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철사를 삽입한 초소형 열사이폰에 관한 기초 실험 연구

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An Experimental Study on Miniature Two-phase Closed Thermosyphons With Inserts

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요 약

본 논문은 가는 철사를 삽입한 이상의 초소형 열사이폰에서의 작동유체의 유동과 그 열전달 특성 및 가시화에 대한 연구 결과를 소개하고자 한다. 가시화 실험은 열사이폰 내의 작동유체의 이상유동 현상을 확실히 보여주었으며, 또한 삽입한 철사의 직경, 증발과 냉각부분의 길이의 비, 그리고 증발부에 가해진 열량이 열사이폰의 열성능에 미치는 영향에 대하여 정량적으로 그 결과를 분석하였다.

Abstract

Reported is a visual and quantitative experimental study on the two-phase flow and heat transfer characteristics of miniature two-phase closed thermosyphons with wire inserts. The visual study clearly demonstrated the two-phase flow involved in such thermosyphons. In the quantitative study, the effects on the heat transfer rate of the insert wire diameter, the ratio of heated-length to cooled length and the applied heat flux were investigated.

Nomenclature :

A : surface area
D : diameter
h : heat transfer coefficient
L : length of thermosyphon
L^+: length ratio; L_e/L_c
Q : heat transfer rate
q : heat flux
T : temperature
U : overall heat transfer coefficient
V : volume
V^+: dimensionless volume of the working fluid; V_l/V_T

Subscripts :

a : adiabatic section
c : condenser section
e : evaporator section
l : liquid
TS: thermosyphon

INTRODUCTION :

Ever since Cotter [1] first introduced an idea of very small micro heat pipes, interest in such micro-heat pipes/thermosyphons has increased greatly as an natural development of the device in new engineering applications. At 6th International Heat Pipe Conference held in Grenoble in 1987, Ito [2] exhibited the first working trapezoidal micro heat pipe having a cross-sectional area of about 1mm² with 57mm in length.

A "micro" heat pipe was initially defined by Cotter [1] as one "so small that the mean curvature of the liquid-vapour interface is necessarily comparable in magnitude to the reciprocal of the hydraulic radius of the total flow channel". The definition was then quantified by Bibin et al. [3]. Peterson [4] further proposed a definition for a micro heat pipe in practical terms as a heat transfer device which is "a small non-circular channel that utilizes the sharp angled regions of the channel as liquid arteries". The production process of such heat pipes/

thermosyphons is very difficult and highly expensive.

The geometry of the very small (micro) thermosyphon used in the present study is circular having an circular solid insert, i.e., a concentric annulus. Unlike that of trapezoidal, there is no sharp angled region to act as liquid artery and the fluid flow involved is quite different from that of the micro heat pipes mentioned above. Furthermore, the manufacturing process of a annular shaped micro thermosyphon is extremely simple and hence very cost effective.

Two phase fluid flow and heat transfer can be found in many engineering practices such as in nuclear, chemical, mechanical and petroleum engineering and has been extensively studied both analytically and experimentally. However, the characteristics of the two-phase fluid flow and heat transfer in annular channels of very small diameter is little known.

The rise of gas or vapour bubbles in liquids is of the special interest that is closely related to the present subject matter. The problem of the rise of a large gas bubble through a vertical channel containing liquid has been investigated theoretically using potential flow theory by several authors [e.g., 5]. In small tubes, however, the surface tension effects become significant and a thin viscous boundary layer of the tube wall can be a significant fraction of the tube radius, thus decreasing the effective tube diameter.

Therefore, the fluid flow and heat transfer in a micro thermosyphon of annular shape is pursued both analytically and experimentally.

Reported in the present paper is an experimental study only made on the heat transfer performance of a miniature two-phase closed thermosyphon. A visual as well as quantitative study have been made.

EXPERIMENT :

Apparatus ;

(i) Visual study

The physical dimensions of the test-thermosyphons used for the visual part of the present study are given in Table 1.

Table 1. Miniature Two-Phase Closed Thermosyphons Used for Visualization

Glass outside dia. mm.	Glass inside dia. mm.	Total tube length mm.	Insert tube dia. mm.	Working Fluid
5.0	3.4	300	1.5	distilled water, Ethanol
4.0	2.4	300	1.0	distilled water, Ethanol
3.0	1.8	300	0.6	distilled water, Ethanol
2.0	1.0	150	0.4	distilled water, Ethanol

As shown in Table 1, all test-thermosyphons were made of glass to observe the heat transfer phenomena during the test operation.

