Theoretical Analysis of Heat Transport Limitation in a Screen Mesh Wick Heat Pipe

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ABSTRACT: The purpose of the present study is to examine the heat transport limitations in a screen mesh heat pipe for electronic cooling by theoretical analysis. Diameter of pipe was 6 mm, and mesh numbers were 50, 100, 150, 200 and 250, and water was investigated as working fluid. According to the change of mesh number, wick layer, inclination and saturation temperature, the maximum heat transport limitations by capillary, entraintment, sonic and boiling were analyzed by a theoretical design method of heat pipe, including capillary pressure, pumping pressure, liquid friction coefficient in wick, vapor friction coefficient, etc. Based on the results, the capillary limitation in a small diameter of heat pipe is largely affected by mesh number and wick layer. Mesh number of 250 is desirable not to be used in pipe diameter of 6 mm, because capillary heat transport limitation decreases by the abrupt increase of liquid friction pressure due to the small liquid flow area. For the heat transport of 15 watt in 6 mm diameter pipe, mesh number of 100 and one layer is an optimum wick condition, which thermal resistance is the smallest.

Nomenclature

c_p	: specific heat [J/kg-K]
d_i, d_o	: pipe inside & outside diameter [m]
d_v	: vapor core diameter [m]
F_l, F_v	: friction coefficient of liquid & vapor [(N/m^2)/(W-m)]
f_v	: drag coefficient for vapor flow
g	: gravitational acceleration [m/sec^2]
K	: wick permeability [m^2]
k_e	: thermal conductivity of mixed liquid & wick [W/m-K]
k_l, k_w	: thermal conductivity of liquid and wick material [W/m-K]
k_p	: thermal conductivity of pipe material [W/m-K]
L_a	: length of adiabatic section [m]
L_c	: length of condenser section [m]
L_e	: length of evaporator section [m]
L_{eff}	: effective length of heat pipe [m]
N	: mesh number of wick [1/in]
P_c	: capillary pressure [N/m^2]
P_{cm}	: maximum capillary pressure [N/m^2]
P_{pm}	: maximum pumping pressure [N/m^2]
ΔP_a	: axial hydostatic pressure [N/m^2]
ΔP_n	: normal hydrostatic pressure [N/m^2]
Q_{bmax}	: boiling heat transport limitation [W]
Q_{cmax}	: capillary heat transport limitation [W]

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Q_{emax} : entraintment heat transport limitation [W]

Q_{smax} : sonic heat transport limitation [W]

r_c : capillary radius [m]

r_n : initial radius of vapor bubble [2.54×10^{-7} m]

R_{pc} : thermal resistance of pipe wall at condenser section [℃/W]

R_{pe} : thermal resistance of pipe wall at evaporator section [℃/W]

R_v : vapor constant [J/kg-K]

R_{vap} : thermal resistance from evaporator to condenser section [℃/W]

R_{wc} : thermal resistance of wick thickness at condenser section [℃/W]

R_{we} : thermal resistance of wick thickness at evaporator section [℃/W]

T_v : vapor temperature [℃]

Greek symbols

ε : porosity of wick

λ : latent heat of vaporization [kJ/kg]

μ_l : viscosity of liquid [kg/m-sec]

ρ_l, ρ_v : density of liquid and vapor [kg/m^3]

σ : surface tension of liquid [N/m]

γ_v : vapor specific heat ratio

1. Introduction

In recent years, the semiconductor capacity of an electronic unit becomes larger. On the contrary, its size is much smaller than before. As a result, a high performance cooling system is needed. In the case of a notebook PC, the thermal dissipation power has been increased dramatically with the process speed of CPU increasing. The thermal dissipation power was 20 W in 1999, 27 W in 2000, and 30 W in 2001, respectively. It is on an increasing trend with the processing speed growth. If CPU develops at this rate, the growth of cooling system may not follow the speed.

Several cooling methods are introduced to solve this problem, and the cooling system using the heat pipe is remarked as a suitable cooling way.[1-4] How much heat the heat pipe can transfer is the most important factor, and it has to be designed to maximize the heat transport ability by optimum design.

