Evaporation thermal analysis of Swallow-tailed Axial-grooved Heat Pipe

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Abstract. A detailed mathematical model that describes evaporating characteristics through thin liquid film at the evaporator section of swallow-tailed axial-grooved heat pipe was developed. The numerical simulation results about thin film profile, liquid-vapor interface temperature, evaporating rate and heat flux at the evaporating thin film region were given by the current investigation and the effect of superheat on the liquid-vapor interface temperature, evaporating mass rate and heat flux was discussed. Meanwhile, thermal model of the meniscus region at the evaporating section was developed to calculate the rate of heat transfer. The ratio of the heat conduction in the evaporating thin liquid film region and total heat rate were also discussed. It is indicated that the thickness of thin liquid film rises in a nearly linear fashion. The disjoining pressure can be neglected with increasing the liquid film thickness, tends to be negligibly small. The heat transfer rate at the intrinsic meniscus cannot be compared with that of the evaporating liquid film region.

1. Introduction
As a typical high-performance grooved heat pipe, the swallow-tailed axial-grooved heat pipe, as shown in Fig. 1, has been widely used in the thermal control under microgravity conditions. Usually, the vapor-liquid interface at the evaporator section consists of the non-existent evaporation region, thin liquid film evaporation and intrinsic meniscus region [1-5]. As illustrated in the Fig.1(C-C), the liquid evaporates when it flows from thin liquid film to no evaporating region along the radial direction. Due to the affinity between the working liquid and solid wall hindering the liquid from evaporating, the heat transfer doesn’t occur in this non-existent evaporation region. In the thin liquid film region of evaporation, the capillary pressure is the driving force together with disjoining pressure and nearly all of the liquid evaporating occur in this region. The liquid flow axially under the capillary pressure in the meniscus region, in which the curvature radius of meniscus region keeps constant, and the disjoining pressure can be neglected compared with the capillary pressure. Only a small part of heat transfer exists in this region.

Fig. 1 (a) Schematic of a heat pipe, (b) Schematic of microgroove and liquid film.
Scholars have done a lot of research on the flow and thermal characteristics for the micro-grooved heat pipe, but the investigation on the evaporation thermal characteristics is very less. Despite the existence of a thin liquid film evaporating heat transfer characteristic investigations [1-8], the evaporating heat transfer characteristic investigations in the whole interface are very deficiency. Comprehensive understanding the evaporating thermal performance at the vapor-liquid interface have a very important guiding significance for the heat pipe stable operation, micro-grooved optimization design. To reveal the evaporating heat transfer mechanism for the swallow-tailed axial-grooved heat pipe. A detailed physical model that describes thermal performance through the thin liquid film of the swallow-tailed axial-grooved heat pipe was developed, the distribution of liquid film and the evaporation thermal performance are discussed. Meanwhile, the effect of superheat on the evaporation thermal performance is discussed about the whole cross-section.

2. Mathematical formulation

2.1 Heat transfer of evaporating thin liquid film

The liquid flow momentum equation in the thin liquid film of evaporation is written as

$$\frac{d^2 u_i}{d\eta^2} - \frac{dP}{ds} = 0 \quad (1)$$

By Eq.(1), the velocity distribution of the fluid can be achieved, It can be found as

$$u_i = \frac{1}{\mu_i} \left( \frac{dP}{ds} \right) \left( \frac{1}{2} \eta^2 - \delta \eta \right) \quad (2)$$

So the liquid mass flux of the unit micro-grooved length of can be written as

$$\Gamma_i = \rho_i \int_0^\delta u_i d\eta = -\frac{\delta^3 \rho_i}{3 \mu_i} \frac{dP}{ds} \quad (3)$$

The decrement of liquid mass flux corresponds to mass flux of evaporation, which can be obtained

$$\frac{d\Gamma_i}{ds} = \dot{m}_i(s) \quad (4)$$

In which, the subscript i indicates that evaporation occurs in the vapour-liquid contact surface, mass flux of evaporation at the contact surface is given as[5,6]

$$\dot{m}_i(s) = a(T_i - T_v) + b(P_i - P_v) \quad (5)$$

Where, the factors of a and b can be expressed in the following form

$$a = 2\left( \frac{M}{2\pi R_u T_i} \right)^{1/2} \left( \frac{P_v h_{lv}}{R_u T_i} \right) \quad (6)$$

$$b = 2\left( \frac{M}{2\pi R_u T_i} \right)^{1/2} \left( \frac{P_v V}{R_u T_i} \right) \quad (7)$$

In which, $R_u$ denotes the generic vapour constant, M represents molecular weight, $h_{lv}$ is latent heat, and $V$ indicates the molar volume of the fluid; the subscript v denotes the vapor.

The pressure difference between liquid and vapour is determined by the disjoining and capillary force, which is shown as [7]

$$P_v - P_i = P_v + \sigma \frac{d^2 \delta_v}{ds^2} \left[ 1 + \left( \frac{d\delta_v}{ds} \right)^2 \right]^{3/2} \quad (8)$$

Simultaneous equations Eqs. (2)-(4) yields

$$-\frac{\rho_i}{3 \mu_i} \frac{d}{ds} \left( \delta_v^3 \frac{dp}{ds} \right) = a(T_i - T_v) + b(P_i - P_v) \quad (9)$$

Considering that heat transfer through liquid film is a dimension and the direction of heat flux is
perpendicular to the wall of microgroove. Due to the thin film being as thin as a wafer, the heat resistance at the contact surface should not be neglected, heat flow at the contact surface is represented by the following equation

$$q_e = (T_w - T_i) / \left( \frac{\delta s}{\lambda_i} + \frac{T_v \sqrt{2\pi R_s T_v}}{h_f \rho_v} \frac{2 - f}{2f} \right)$$  \hspace{1cm} (10)