(ii) Quantitative study

The experimental apparatus for the quantitative study is schematically illustrated in Fig. 1. The main heat transfer loop consists of the test thermosyphon, a power supply, a cooling jacket, a cooling system and related instrumentation.

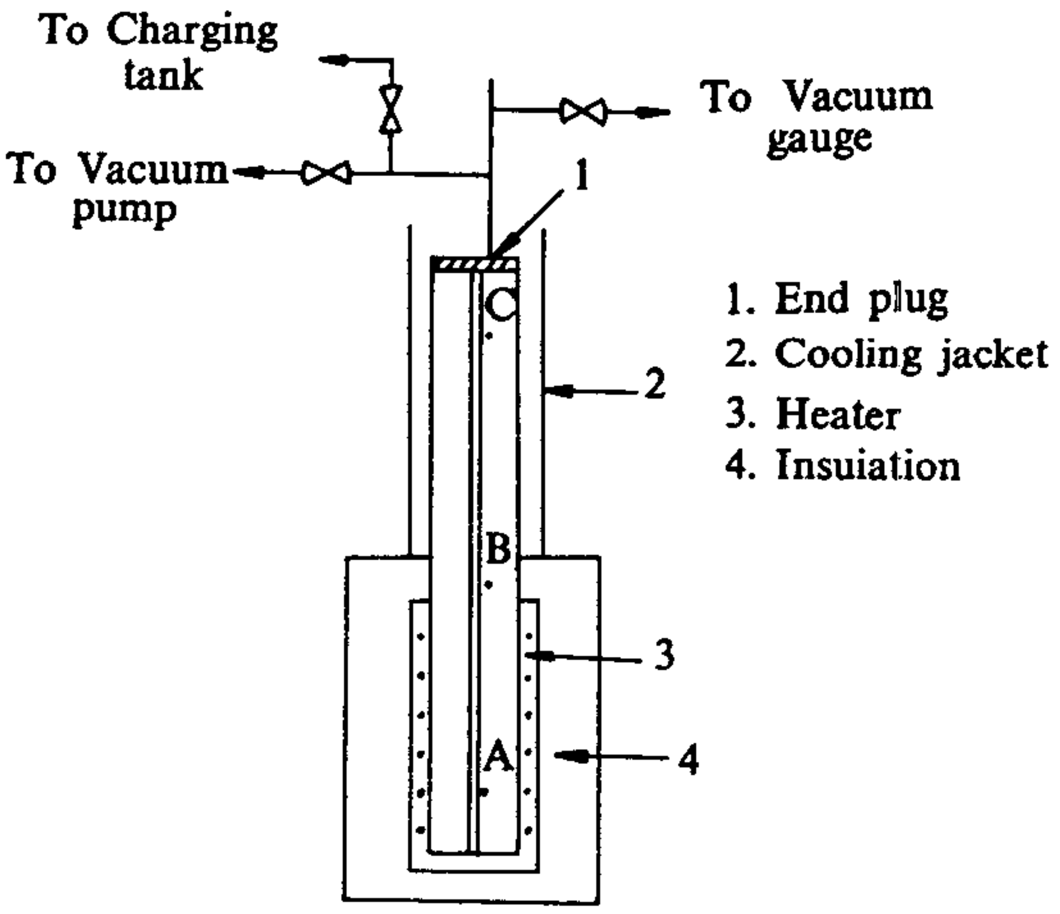

Fig. 1 Schematic Diagram of the Experimental Apparatus

The physical characteristics and dimensions of the test thermosyphons made of S.S. 304 tubes are given in Table 2. The insert wires were all made of stainless steel.

A copper tubing was welded on the upper section of each test-thermosyphon which provided link to the vacuum system and the charging line of the working fluid. The evaporator sections of the test thermosyphons were electrically heated by nicrome wires, wound over the electrically insulated lower part of the test-tubes. The power to the evaporator section was provided with electric power. Power was measured by a digital voltmeter and an ammeter through the measuring circuits. The probable maximum error in the wall heat flux is estimated to the about 10%.