In the case of the wick type heat pipe, the capillary limitation is the most influential factor to maximize heat transport among operation limits, and it is affected by pumping pressure, friction loss toward length, and inclination angle. Usually, small size heat pipes of 3~6 mm are usually installed with a little inclination, so they have a capillary structure like wick.

In this study, the heat transport limitations and the thermal resistance were investigated by theoretical analysis according to the change of mesh number, wick layer and inclination. And capillary pressure, pumping pressure, liquid friction coefficient in wick, vapor friction coefficient and capillary limitation are analyzed by theoretical design method of heat pipe.

2. Design theory of screen mesh heat pipe

2.1 Specification of heat pipe and screen wick

Table 1 shows the specification of heat pipe used in theoretical analysis. The material of

Table 1 Specification of the heat pipe

Parameters	Specification
Pipe	
material	Copper
total length	300 mm
length of evaporator zone	50 mm
length of adiabatic zone	100 mm
length of condenser zone	150 mm
Working fluid	Distilled water
Pipe diameter (thickness)	4 mm (0.3 mm)
	6 mm (0.4 mm)
	8 mm (0.7 mm)

Table 2 Specification of screen wick

Mesh number	Mesh diameter (mm)
50	d_w=0.216
100	d_w=0.114
150	d_w=0.065
200	d_w=0.053
250	d_w=0.040

pipe and the working fluid are copper and water respectively, as shown in Table 1. And the length of evaporator section, adiabatic section and condenser section are 50 mm, 100 mm and 150 mm respectively. Table 2 shows the specification of mesh diameter in screen mesh wick by mesh number. These data of mesh diameter are from wick manufacturing company in Korea.[5] Mesh size is usually specified in mesh number, which is defined as the number of meshes per inch. The wire size is approximately equal to the wire spacing. The large mesh number means the size and diameter of mesh is small.

The porosity of each screen mesh wick, which mesh number is 50, 100, 150, 200 and 250, was calculated as 0.68, 0.65, 0.63, 0.68 and 0.66, respectively. The boundary conditions in analysis is from the surface of evaporator to the surface of condenser of heat pipe element with screen mesh wick.

2.2 Equation of heat transport limitation and thermal resistance

At the top heat mode, which evaporator section is located upper position than condenser section, wick must be needed for returning the working fluid to evaporator section by capillary pressure. It is very important to calculate maximum heat transport limitation in wick heat pipe. Design theory of screen mesh wick for capillary pressure is as follows;[6-7]

Maximum capillary heat transport limitation is defined as maximum heat transport factor divided by effective length, as shown in Eq. (1)

$$Q_{c,max} = \frac{(QL)_{c,max}}{L_{eff}} \tag{1}$$

And maximum heat transport factor, $(QL)_{c,max}$ is defined as maximum pumping pressure divided by liquid friction coefficient plus vapor friction coefficient.

$$(QL)_{c,max} = \frac{P_{pm}}{F_l + F_v} \tag{2}$$

The friction coefficient by the liquid flow, F_l in the screen mesh is defined as Eq. (3). Therefore, when the permeability and the cross-section area of the wick increase, the friction coefficient by the liquid flow decreases. The cross section area and the permeability of wick are calculated from Eq. (4) and Eq. (5). And wick porosity in screen mesh wick is defined as Eq. (6) and crimping factor, S is considered as 1.05. The friction coefficient by vapor flow is expressed as Eq. (7). It increases, when the cross-section area, A_v for vapor flow decreases by the thickness of the mesh wick.

$$F_l = \frac{\mu_l}{KA_w \rho_l \lambda} \tag{3}$$

$$A_w = \frac{\pi(d_i^2 - d_v^2)}{4} \tag{4}$$

$$K = \frac{d_w^2 \varepsilon^3}{122(1-\varepsilon)^2} \tag{5}$$

$$\varepsilon = 1 - \frac{\pi S N d_w}{4} \tag{6}$$

$$F_v = \frac{(f_v Re_v)\mu_v}{2A_v r_{h,v}^2 \rho_v \lambda} \tag{7}$$

Maximum pumping pressure, P_{pm} is defined as the difference between maximum capillary pressure and (normal hydrostatic pressure plus axial hydrostatic pressure), as shown in Eq. (8)

$$P_{pm} = P_{cm} - \Delta P_n - \Delta P_a \tag{8}$$

Here, ΔP_n and ΔP_a is as follows;

$$\Delta P_n = \rho_l g d_v \cos\psi \tag{9}$$

$$\Delta P_a = \rho_l g L_t \sin\psi \tag{10}$$

Maximum capillary pressure is defined as double liquid surface tension divided by effective capillary radius, as in Eq. (11)

$$P_{cm} = \frac{2\sigma}{r_c} \tag{11}$$

Effective capillary radius, r_c is expressed as inversely double mesh number, as in Eq. (12).

