to the copper thermosyphon, a glass thermosyphon made to the same dimensions was prepared to observe in more detail the phenomena in the tube.

The inside surface of the thermosyphon was cleaned thoroughly by a neutral cleanser, ethanol and distilled water. A plug was placed in the tube wall near the end of the condenser in order to allow the inner space of the thermosyphon to be evacuated and the working fluid to be injected.

Ten thermocouples were soldered on the outside surface of the tube along its length and another 8 thermocouples were uniformly spaced on the circumference at the center of the evaporator and condenser. Four more thermocouples were placed at the inlets and the exits of two water jackets. The outputs of these thermocouples were recorded on a digital thermometer.

The inclination of the thermosyphon could be set at an arbitrary angle. A mechanical vacuum pump with a rating of 10^{-3} Torr was used to remove air and other non-condensable gases.

In the present study, distilled water and ethanol were chosen as the working fluids, since these are compatible with copper and safe materials to work with. The working fluid was injected into the tube after evacuating air.

After injecting the working fluid, heating and cooling water flowed into the evaporator and the condenser jackets, respectively. A small amount of non-condensable gas was collected at the end of the condenser after a few minutes of operation. This was gas which had been solved in the working fluid at atmospheric pressure and temperature. This gas was removed through the plug by the vacuum pump mentioned previously.

The experimental conditions were set as follows. The mean temperature of cooling water was kept at 25°C. The heating water temperature was varied. The amount of working fluid was varied from 1 to 20 ml corresponding to a ratio of fill charge volume to inner volume of the evaporator zone of 5–100%. The angle of the thermosyphon was changed between 90° (vertical situation) and −10°.

The heat transfer rate was obtained from the temperature rise and the mass flow rate of cooling water through the condenser jacket. The flow rate of heating or cooling water was set at a value such that the temperature difference along each length of the evaporator or condensor was less than 1.0°C in ordinary operation. The temperature distributions on the evaporator and the condenser walls were recorded. The evaporation, the condensation of vapor and the liquid movement were observed.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. *Effects of amount of working fluid and inclination angle*

3.1.1. *Water thermosyphon.* The heat transfer performance of the water thermosyphon is shown in Fig. 2 as a function of the working fluid fill ratio and the inclination angle. The temperatures of the heating and cooling water were set at 85 and 25°C, respectively.

In general, in order to obtain a high heat transfer rate, it is necessary to fill more than 25% of the inner volume of the evaporator zone with working fluid and set the inclination at a larger angle than 5°. The maximum heat flux is obtained at an inclination angle between 20 and 40°.

Figure 3 shows the temperature distribution and behavior of working fluid for inclination angles of 90, 20, 9 and 7.5°, with a fill ratio of 5%. At this fill ratio, even though the tube was vertical, the liquid did not form a pool at the end of the evaporator. Instead, many liquid drops were scattered on the wall by boiling as shown in Fig. 3(a). The liquid drops were distributed from the end to the center of the heating region and they evaporated from there one after another. On the other hand, in the condenser region, drop-wise condensation was

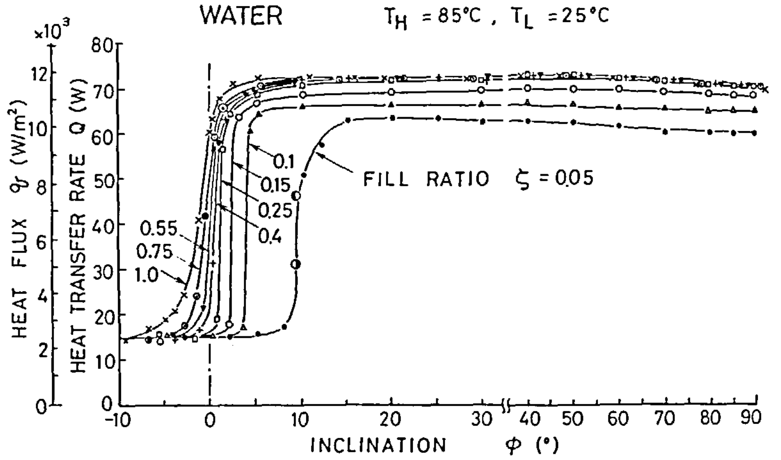

FIG. 2. Heat transfer performance of water thermosyphon.

observed. The condensate returned to the evaporator as it formed one or more rivulets. The mean temperature difference between evaporator and condenser was 14.3°C. The active evaporation led to the lower temperature distribution on the half length of the evaporator as shown in Fig. 3(a).