Three chromel-alumel (K-type) thermocouples were welded on the outside wall of the test thermosyphon, One for the measurement of the outer surface temperature of the evaporator section of the thermosyphon, the second for the condenser section and the third for the adiabatic section. The heat from the test section was removed at the upper part of the thermosyphon test tubes by a coolant jacket. The amounts of

Table 2. Miniature Two-Phase Closed Thermosyphons Used for Quantitative Study

Case	Outside dia.	Inside dia.	Length	Inside wire dia.	Working fluid
1	3.0mm	2.3mm	300mm	0.50mm	Ethanol
2	2.0mm	1.5mm	220mm	0.40mm	Ethanol
3	2.0mm	1.5mm	130mm	0.40mm	Ethanol

the working fluid charged at a vacuum of about 10^{-3} torr was about 15% of the total test tube by volume which was chosen from the preliminary test results of several thermosyphons with different amount of fill. This finding is consistent with that previously reported on the optimum amount of fill [6].

TEST PROCEDURE:

All tests reported here, unless otherwise stated, are those obtained at the steady state and the vertical orientation only. After the system was evacuated, a known amount of the working fluid was charged into the tube. The power to the evaporator heating section was increased in steps to the desired heat flux. When a steady state was reached (within 10-20min), all the test data were acquired.

RESULTS AND DISCUSSION:

(i) Visual study

For the case of the test thermosyphon having ID 3.4mm(the test thermosyphon with the largest ID), it was observed that with water as the working fluid, the bubble ceased to rise immediately when heat was applied. Having a steel wire insert, however, the normal operation as a two-phase closed thermosyphon was achieved. With ethanol as the working fluid, the normal operation was possible even without the steel wire insert with the same test thermosyphon(ID 3.4mm). This phenomenon was thought due to the greater surface tension of water than that of ethanol at the same temperature.

For the test thermosyphons of ID 2.3, 1.8, and 1.0mm, the normal operation was possible only when steel wire inserts were present, even when ethanol was used as the working fluid. From these observation, it is concluded that it is indeed necessary to have insert wire when the ID of a two-phase closed thermosyphon is very small (ID<2.3mm) to achieve the normal operation as heat transfer element.

(ii) Quantitative Study

A purely theoretical study of the miniature two-phase closed thermosyphon is not possible at present due to lack of information and the complexity of the condensation and boiling processes in a very narrow and closed cavity. In the present study, the tube heat transfer coefficient are defined by

$$Q=h_eA_e(T_e-T_a)=h_cA_c(T_a-T_c) \\ =U_{TS}A_e(T_e-T_c) \qquad (1)$$

We can also obtain the overall heat transfer coefficient of the test thermosyphon, U_{TS}, from Eq. (1) as:

$$1/U_{TS}=1/h_e+L^+/h_c \qquad (2)$$

Some typical equilibrium temperature distributions of the test thermosyphon of ID 2.3mm at various supplied power level are illustrated in Fig. 2. The test thermosyphon performed normal up to the power input of 13 watts. A dry-out was observed at power input of 15 watts as shown in Fig. 2.