$$r_c = \frac{1}{2N} \tag{12}$$

And the heat transport limitations of entraintment, boiling and sonic are defined as in Eq. (13), Eq. (14) and Eq. (15), respectively.[6]

$$Q_{emax} = A_v \lambda \left(\frac{\sigma\rho_v}{2r_{h,s}}\right)^{1/2} \tag{13}$$

$$Q_{bmax} = \frac{2\pi L_e k_e T_v}{\lambda\rho_v \ln(r_i/r_v)}\left(\frac{2\sigma}{r_n} - P_c\right) \tag{14}$$

$$Q_{smax} = A_v \rho_v \lambda \left[\frac{\gamma_v R_v T_v}{2(r_v+1)}\right]^{1/2} \tag{15}$$

Here, effective conductivity combined with liquid and wick material, k_e, is expressed as follows;

$$k_e = \frac{k_l[(k_l+k_w)-(1-\varepsilon)(k_l-k_w)]}{[(k_l+k_w)+(1-\varepsilon)(k_l-k_w)]} \tag{16}$$

For the returning force of working fluid to evaporator section, wick increases the thermal resistance in heat pipe. When the mesh number and the thickness of the mesh wick are determined for the same heat transport operation of heat pipe, we have to select the wick specification which the thermal resistance is smaller, if possible. Thermal resistance is defined as the total surface temperature difference between evaporator and condenser divided by the heat quantity, as shown in Eq. (17)

$$R_t = R_{pe} + R_{we} + R_{vap} + R_{wc} + R_{pc} \tag{17}$$

Here, R_{pe}, R_{we}, R_{vap}, R_{wc} and R_{pc} are the thermal resistance by the pipe wall and the saturated wick at the evaporator section, the vapor flow from the evaporator section to the condenser section, the saturated wick and the pipe wall at the condenser section, respectively, as in Eq. (18).

$$\begin{aligned}
R_{pe} &= \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi L_e k_p} \\
R_{we} &= \frac{\ln\left(\frac{r_i}{r_v}\right)}{2\pi L_e k_{ee}} \\
R_{vap} &= \frac{T_v F_v\left(\frac{L_e}{6} + L_a + \frac{L_c}{6}\right)}{\rho_v \lambda} \\
R_{wc} &= \frac{\ln\left(\frac{r_i}{r_v}\right)}{2\pi L_c k_{ec}} \\
R_{pc} &= \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi L_c k_p}
\end{aligned} \tag{18}$$

3. Simulation results and discussion

3.1 Maximum capillary pressure

The capillary pressure is fundamental data for returning force of working fluid in selecting the mesh number. The capillary pressure can be varied by the saturation temperatures, because capillary pressure is a function of the capillary radius and the surface tension.

Figure 1 shows maximum capillary pressure according to mesh number, when the saturation

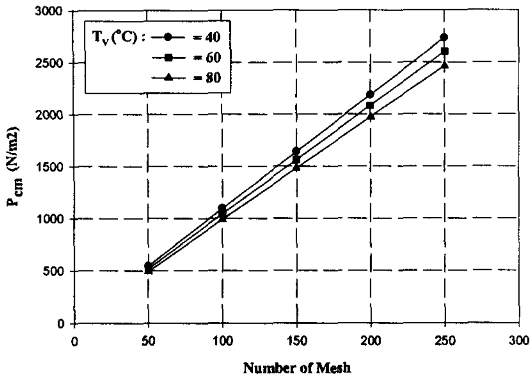

Fig. 1 Capillary pressure according to mesh number and temperature (d_o=6 mm).

temperatures are 40℃, 60℃ and 80℃, respectively.[8-9] Maximum capillary pressure is increased, when mesh number becomes larger. The large mesh number means that its wire diameter is smaller than in small mesh number. As shown in Eq. (12), if mesh number is large, capillary radius becomes small. Maximum capillary pressure is proportional to surface tension of working fluid, but inversely proportional to capillary radius from Eq. (13). Maximum capillary pressure is increased to 2500 N/m^2 at mesh number 250 compared with 500 N/m^2 at mesh number 50.