Substituting Eq. (7) into Eq. (8) yields a fourth-order ordinary differential equations. The boundary conditions can be expressed as

$$\begin{align*}
\left. \delta_s \right|_{s=0} &= \delta_0 \\
\left. (P_t - P_v) \right|_{s=0} &= \sigma K_0 \\
\left. (P_t - P_v) \right|_{s=0} &= 0
\end{align*}$$  \hspace{1cm} (11)

Considering that working fluid is in saturation, and the superheat degree between the wall temperature and vapor is given. Then choosing the value of liquid film thickness is to control the value of interface temperature at the position of s=0. Finally, the Eq. (9) can be solved by fourth order ordinary Runge-Kutta method and then the liquid film can be obtained along s direction.

2.2 Thermal analysis in the meniscus region

The vapor-liquid temperature is nearly equal to temperature of vapor in the meniscus region. Considering that the heat flux is perpendicular to the vapor-liquid contact surface and the heat transfer is one-dimensional.

Therefore, the expressions of heat load in the evaporating and meniscus region are written respectively as

$$Q_e = \int_0^s q_e ds$$  \hspace{1cm} (12)

$$Q_m = \int_s^L q_m ds + \int_0^{s/2} q_m dx$$  \hspace{1cm} (13)

The total heat load can be written as

$$Q_{tot} = Q_e + Q_m$$  \hspace{1cm} (14)

3. Results and discussion

The heat and mass transfer at the contact surface mainly occur in the thin liquid film region of evaporation, which is controlled by the capillary and disjoining force, and make liquid flowing to the no evaporating region. To investigate the evaporating thermal performance in this region is propitious to deeply understand the evaporating heat transfer mechanism. In this paper, working fluid of heat pipe is ammonia, and aluminum alloy is chosen as solid material.

The heat mass flux and the thin liquid film variation along s direction in the thin liquid film region of evaporation for the heat pipe with axially swallow-tailed microgrooves are shown as Fig.2. The evaporating heat mass flux becomes very small in starting point (the coordinate origin), and then sharply rises to the maximum value, and finally gradually reduces along s direction. At the starting point, the capillary pressure can be neglected compared to the disjoining pressure. Due to a very thin liquid as thin as a wafer adsorbing on the solid surface (similar to the no evaporating region), the liquid thin film thickness is close to 0. There is nearly no liquid evaporation near the starting point, mainly because the appetency between the solid and working fluid becomes very large, and make the evaporation of working liquid being hindered.
Fig. 2 Heat flux and thin film thickness variation along s direction

The mass flux of evaporation and temperature variation at contact surface in the thin liquid film region of evaporation for the swallow-tailed axial-grooved heat pipe are represented by the Fig. 3. The contact surface temperature in the thin liquid film of evaporation is nearly close to the solid temperature at starting point and as the thin liquid film gradually becomes thicker, the vapor-liquid interface temperature sharply decline. Once the thickness of thin film gets to a certain value, the evaporating mass flux decreases with an increase of contact surface temperature. At the position of joint between non-evaporation zone and thin liquid film region of evaporation, due to thin liquid film as thin as a wafer, the affinity between working liquid and solid hinders the liquid evaporating. In other words, the very thin liquid film covers on the solid at the no evaporating region, which is equivalent to insulation layer to hinder the heat transfer. Numerical simulation results show that the vapor-liquid contact surface temperature is nearly close to the gas temperature in the intrinsic meniscus region, so the evaporating mass flux is minimal in this region.

Fig. 3 Evaporating mass flux and variation temperature at the vapor-liquid interface

The thin liquid film thickness and heat mass flux variations along s direction for different overheating in the thin liquid film region of evaporation for the swallow-tailed axial-grooved heat pipe are depicted in the Fig. 4 and 5 respectively. As can be seen from the figures, the thickness of thin liquid film and maximum heat load increase with the increasing of the superheat under certain conditions.
This paper chooses three typical cross-sections to investigate the heat rate in the evaporating liquid film for the swallow-tailed axial-grooved heat pipe. The meniscus radiuses of the three typical cross-sections calculated respectively are $r_c(z = 0) = 2.9\text{mm}$, $r_c(z = 350\text{mm}) = 3.1\text{mm}$, $r_c(z = 700\text{mm}) = 3.9\text{mm}$. It is assumed that the heat load is 200W, the working temperature is 293K. Figure 6 shows the effect of meniscus radius on the $Q_e/Q_{tot}$ for different superheat. As represented by the figure, thermal ratio at the thin liquid film of evaporation is extraordinary large, and $Q_e/Q_{tot}$ declines with the increase of superheat. The more the meniscus, the larger of $Q_e/Q_{tot}$ for corresponding the same superheat. Considering the influence of overheating, heat pipe material and the working fluid have a significant impact on the thermal characteristics.
4. Conclusions

(1) The vapor-liquid contact surface temperature in thin liquid film of evaporation is nearly close to the solid temperature at the starting point and with liquid film gradually becoming thicker, the vapor-liquid interface temperature sharply decline. Thin liquid film increases in a nearly linear fashion.

(2) The evaporating heat mass flux becomes very small in starting point (the coordinate origin), and then sharply rises to the maximum value, and finally gradually reduces.

(3) Compared with the meniscus region, the heat rate in the thin liquid film region of evaporation is extraordinary large.

(4) The liquid film thickness, the contact surface temperature, heat rate and the evaporating rate correspondingly increase with the superheat, however, \( Q_e / Q_{tot} \) declines with the increase of the superheat.

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