When the inclination angle was 20° [Fig. 3(b)], the distribution of liquid drops was spread over the full length of the evaporator, so that the temperature distribution along the length of tube became flat and the temperature difference on the circumference did not exist. It is obvious that the scattering of liquid drops contributes effectively to uniformalize the temperature distributions along the length and on the circumference of the thermosyphon.

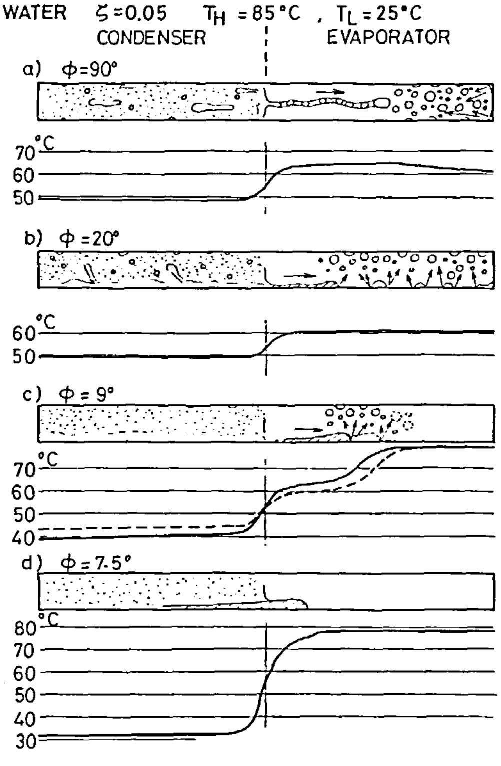

FIG. 3. Boiling, scattering, condensation of working fluid and temperature distribution (water, fill ratio = 5%).

When the inclination angle was 15°, a dry-out phenomenon began to appear from the end of the evaporator, hence the heat transfer rate fell down rapidly as shown in Fig. 2.

At an inclination angle of 9°, the condensate rivulet could return to only about 1/3 of the length of the evaporator region. There was a small amount of boiling at the front of the rivulet and the small scattering of drops remained there. The location of the front of the rivulet was unstable and it fluctuated between the solid line and the dotted line as shown in Fig. 3(c). Consequently, two different heat transfer rates are plotted at $\Phi = 9°$ in Fig. 2.

When the inclination angle became 7.5° [Fig. 3(d)], the front of the rivulet retreated to about 1/5 of the length of the evaporator region and boiling stopped completely. The tube had not operated as a thermosyphon, so that the temperature difference between evaporator and condenser had reached 47°C.

At a smaller inclination angle than 7.5° including negative angles, the entire amount of working fluid was collected into the condenser section, consequently the evaporator was wholly dried up. In this situation, the heat transfer rate was 15 W which was transferred by only the thermal conduction of the container.

When the amount of working fluid was increased to 10% and the inclination angle was larger than 40°, the liquid formed a pool at the end of the evaporator. The boiling was then considered to be pool boiling. Many drops of liquid were scattered on the wall of the evaporator by the boiling and they evaporated one after another.