It is shown that the maximum capillary pressure is decreased according to the increase of the saturation temperature of working fluid. This reason is because the surface tension becomes smaller in the higher saturation temperature.

3.2 Maximum pumping pressure

Figure 2 shows maximum pumping pressure. Maximum pumping pressure is a little smaller than the maximum capillary pressure. This decrease is due to the effects of the gravitational pressure in the direction perpendicular to the heat pipe axis and of the axial hydrostatic pressure by the inclination angle to the horizontal level from Eq. (8).

As shown in Fig. 2, the pumping pressure is increased by the increase of the mesh number, but decreased to 100 N/m^2 according to 2 degree increase of inclination angle.

3.3 Liquid friction coefficient

Liquid friction coefficient is a friction for the liquid flow in wick, and it is inversely proportional to wick cross sectional area and permeability from Eq. (3). Large mesh number wick means that wick wire is thin. Therefore, its cross section of wick for liquid flow is thinner than in small mesh number.

As shown in Fig. 3, liquid friction coefficient becomes larger at large mesh number which

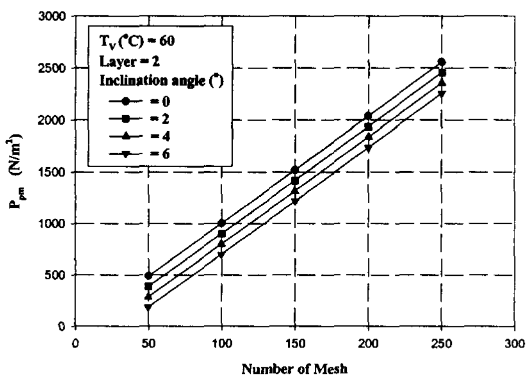

Fig. 2 Pumping pressure according to mesh number and inclination (d_o=6 mm).

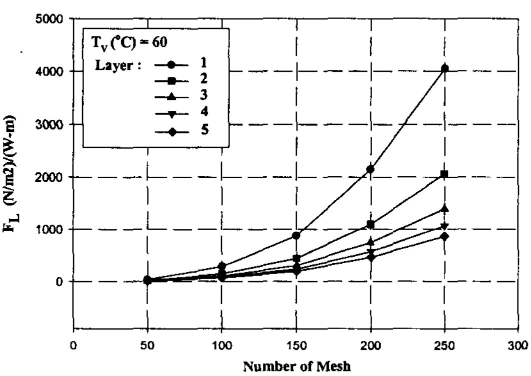

Fig. 3 Liquid friction coefficient according to mesh number and layer (d_o=6 mm).

mesh size becomes smaller. And liquid friction coefficient is smaller, because the cross section of wick is increased when layer becomes thicker. But the large mesh number is largely affected by layer because of small mesh wire diameter, as shown at mesh number 250 in Fig. 3. As shown in Fig. 3, liquid friction coefficient is not almost affected by mesh layer in the case of mesh number 50, but in the case of large mesh number, such as mesh number 250, liquid friction coefficient is largely affected by the mesh layer. For example, its value is approximately 4000 (N/m^2)/(W-m) in one layer and 900 (N/m^2)/(W-m) in 5 layers.

3.4 Vapor friction coefficient

Vapor friction coefficient is a friction for the vapor flow in vapor core, and it is inversely proportional to cross sectional area of vapor core from Eq. (7). Small mesh number means that wick wire diameter is large. Therefore, the cross sectional area of vapor flow is less, when mesh number becomes small. As shown in Fig. 4, vapor friction coefficient is inversely proportional to mesh number. It becomes larger, when mesh number is smaller and layer is increased. Layer is increased from 1 to 5 at mesh number 50, vapor friction coefficient is increased to about 400 times.

