Effect of Micro Grooves on the Performance of Condensing Heat Transfer of the Micro Grooved Thermosyphons

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Key words: Two-phase closed thermosyphon, Condensation, Condensing heat transfer coefficient, Working fluid, Micro grooves

Abstract

This study concerns the performance of the condensing heat transfer performance of two-phase closed thermosyphons with plain copper tube and tubes having 50, 60, 70, 80, 90 internal micro grooves. Distilled water, methanol, ethanol have been used as the working fluid. The numbers of grooves and operating temperature have been investigated as the experimental parameters. Condensing heat transfer coefficients and heat flux are obtained from experimental data for each case of specific parameter. The experimental results are assessed and compared with existing correlations. The results show that working fluids, numbers of grooves are very important factors for the operation of thermosyphons. The working fluid with high latent heat such as water has a good heat transfer rate compared to methanol and ethanol. The relatively high rate of heat transfer is achieved when the thermosyphon with internal micro grooves is used compared to that with plain tube. Condensing heat transfer coefficient of grooved thermosyphon is 1.5~2 times higher in methanol and 1.3~1.5 times higher in ethanol compared to plain tube. The best condensation heat transfer performance is obtained for 60 grooves, and the maximum value of this case is 2.5 times higher than that of the plain tube.

Nomenclature

A : heat transfer area [m^2]

C_p : specific heat [J/kgK]

D : diameter [m]

g : gravitational acceleration [m/s^2]

h : heat transfer coefficient [W/m^{2}K]

h_{fg} : latent heat of vaporization [J/kg]

k : thermal conductivity [W/mK]

L : length [m]

m : mass flow rate [kg/s]

Q : heat flow rate [W]

q : heat flux [W/m^2]

T : temperature [℃]

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Greek symbols

ρ : density [kg/m^3]
μ : dynamic viscosity [Ns/m^2]
ϕ : liquid fill ratio
ν : kinematic viscosity [m^2/s]

Subscripts

atm : atmosphere
avg : average
c : condensation section
cool : cooling water
hot : hot water
l : liquid
Nu : Nusselt
s : saturated
Se : Semena
v : vapor
w : wall

1. Introduction

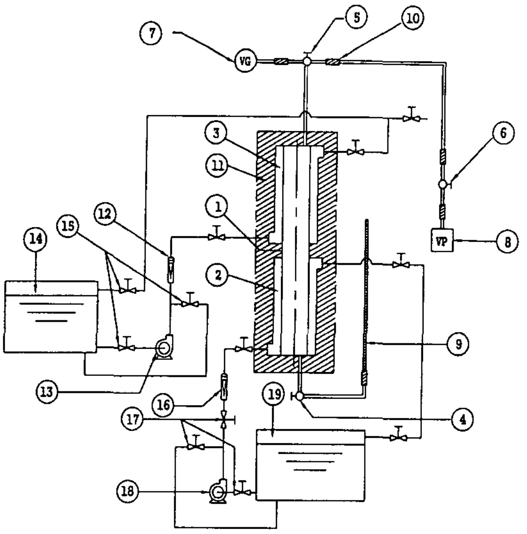
A thermosyphon is a heat transfer device with very high thermal performance. New fields of application and growing concern of a more intensive use of energy have stimulated and revived many suggestions for economic heat transfer devices.(1-2) In these applications, two-phase closed thermosyphons operate with the condenser on the upper part, so that the gravitational force can help the liquid return to the heated zone. In this way, high heat flow rates through two-phase closed thermosyphon were obtained.

Many researches on thermosyphon have been performed due to these advantages since the principle of thermosyphon was first suggested by Gaugler(3) in 1942. Such researches focused on pool boiling in evaporation section, liquid film boiling, working principle of thermosyphon based on its flow pattern, study for the improvement and the estimation of heat transfer coefficient.(4-5) Water, ammonia, CFC-11, CFC-12 and CFC-22 were common working fluids investigated. However, owing to their ozone depleting potential, CFC-11 and CFC-22 are now banned. CFC-134a and CFC-141b are an environmentally friendly refrigerant and has been generally accepted as substitutes of CFC-11, CFC-22. Park(6) carried out the researches on the effect of the types of working fluid and Chen,(7) Botemps et al.,(8) Fledman and Srinivasan,(9) Imura et al.,(10) Cohen and Bayley,(11) Lee and Mital(12) performed the research on the effect of liquid fill quantity ratio. Tu et al.,(13) Hahne and Gross,(14) Negishi and Sawards,(15) Nitipong(16) have reported the effect of inclination angle. Noie and Ayani(17) investigated experimentally the performance of vertical two-phase thermosyphon and used water as working fluid. They investigated the influence of operating parameters on the maximum performance either by dry-out or burnout limits. Tube diameter effect on the heat transfer coefficient was performed by Clements and Lee.(18) But plain tube has been used in most of those studies and only a few research was performed using micro grooved tube. Heat pipe with internal triangular shaped groove was analyzed by Peterson.(19) A large effect for improving heat transfer rate is expected in thermosyphon when micro grooved tube is used.