Figure 4 shows the liquid movements and the temperature distributions on the container wall at a fill ratio of 25%. In a vertical situation [Fig. 4(a)], typical nucleate boiling in a low pressure vessel consisting of a narrow passage was observed: a boiling bubble

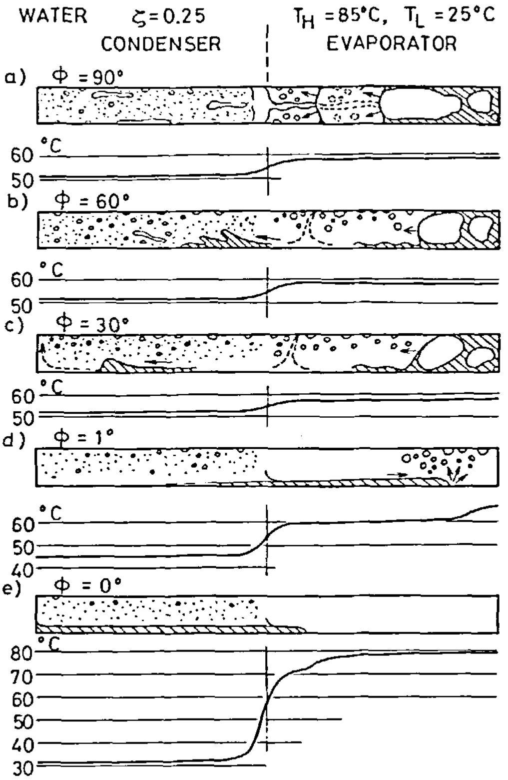

FIG. 4. Boiling, turbulent motion, scattering, condensation of working fluid and temperature distribution (water, fill ratio = 25%).

departed from the bottom corner which played the role of a cavity, it expanded rapidly to the full inner diameter of the tube and rose up the tube. The bubble was transformed into a film of liquid as it rose along the tube wall. The limit of the film's movement was between 1/2 and 4/5 of the height of the evaporator. The film broke there and was transformed into many liquid drops. The temperature difference between evaporator and condenser was 4.8°C.

When the thermosyphon was inclined, a noteworthy phenomenon was observed: the turbulent motion of the liquid caused by the explosion of a boiling bubble. At the same time, a large amount of liquid was dashed against the upper part of the tube. It may be regarded as the pattern of flooding introduced by Nguyen-Chi and Groll [6].

At an inclination angle of 30°, the dashing tip of the liquid movement reached the end of the condenser. It is considered that the heat transfer mechanism in the condenser consisted of the condensation of vapor and forced convection by the dashing liquid. In addition, the freshly condensed surface is exposed to the vapor after the surface has been cleared by the passage of the dashing liquid. Consequently the heat transfer performance is improved there. The temperature difference between evaporator and condenser was 4.0°C in this situation.

When the inclination angle was 2°, the liquid movement (dashing distance) lessened and the heat transfer rate decreased. At an inclination angle of 1°, the dashing motion of liquid disappeared completely, dry-out occurred at the end of the evaporator and led to a lower heat transfer rate. The temperature difference between evaporator and condenser increased to 14.0°C. The temperature difference on the circumference did not exist. A small amount of boiling and scattering of liquid drops was still observed at the front of the rivulet.

In the horizontal situation, the boiling disappeared. At a negative angle, all the liquid collected in the condenser and the heat transfer rate fell to 15 W. The temperature difference between evaporator and condenser was 44°C and that on the circumference was less than 0.2°C at the center of the condenser.

A gradual increase in the amount of working fluid slightly improved the heat transfer rate, due to the fact that the dashing motion of liquid became more active with increasing amounts of liquid.

At a fill ratio of 55% and with a vertical situation, the liquid film rose up to the end of the condenser. Even in a horizontal situation, the dashing motion of the liquid persisted and reached the end of the condenser. At a negative angle, the dashing motion began to disappear and there was only a small amount of boiling at the end of the evaporator, consequently the heat transfer rate decreased gradually. When the inclination angle was −0.5°, dry-out appeared at the end of evaporator and the heat transfer rate decreased.