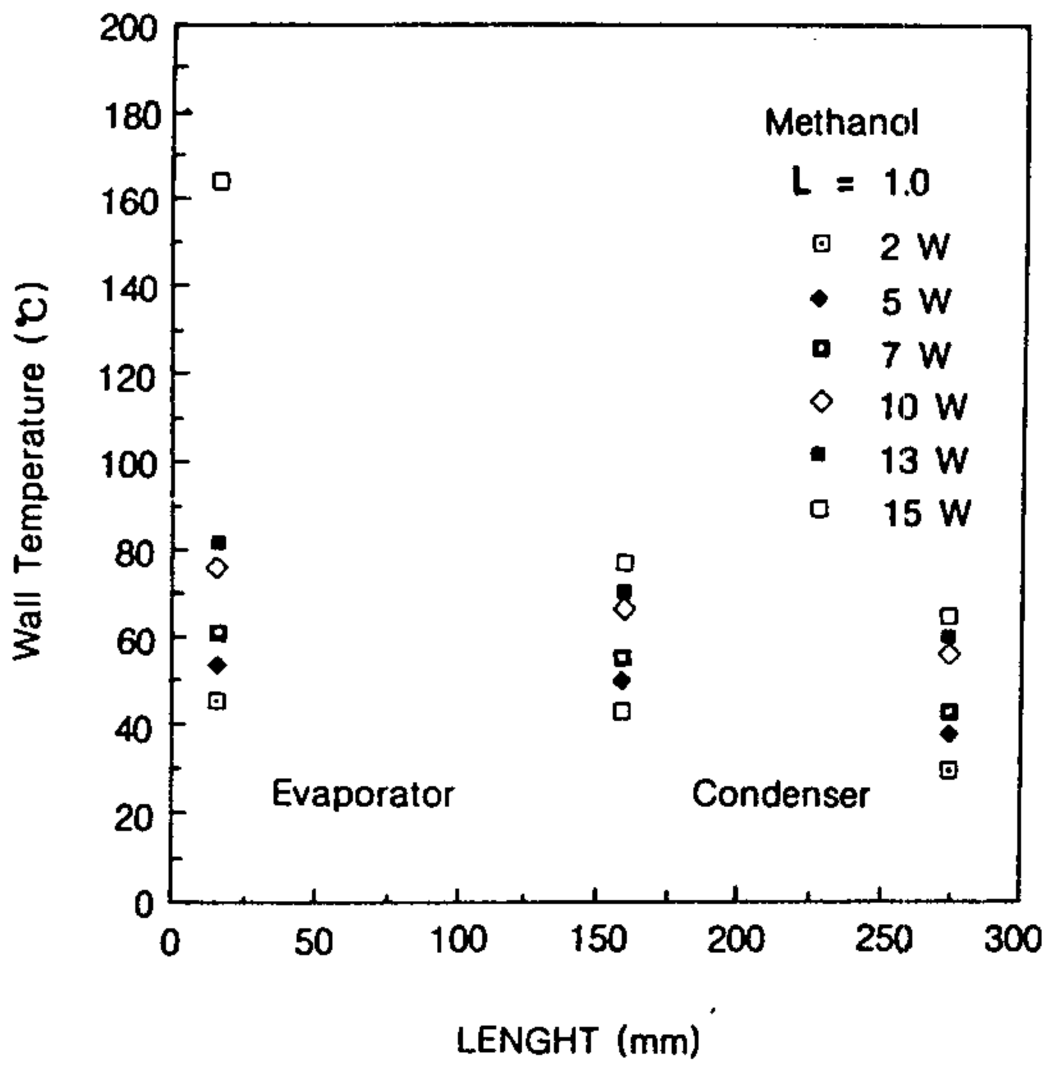

Fig. 2 Typical Stabilized Wall Temperature Distribution for Various Heat Fluxes

The steady state heat transfer rates of the two test thermosyphons, Cases 1 and 2(ID 2.3 and 1.5mm, respectively) are shown in Fig. 3 as a function of the operating temperature(i.e., the arithmetic average temperature of T_e and T_c). Heat transfer rate increased with increasing operating temperature up to its individual maximum heat transfer rate. It can be seen that the dryout occurred at the power input of about 13 W for the test thermosyphon of Case 1 whereas for Case 2, it occurred at about 8 W. This implies that the smaller the diameter of the test thermosyphon, the lower the critical heat flux.