In this paper, experimental studies on the vertical thermosyphon with micro grooves have been carried out. Especially the effects of groove number, types of working fluid on the heat transfer rate were investigated and analyzed.

2. Experimental apparatus and method

Fig. 1 shows the schematic diagram of experimental apparatus. It consists of five parts such as test section, cooling water circulation line, heating water circulation line, high vacuum system, temperature measurement and recording system. The geometric specification of plain



1. Test tube
2. Heating water chamber
3. Cooling water chamber
4. Vacuum valve
5. Vacuum valve
6. Vacuum rubber hose
7. Vacuum gauge
8. Vacuum pump
9. Measuring device for liquid level
10. Vacuum rubber hose
11. Insulation
12. Coolant flow meter
13. Coolant pump
14. Coolant constant temperature bath
15. Coolant control valve
16. Heating water flow meter
17. Heating water control valve
18. Heating water pump
19. Heating water constant temperature bath

Fig. 1 Schematic diagram of experimental apparatus.

and grooved thermosyphon is shown in Table 1. And a cross sectional view of 25 times enlarged micro groove is shown in Fig. 2.

Test section of thermosyphon is illustrated in Fig. 3. The total length of thermosyphon is 1200 mm. It consists of evaporation and condensation section with 550 mm in length respectively and adiabatic section with 100 mm in length. The test tube has a 14.35 mm inside

Table 1 Geometric specification of grooved thermosyphon

No.	D_o (mm)	D_i (mm)	Groove (No.)	Groove (mm)	Groove (deg.)
1	15.85	14.35	50	0.29	42.1
2	15.85	14.35	60	0.29	42.1
3	15.85	14.35	70	0.29	42.1
4	15.85	14.35	80	0.29	42.1
5	15.85	14.35	90	0.29	42.1

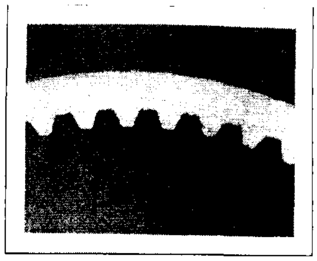


Fig. 2 Cross section of enlarged micro grooves (60 Grooves).

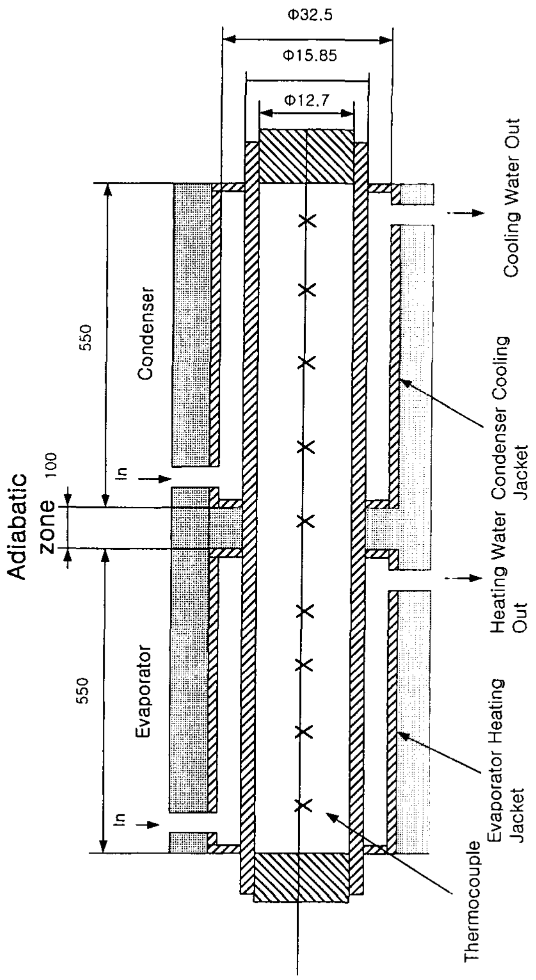


Fig. 3 Cross-sectional view of the experimental two-phase closed thermosyphon.

diameter and a 15.85 mm outside diameter.