Another interesting phenomenon was found at fill ratios more than 70%. A strange sound was heard that reminded the observers of smacking. At the same time, the tube oscillated violently. This sound was caused by a large mass of the working fluid which, having been pushed up to the end of the condenser by the explosive expansion of a boiling bubble, collided with the end of the condenser. The vapor in the condenser space was compressed and condensed in an instant by the piston motion of the liquid mass. This instantaneous disappearance of the vapor space is considered as a phenomenon of the collapse of a vapor bubble and the strange sound is the sound of the collapse. It is a kind of water hammer or steam hammer phenomena. If it continues for a long time, the container wall will be damaged.

In order to avoid this dangerous phenomenon, the fill ratio of water as the working fluid should be limited to less than 60%.

3.1.2. *Ethanol thermosyphon.* In addition to water, ethanol was also used as a working fluid to study the effect of the fluid on the characteristics of the thermosyphon.

Figure 5 shows the heat transfer performance of an ethanol thermosyphon. The temperatures of the heating and cooling flows were set at 85 and 25°C, respectively. The fill ratio of ethanol was varied from 5 to 100%.

Ethanol underwent pool boiling even though the fill rate was 5%. Many drops were scattered on the wall of

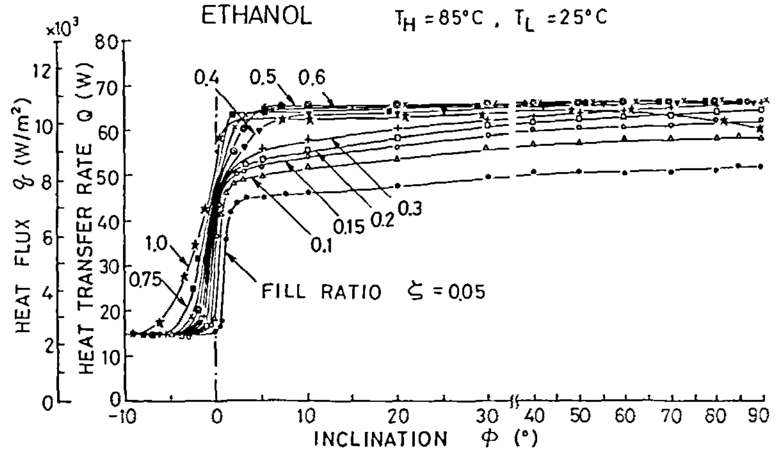

FIG. 5. Heat transfer performance of ethanol thermosyphon.

the evaporator. The drop diameter was smaller than that with water. In the condenser region, film condensation was observed.

When the fill ratio was 40%, the dashing motion of the liquid began to appear. The amplitude and the dashing distance of the motion were smaller than those of water. This may be due to the differences of the viscosity and the thermophysical properties between ethanol and water.

Another property distinguishing ethanol from water as a working fluid was the fact that the maximum heat transfer rate was obtained in the vertical situation when the fill ratio was less than 30%. This was because the boiling and the scattering of liquid drops were not so active as for water, the extension of the surface area for the evaporation was not so effective and the dashing distance of liquid movement to the condenser region was shorter than that of water.

When the inclination angle was larger than 5° and the fill ratio was between 40 and 75%, the thermosyphon could have a steady heat transfer rate of 65 W. When the fill ratio neared 100%, the heat transfer rate was lower. This may be explained by the fact that the corresponding volume of liquid to the sum of the volumes of many small boiling bubbles occupied continuously a part of the active condenser region. In the case of water, such behavior was not observed, the liquid went down into the evaporator at each dashing motion caused by a big bubble.

3.2. *Heat transfer coefficients*

The heat transfer mechanism of an inclined two-phase closed thermosyphon is an intricate complex consisting of evaporation with or without boiling, steady or unsteady condensation, steady or unsteady condensate rivulet formation and the turbulent dashing motion of liquid, as mentioned previously. These phenomena depend strongly on the amount of working fluid and the inclination angle. Therefore it is almost impossible to represent the heat transfer coefficients by a simple formula.