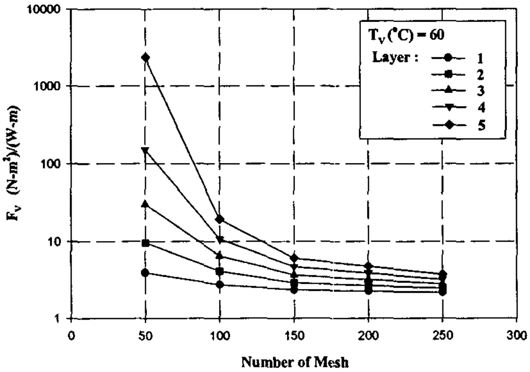

Fig. 4 Vapor friction coefficient according to mesh number and layer (d_o=6 mm).

3.5 Maximum capillary limitation

Figure 5 shows maximum capillary limitation according to mesh number at saturation temperatures of 40℃, 60℃, 80℃, respectively in layer 2, when mesh numbers are 50, 100, 150, 200 and 250, respectively. The heat transport limitation of capillary pressure is increased because of the increase of surface tension, when saturation temperature becomes higher.

But it is decreased in the case of the larger mesh number, because the liquid friction coefficient becomes larger by the smaller mesh wire diameter. Figure 6 shows capillary heat transport limitation according to inclination. It becomes smaller by the decrease of pumping

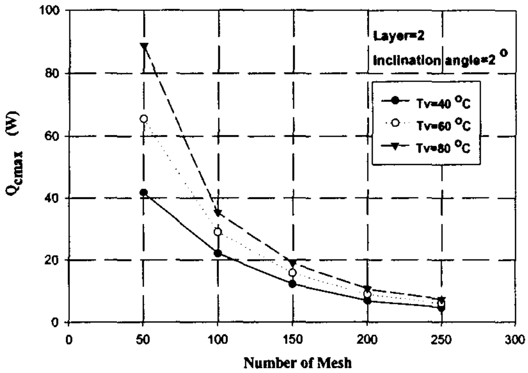

Fig. 5 Capillary limitation according to mesh number and temperature (d_o=6 mm).

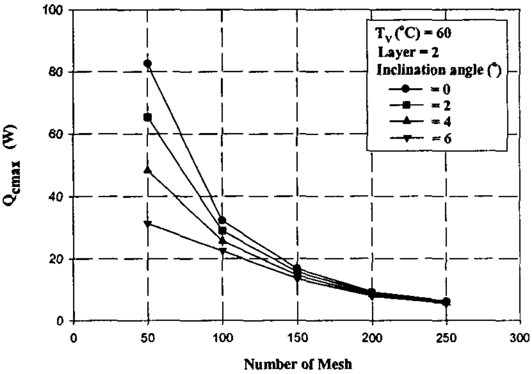

Fig. 6 Capillary limitation according to mesh number and inclination (d_o=6 mm).

pressure when inclination is increased from Eq. (8). When the heat pipe with 2 layers of 100 mesh number is located at inclination angle 6 degree, Q_{cmax} is 22 watt. But when inclination angle is 2 degree, it is 30 watt. As shown in Fig. 7, when layer is increased more than 3 in mesh number 50, it becomes rather decreased by the increase of mesh layer, because of the abrupt increase of vapor friction coefficient by the decrease of the vapor flow area. Figure 8 for diameter 4 mm and Fig. 9 for diameter 8 mm show these phenomena obviously.

When at mesh number 50, layer in diameter 4 mm is increased to more than 2, and layer in diameter 8 mm is increased more than 4, it becomes rather decreased by the increase of mesh layer. So we can know that there is the optimum wick number and layer for maximum capillary heat transportation in same diameter.

3.6 Maximum limitation of entraintment, sonic and boiling

In addition to the capillary limitation, limitations by entraintment, sonic and boiling must be considered in screen mesh wick. Entraintment limitation occurs by shear force at the liquid-vapor interface. When wick thickness becomes thick, vapor flow diameter becomes small and vapor velocity is abruptly increased. This occurs when liquid is torn from the surface of wick by vapor. As shown in Fig. 10, when the

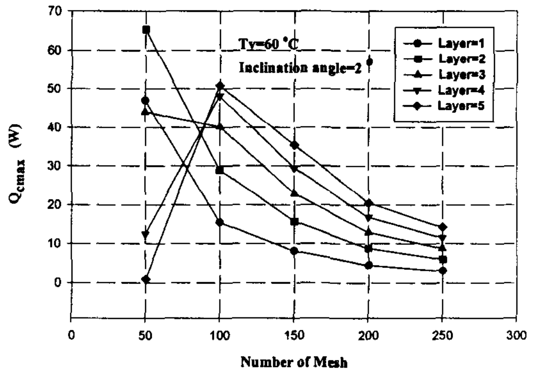

Fig. 7 Capillary limitation according to mesh number and layer (d_o=6 mm).