Two 550 mm long water jackets are set on the test tube as mentioned above. One is used as a heating jacket for an evaporator and the other is used as a cooling jacket for a condenser. An inlet small tube for heating or cooling water flow into each jacket is directed at a tangent to the inside surface of the jacket.

The thermosyphon can be positioned with any inclination angle from 0° to 90° with respect to the horizontal position. Nine thermocouples are soldered on the outside surface of the tube along its length to measure surface temperatures. Another nine thermocouples are inserted into the inside of thermosyphon to measure inside vapor temperatures. To measure the temperature distribution of working fluid in the test thermosyphon, a stainless tube of 2.0 mm o. d. was provided at the center of the thermosyphon. Nine Pt. 100 Ω temperature sensors were arranged inside a stainless tube. The stainless tube was sealed hermetically. Four Pt. 100 Ω temperature sensors are placed at the inlets and the outlets of two water jackets. The temperature outputs are recorded on a data logger and it is connected to a personal computer to analyze recorded data. A rotary vacuum pump and a diffusion pump with a rating of 10^{-6} Torr are used to remove air and other non-condensable gases. Distilled water, methanol and ethanol are chosen as working fluids, since these are compatible with copper and safe materials to work with. The working fluid is injected into the tube after evacuating air. After injecting the working fluid, heating and cooling water flow 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 gas is removed again by vacuum pump for perfect operation of thermosyphon.

The experimental conditions are set as follows. The heating and cooling water temperature are varied. Two constant water temperature baths maintain hot or cool water within ±0.1℃ difference for each setting temperature. The temperature distribution, heat flux, heat transfer coefficients (condensation, boiling) are obtained with respect to inclination angle, liquid fill quantity ratio, number of groove, temperature changes of heating water or cooling water and working fluids.

An uncertainty analysis along the lines suggested by Kline and McClintock[20] showed that the uncertainty due to measurement errors in the determination of q_e and q_c was about 3.9 and 5.0 percent, respectively. An uncertainty for the value of h_e at a ΔT of 4.6 K is about 6.9 percent and that for the value of h_c at a ΔT of 3.0 K is about 8.8 percent.

3. Results and discussion

3.1 Temperature distribution of outside wall of thermosyphon

Temperature distributions of heated wall, adiabatic section and cooled wall on the thermosyphon with plain tube are shown in Fig. 4 and

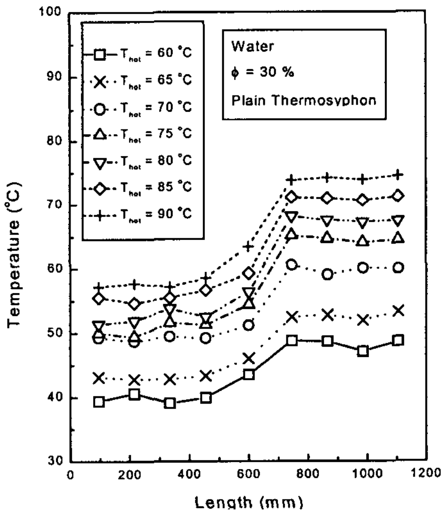


Fig. 4 Temperature distribution along the length of plain thermosyphon.

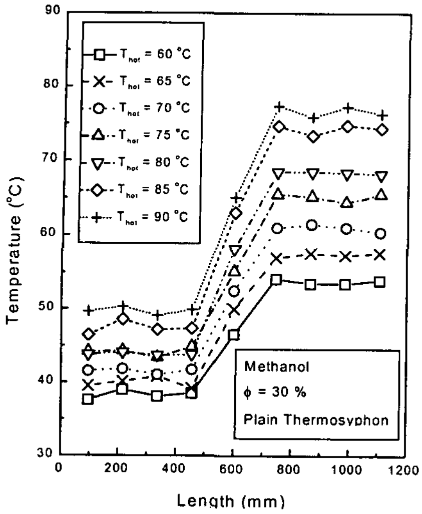


Fig. 5 Temperature distribution along the length of plain thermosyphon.

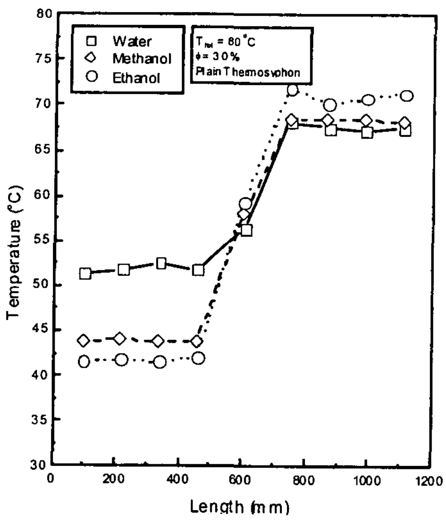


Fig. 6 Temperature distribution along the length of plain thermosyphon.