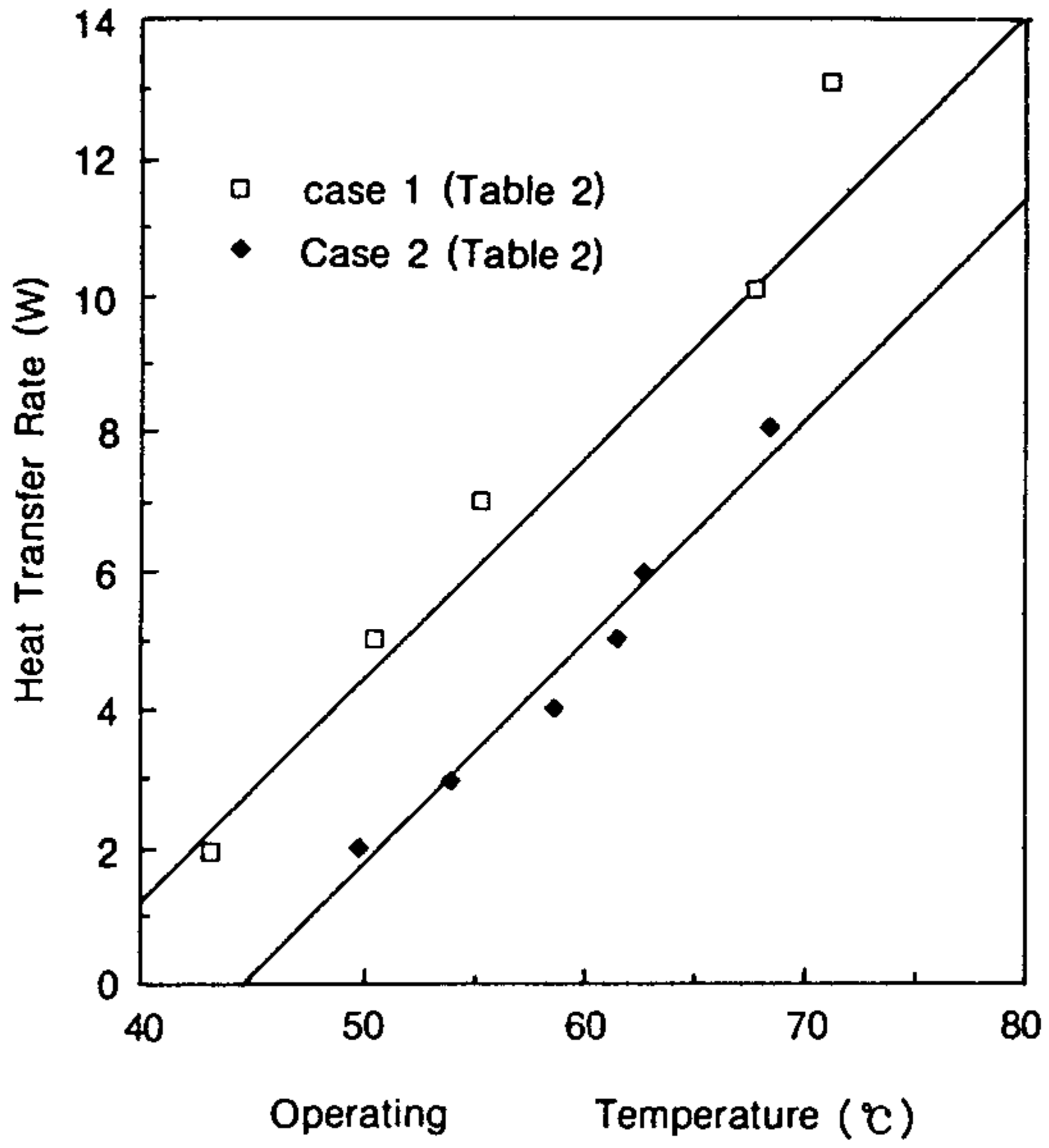

Fig. 3 Heat Transfer Variation

In Fig. 4, the result of Case 2 and 3(the same ID with the insert wire of the same dimension) are compared. The only difference between the two test thermosyphons is the length. It can be seen in Fig. 4 that while the total heat transfer rate may increase with an increse in the length, the overall heat transfer coefficient decreased with increasing length of the test thermosyphon for the same value of L^+ at a given operating temperature as seen in Fig. 5. The sample calculation using the test data showed that this is due to fact that while there was a slight increase in the heat transfer coefficient of the condenser section with increasing length, a decrease in the heat transfer coefficient of the evaporator section was observed. That is, the larger value of L/D for a given D does not necessarily bring an increase in the overall heat transfer coefficient. This trend is similar to those of the two-phase closed thermosyphons of ordinary size.