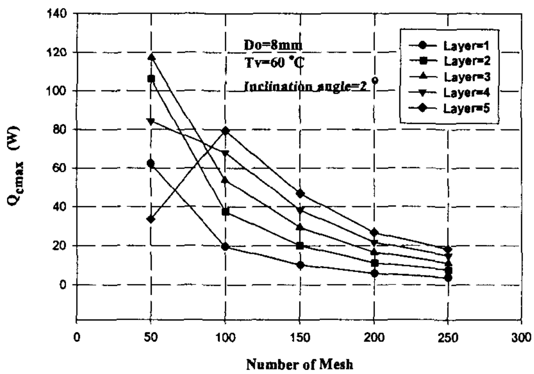

Fig. 9 Capillary limitation according to mesh number and layer (d_o=8 mm).

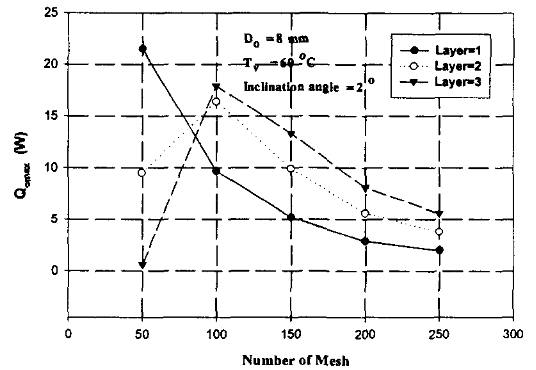

Fig. 8 Capillary limitation according to mesh number and layer (d_o=4 mm).

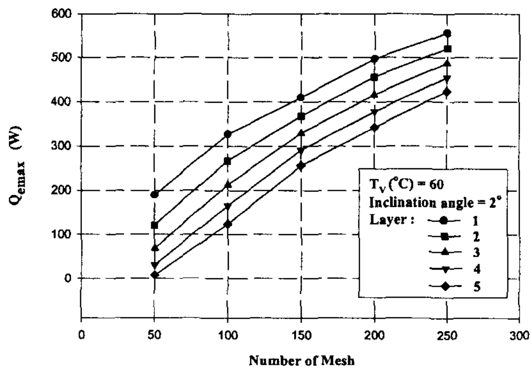

Fig. 10 Entrainment limitation according to mesh number and layer (d_o=6 mm).

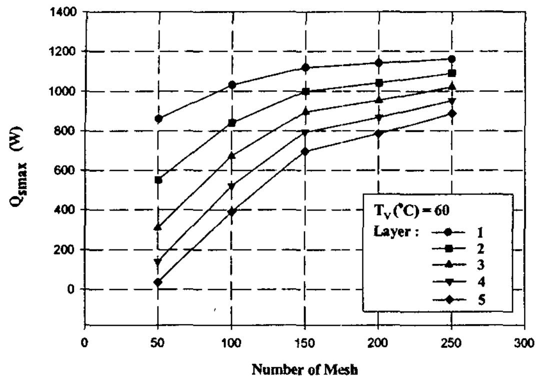

Fig. 11 Sonic limitation according to mesh number and layer (d_o=6 mm).

layer of wick in mesh number 50 is increased from 1 to 5, Q_{emax} decreases by about 0 from 190. Q_{emax} is more than Q_{cmax} except mesh number 50. Sonic limitation occurs when the vapor velocity at the evaporator exit is sonic, which is like entraintment limitation. Sonic limitation is also higher than capillary limitation except mesh number 50 from Fig. 11.

Entraintment and sonic limitation are increased according to the increase of mesh number.