In the present study, the overall heat transfer coefficients in the inclined thermosyphon for practical applications have been obtained. The fill ratio of the working fluid was chosen to be 40 and 50% for water and ethanol, respectively, and the inclination angle was 30° for both the liquids. These conditions were intended to give a high heat transfer rate, as judged from the previous results (Figs. 2 and 5).

The overall heat transfer performance of a heat pipe is generally characterized by the following equation introduced by Chi [8]:

$$Q = UA(T_E - T_C)$$

where U is an overall heat transfer coefficient, A is an inside surface area of the evaporator or the condenser, T_E and T_C are the temperatures on the outside surfaces of the evaporator and the condenser, respectively.

The temperature difference between the inside and outside surfaces of the tube was less than the value of 0.03°C that was found from a calculation using the heat flux and the thermal conductivity of copper. Consequently, it is no problem to consider T_E and T_C as the temperatures of the inside surfaces of the evaporator and condenser.

Figure 6 shows the overall heat transfer coefficient U when the cooling water was kept at 25°C and the temperature of heating water was varied between 45 and 90°C. The operating temperature is defined as an average temperature of the evaporator and the condenser, hence it can be considered as the temperature of the working fluid.

With water as the working fluid, the overall heat transfer coefficient varied from 2.4×10^3 W m^{-2} K^{-1} to 3.0×10^3 W m^{-2} K^{-1}, with that for ethanol being between 0.9×10^3 W m^{-2} K^{-1} and 1.1×10^3 W m^{-2} K^{-1}, for the operating temperature between 30 and 60°C. The overall heat transfer coefficient increases slightly with the operating temperature. This is due to the fact that an increase in the operating temperature brings an increase in the activity of the dashing motion of liquid.

For the comparison, the results of a vertical thermosyphon reported by Imura [2] and Shiraishi [3] are plotted in Fig. 6. It is obvious that the present results are in reasonable agreement with those of the references considering the differences in inclination angles.

3.3. *Thermal diode characteristics*

As the inclination of the thermosyphon was changed gradually from a large angle to a small one, dry-out phenomena began to appear from the end of the evaporator, hence the heat transfer rate decreased rapidly. Moreover, at a negative angle, the entire amount of working liquid was collected into the condenser section. The tube could not operate as a thermosyphon in this situation, and only a very small amount of heat transfer (by the thermal conduction of the container) took place. The sudden change of the heat transfer rate depended on the inclination angle is a thermal diode characteristic of the inclined thermosyphon.

A thermal diode angle Φ_D is defined as the inclination angle when the heat transfer rate is the mean value between the maximum and the minimum rates. Figure 7 shows that the thermal diode angle depends on the fill ratio of the working fluid. In general, the thermal diode angle takes a large positive value when the fill ratio is small and it decreases rapidly with increasing fill ratio. At an extremely large fill ratio, the thermal diode angle takes a negative value and changes little with variations in the fill ratio. When the thermosyphon is used as a thermal switch, a small fill ratio is better for shutting off the heat flow than a larger one. This means that the heat transfer curve at the diode angle then has a steep gradient.

Water, as the working fluid, has a larger thermal diode angle than that of ethanol, due to the difference of boundary energy between the working liquid and the container material.

4. CONCLUSIONS

The conclusions of the present study can be summarized as follows:

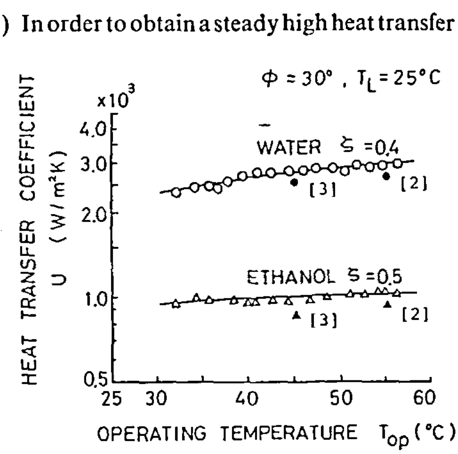

FIG. 6. Plot of heat transfer coefficient against operating temperature.