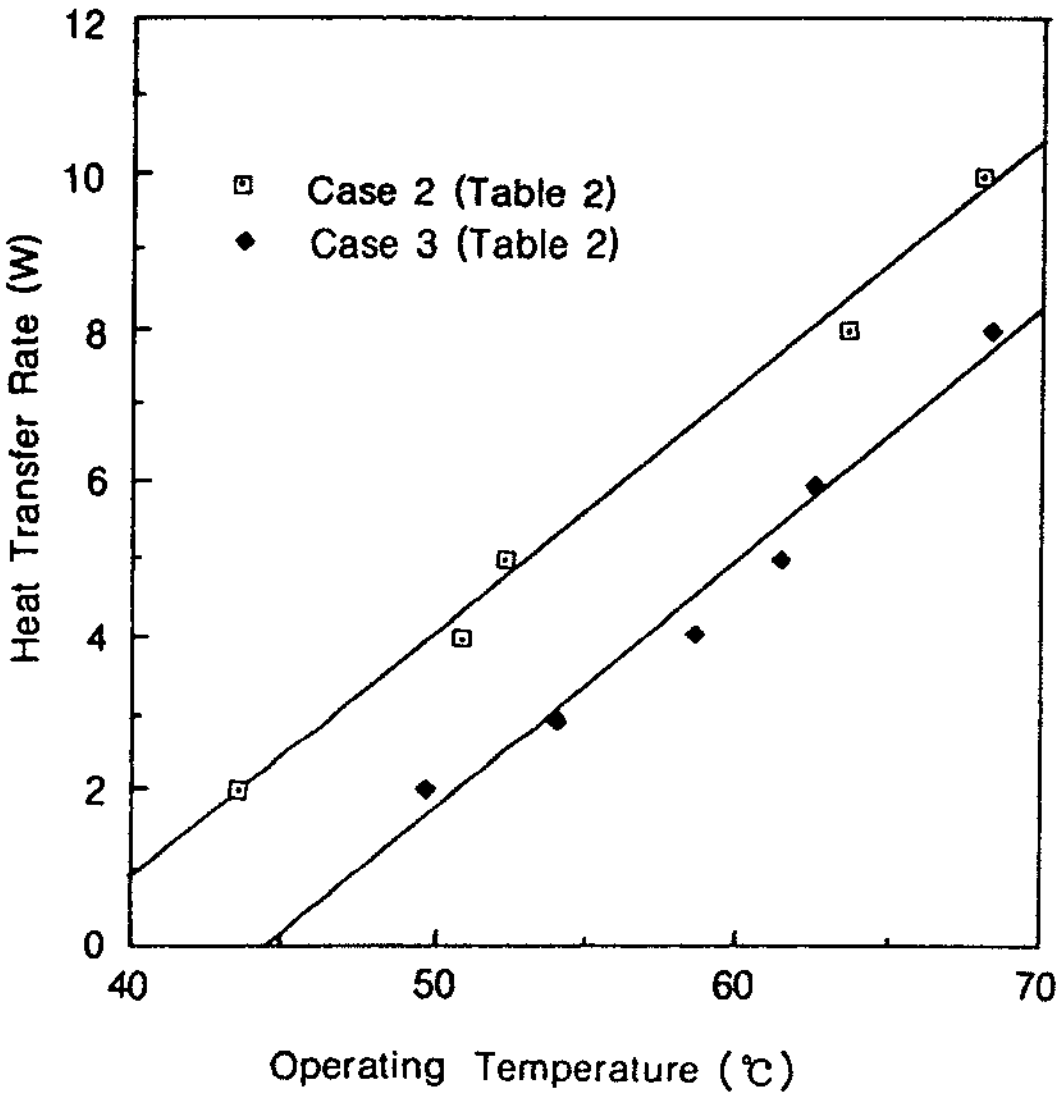

Fig. 4 Heat Transfer Variation

It was also noticed during the experiment that the performance of the shorter test thermosyphon used in the present study was more stable than that of the longer test thermosyphon.

The total heat transfer coefficient was seemed to increase with a decrease in the heated length-cooled length, L^+. Lee and Bedrossian [7] reported similar effects in their study on a two-phase closed thermosyphon. A decrease in L^+ means that the area of condensing region increased while that of the evaporator decreased. This can be related by the following equation which may obtained from an energy balance for the whole test thermosyphon :

$$q=q_c/L^+ \tag{3}$$

Where q_c is the heat flux of the condenser section at a given operating condition. The increased condenser area seems to provide a more efficient system as a whole. However, there is limiting L^+ below which the trend becomes opposite.