This phenomena is the reason that the velocity in vapor core is lower by the larger cross section of vapor core as the result of the thin thickness of mesh in the case of the large mesh number. The boiling limitation is larger than the capillary limitation, and is also increased when mesh number becomes larger from Fig. 12. But the difference in boiling and the others is that the boiling limitation is a limitation of the radial heat flux, while the other limitations are of the axial heat flux. As the results, we know that heat transport limitation in screen mesh heat pipe is caused by capillary limitation

3.7 Thermal resistance

Thermal resistance means the temperature difference needed to transport the heat of one watt in heat pipe section. Figure 13 shows thermal resistance according to the layer of wick and mesh number. It is increased when wick layer becomes thicker and mesh number becomes smaller. The small mesh number means that mesh wire diameter is large. Therefore the mesh thickness of small mesh number is thicker than in large mesh number. So thermal resistance becomes higher when mesh number is small and layer becomes thicker. The merit of heat pipe is that the temperature difference is small in pipe because heat transport is performed by the latent heat of working fluid.

Therefore, if it is possible to transport the same heat rate in same diameter, we have to

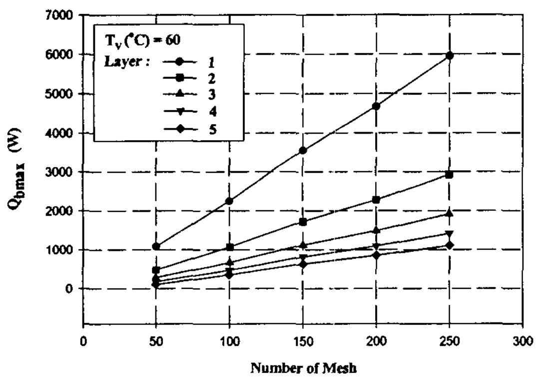

Fig. 12 Boiling limitation according to mesh number and layer (d_o=6 mm).

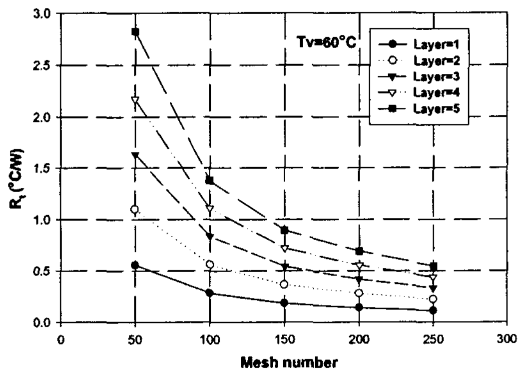

Fig. 13 Thermal resistance according to mesh number and layer (d_o=6 mm).

select the layer and mesh number of wick that thermal resistance is small. For example, when heat transportation rate is 15 watt in case of inclination angle 2, we can select the wick condition as follows from Fig. 9; one layer in 100 mesh, 2 layers in 150 mesh, 3 layers in 200 mesh and 5 layers in 250 mesh. But thermal resistance is as follows from Fig. 13; 0.27℃ in 100 mesh, 0.35℃ in 150 mesh, 0.4℃ in 200 mesh and 0.55℃ in 250 mesh. As the results, we can estimate the optimum condition of wick is one layer of 100 mesh.

4. Conclusions

The heat transport limitations of screen wick were investigated by theoretical analysis according to the mesh number, layer and inclination. Water was used as a working fluid for the copper tube, which its diameter is 6 mm. The results are as followings.

(1) Capillary pressure is higher in the small mesh size, which the diameter of mesh wire is small, but maximum heat transport factor becomes less in small mesh size.

(2) The liquid friction coefficient in small mesh size is higher than the vapor friction coefficient by the decrease of vapor flow area in large mesh size.

(3) Mesh number 50 is desirable not be used with layer more than 3 in pipe diameter 6 mm, because capillary heat transport limitation becomes rather decreased by the abrupt increase of vapor friction pressure.

(4) Mesh number 250 is desirable not to be used in pipe diameter 6 mm, because capillary heat transport limitation becomes decreased by the abrupt the increase of liquid friction pressure by the small liquid flow area

(5) Heat transportation limit in mesh wick heat pipe is affected by capillary rather than entraintment and sonic.

(6) For the heat transport of 15 watt in 6 mm diameter pipe, mesh number 100 and one layer is optimum wick condition, which thermal resistance is the smallest.

Acknowledgments

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