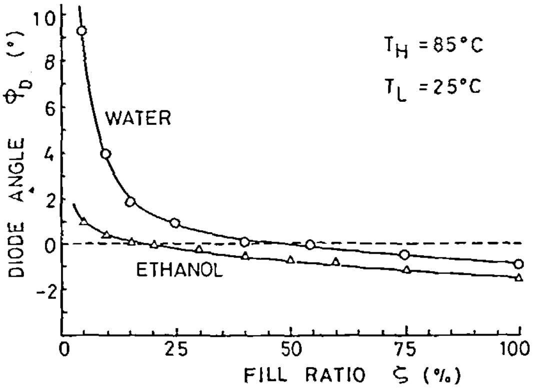

FIG. 7. Plot of thermal diode angle against fill ratio.

(1) In order to obtain a steady high heat transfer rate, it is necessary to fill between 25 and 60% of the evaporator inner volume with water as the working fluid, or between 40 and 75% for ethanol. Also the inclination must be between 20 and 40° for water, and more than 5° for ethanol.

(2) The turbulent dashing motion of liquid associated with the boiling and scattering of liquid drops, contribute to effectively equalize the temperature distribution and to increase the amount of heat transfer.

(3) The overall heat transfer coefficient of a water thermosyphon is 2.4×10^3 W m^{-2} K^{-1}–3.0×10^3 W m^{-2} K^{-1} and that of an ethanol thermosyphon is 0.9×10^3 W m^{-2} K^{-1}–1.1×10^3 W m^{-2} K^{-1}.

(4) The thermal diode characteristics of an inclined thermosyphon depend upon the fill ratio of working fluid. In order to stop the heat flow at a larger inclination angle, it is necessary to use a smaller fill ratio.

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PERFORMANCE DE TRANSFERT THERMIQUE D'UN THERMOSYPHON INCLINE, FERME ET DIPHASIQUE

Résumé—On décrit une approche expérimentale de la performance de transfert thermique d'un thermosyphon incliné, fermé et diphasique. La quantité de fluide de travail et l'angle d'inclinaison sont les paramètres expérimentaux. Une visualisation du mouvement de fluide en ébullition, la dispersion des gouttes de liquide et la condensation de la vapeur ont clarifié le mécanisme de transfert thermique dans le thermosyphon. De plus les coefficients globaux de transfert thermique et les caractéristiques de diode thermique sont obtenus.

WÄRMEÜBERTRAGUNGSVERMÖGEN EINES GENEIGTEN, GESCHLOSSENEN ZWEI-PHASEN-THERMOSYPHONS

Zusammenfassung—Es wird eine experimentelle Untersuchung des Wärmeübertragungsvermögens eines geneigten, geschlossenen Zwei-Phasen-Thermosyphons beschrieben. Als Arbeitsfluide dienten Wasser und Äthanol. Versuchsparameter waren die eingefüllte Menge des Arbeitsfluids und der Neigungswinkel. Die Sichtbarmachung der Flüssigkeitsbewegung beim Sieden, beim Versprühen von Flüssigkeitstropfen und bei der Dampfkondensation diente zur Klärung des Wärmeübertragungs-Mechanismus im Thermosyphon. Zusätzlich wurden Gesamt-Wärmeübergangskoeffizienten und die Charakteristik als thermische Diode ermittelt.

ХАРАКТЕРИСТИКИ ТЕПЛОПЕРЕНОСА В НАКЛОННОМ ДВУХФАЗНОМ ЗАМКНУТОМ ТЕРМОСИФОНЕ

Аннотация—Описано экспериментальное исследование характеристики теплопереноса в наклонном двухфазном замкнутом термосифоне. В качестве рабочих жидкостей использовались вода и этанол, а в качестве экспериментальных параметров—количество рабочей жидкости и угол наклона термосифона. Визуализация течения жидкости при кипении, разброса жидких капель и конденсации пара позволила выяснить механизм теплопереноса в термосифоне. Кроме того, получены средние коэффициенты теплопереноса и термические характеристики диодов.