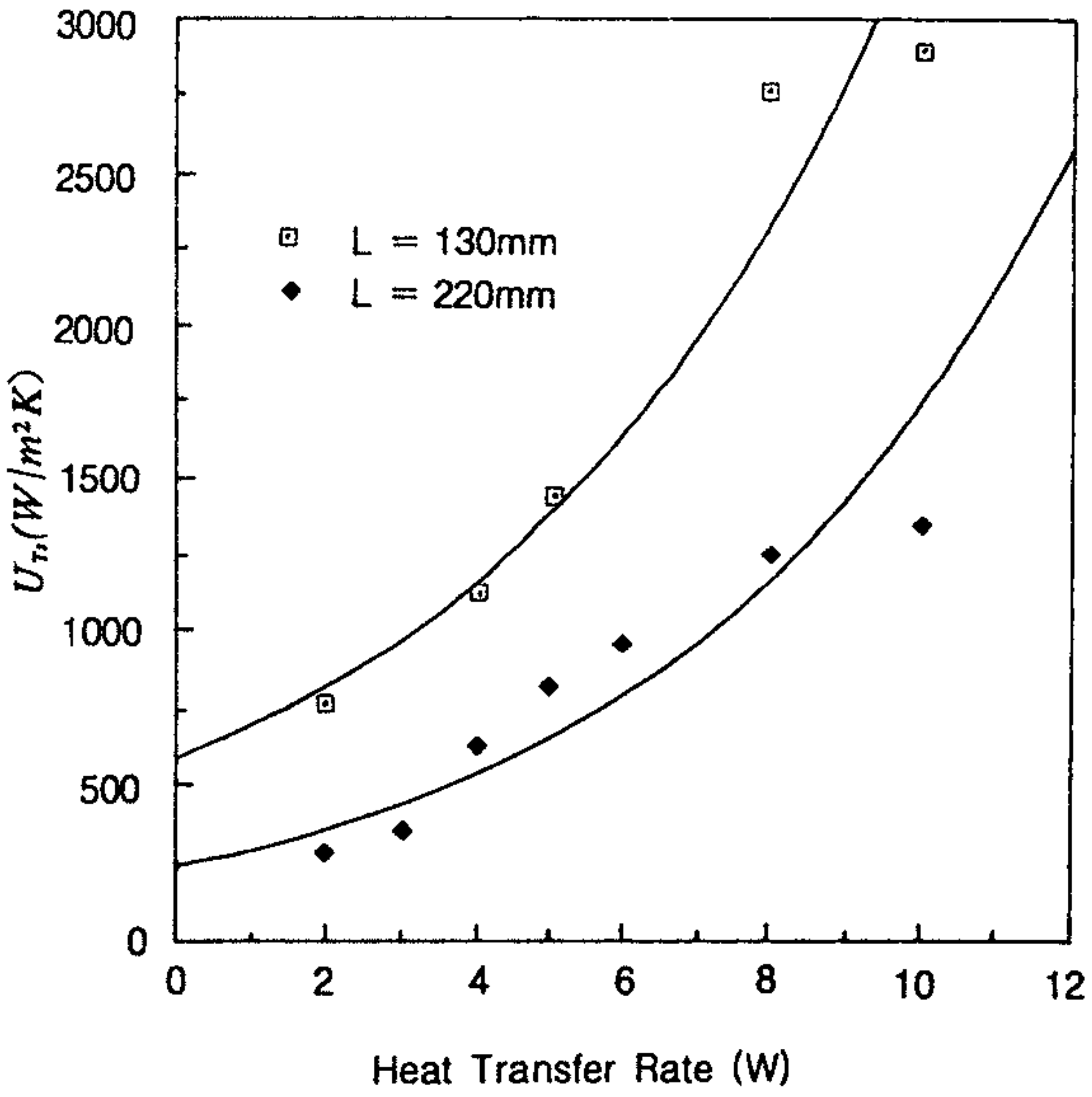

Fig. 5 Effect of Thermosyphon Tube Length on Overall Heat Transfer Coefficient

CONCLUSION

From a visual and quantitative experimental study made on the heat transfer characteristics of a two-phase closed thermosyphons made of a very small diameter circular tube with an insert wire, the following conclusions may be made.

1. For a two-phase closed thermosyphon made of a very small diameter tube(ID< 2.3mm), it is necessary to have insert wires to achieve the normal operation as a heat transfer element.
2. The heat transfer characteristics of such two-phase closed thermosyphons with wire inserts are very similar to those of the two-phase closed thermosyphons made of large diameter tubes without wire inserts.
3. The diameter of wire inserted appears to affect the thermal performance of a miniature thermosyphon.
4. For a miniature thermosyphon of 2.3mm ID and 3000mm in length, the maximum heat transport rate was 13 watts. It attained a value of 8 watts for ID of 1.5mm and 220mm in length.

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