Fig. 5. The working fluid used in experiment is distilled water and methanol. Heating water temperature is 60~90℃ and an inlet temperature of cooling water is kept at 18℃. Fig. 4 and Fig. 5 is the results for the effect of the heat flux with the other variables being almost constant. The temperature distributions on the heated wall scatter to some degree but the scattering is not too pronounced. When the heat flux was small, the rate of vapor generation due to evaporation and boiling in heated section was small and condensate film down onto heated wall then was so thin that it was apt to break down easily. On the contrary, as an increase of the heat flux raised the flow rate of the condensate film, the film became rather stable. Heating water temperature is 80℃ and liquid fill quantity ratio is 30% in Fig. 6. The working fluids used in Fig. 6 are water, methanol and ethanol. The temperatures of heated and cooled wall using water as a working fluid are closer to adiabatic temperature compared to those when methanol and ethanol are used as working fluid. This means that using the working fluid with high latent heat such as water is good for obtaining high heat transfer rate.

3.2 Heat transfer coefficient and heat flux

The mass flow rate of condensate is given by Eqs. (1).

$$Q_c = m_c h_{fg}'' \tag{1}$$

The heat flow rate of condenser zone and evaporator zone are given by Eqs. (2).

$$Q_{cool} = m_{cool} C_{p,cool} (T_{out} - T_{in})_{avg} \tag{2}$$

and the experimental condensing heat transfer coefficient is given by Eqs. (3).

$$h_c = \frac{Q_{cool}}{A_i (T_{wc} - T_{sc})_{avg}} \tag{3}$$

When the fill quantity is small, the film condensation occurs in the cooled section, but as the fill quantity increases, the surface of the two-phase mixture is elevated into cooled section and two-phase mixture convection takes place there. Here, we compared the data with the correlations of Nusselt[21] equation (4) and Semena[22] equation (5) for film condensation of

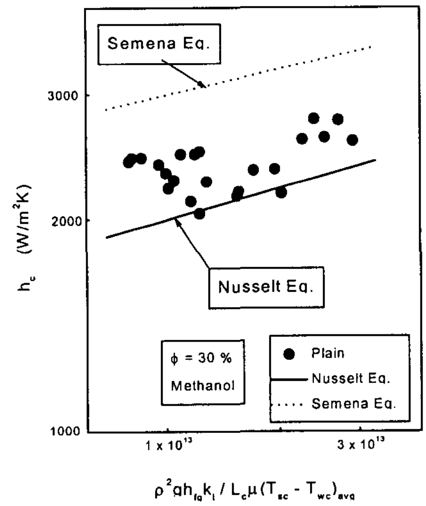


Fig. 7 Comparison of the experimental data with Correlations.

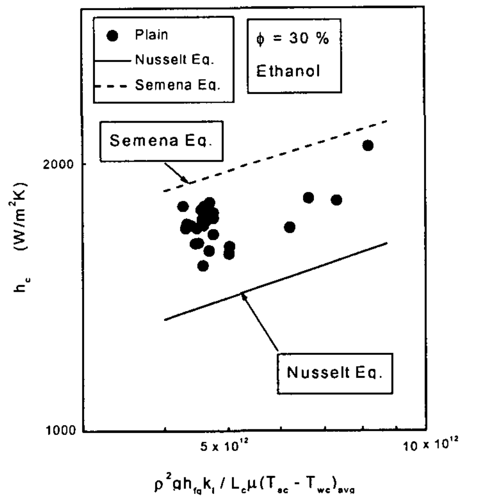


Fig. 8 Comparison of the experimental data with correlations.

vertical thermosyphons.

$$h_{Nu} = 0.943\left[\frac{\rho_l^2 g h_{fg} k_l^3}{L_c \mu_l (T_{sc} - T_{wc})_{avg}}\right]^{1/4} \tag{4}$$

$$h_{Se} = 0.95 k_l \left(\frac{\nu^2}{g}\right)^{-0.33} \left(\frac{4G}{\mu}\right)^{-0.28} \tag{5}$$

Figs. 7 and 8 shows a comparison of the experiment results with equations (4) and (5).

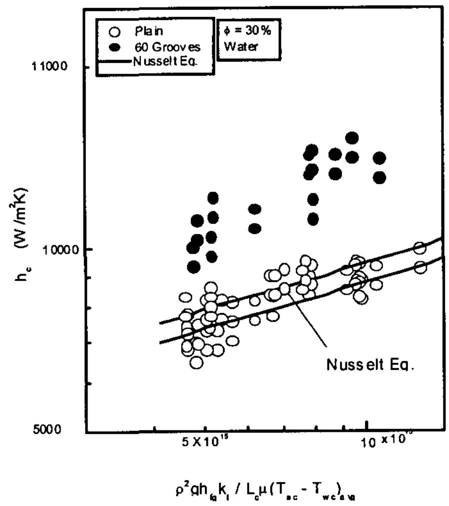


Fig. 9 Comparison of condensation heat transfer coefficient between plain and grooved thermosyphon.

The heat transfer coefficients with methanol and ethanol having a high latent heat of vaporization and high thermal conductivity scatter around the solid and the scatter of the data is not small, but it has a tendency to become small at the increase of the heat transfer rate. This may be due to a relatively small temperature difference between the vapor temperature and the inside wall temperature compared to the accuracy of the measurement.

Fig. 9 shows condensation heat transfer coefficient for plain and 60 grooved thermosyphon. 30% of liquid fill quantity ratio and water is used as a working fluid. Plain tubes data is compared with Nusselts condensation theory and the data matches well with his theory. Condensation heat transfer coefficient for 60 grooves is higher than that of plain tube in all range of experimental data. The maximum enhancement is about 2.5. The slope line on the data of grooved tube is larger than the slope line on the data of plain tube.

3.3 Effect of number of groove

Fig. 10 and Fig. 11 show the condensation

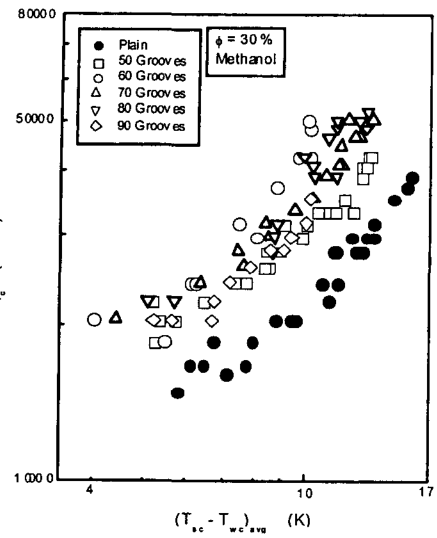


Fig. 10 Measured average heat flux vs. vapor-to-wall temperature difference of the condenser zone.

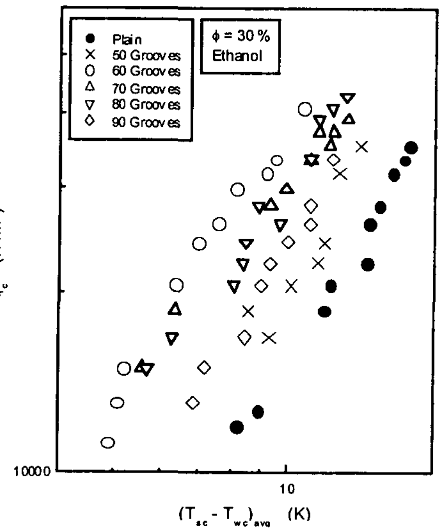


Fig. 11 Measured average heat flux vs. vapor-to-wall temperature difference of the condenser zone.

heat flux against the vapor-to-wall temperature difference. The number of groove varies from 50 to 90. The results of all of the grooved tubes locate higher than that of plain tube. The highest is 60 grooves and the lowest is plain and the rest of it is positioned in between. Heat transfer surface increase by increased groove density results in heat transfer enhancement. However, the increase of capillary force interrupts the saturated liquid to flow downward opposed to a gravitational force.

This means that the increased flow resistance caused by narrow groove width caused the decrease of heat transfer rate. Therefore, the optimum number of groove must be decided by a consideration of three effects of surface area, capillary and gravitational force at the same time.

4. Conclusions

The conclusions of this study can be summarized as follows;

(1) The working fluid with high latent heat such as water has a good heat transfer rate compared to methanol and ethanol.

(2) Plain thermosyphonss data matches well with Nusselts.

(3) Condensing heat transfer coefficient of grooved thermosyphon is 1.5~2 times higher in methanol and 1.3~1.5 times higher in ethanol compared to plain tube.

(4) The best condensation heat transfer performance is obtained for 60 grooves, and the maximum value of this case is 2.5 times higher than that of the plain tube.

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