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Capillary Limit of Micro Heat Pipe with Compound Structure of a Sintered Wick on Trapezium-grooved Substrate

***Abstract**. A micro heat pipe's (MHP) performance is largely determined by its capillary limit. Based on comprehensive analyses of lower backflow resistance of working fluid in trapezium-grooved-wick MHP and greater capillary suction in a sintered-wick MHP, this paper established the mathematical model of capillary limit for a MHP with the compound structure of a sintered wick on trapezium-grooved substrate. The analyses show that a MHP with such compound structure has a higher capillary limit than that a MHP with a simplex sintered- or trapezium-grooved wick structure.*

***Streszczenie.** Właściwości podgrzewanej mikrorurki zależą od parametrów kapilary. W artykule zaprezentowano model matematyczny mikrorurki z kapilarą uwzględniający skład . Zaproponowano optymalizacje konstrukcji. (**Limit kapilary w podgrzewanej mikrorurce o strukturze kompozytowej na podłożu trapezoidalnie rowkowanym**)*

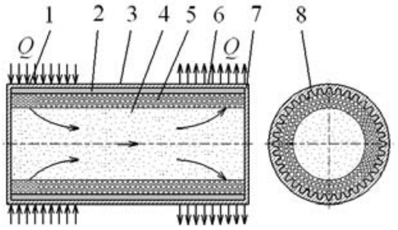
Keywords: Micro heat pipe, Trapezium groove, Sintering, Capillary limit.
Słowa kluczowe: mikrorurka, kapilara.

Introduction

With fast development of micro electronics technology, sharply increase in microprocessor-chips' integration leads to dramatic increases in power consumption for unit volume chip, causing the fatal problem of high heat-flux. Power consumption and heat dissipation, which were of less importance before, have become the bottleneck for microelectronics from further development. If not dissipated in time, the heat consumed in electronic components is continuously accumulated, causing rapid temperature rise in chips and sharp decline in reliability and performances [1-3]. As micro heat pipes have many advantages (such as higher heat transfer capacity, lower thermal resistance and smaller structural dimension etc.), micro heat pipes are widely used in such electronic components as microprocessors in laptops and desktops [4]. So it is of increasing necessity to study micro heat pipes to meet higher requirements on heat dissipation. Recently, Kempers investigated heat transfer performance and thermal resistance of groove-wicked heat pipes [5]. Nguyen and Do experimentally studied the phenomena in micro heat pipe's evaporator [6-7]. Liang analyzed and presented the structure and testing for micro heat pipes with radial grooved wicks [8]. BAI Tong made theoretical and experimental investigations into two-phase flow in grooved-wick micro heat pipes, studied steam flow in rectangular micro grooves [9-10]. And Modern Manufacturing and Engineering Establishment of SCUT (South China University of Technology) has done a great deal of research on grooved-wick heat pipes, sintered-wick heat pipes, flat heat pipe and capillary pumped loops etc. from the perspectives of both heat-pipe theory and manufacturing [11-15]. In this study, capillary limit of micro heat pipes with the compound structure of a sintered wick on trapezium-grooved-wick substrate were theoretically investigated, and then compared with the capillary limits of sintered-wick and trapezium-grooved-wick micro heat pipes respectively.

Working Principle and Basic Properties

A micro heat pipe consists of a container, wick and end caps. Its working principle is shown in Fig.1: pumped to $1.3\times(10^{-1}\text{-}10^{-4})$Pa , the pipe is filled with appropriate quantity of working fluid, which fills the multi-orifice capillary wick close to inner wall, and sealed; one end is evaporator, the other condenser, and if necessary, adiabatic section can be arranged in the middle. When evaporator is heated, liquid in capillary wick evaporates and vaporizes. Vapor flows to condenser under the tiny pressure differential, emitting heat and changing into liquid, which flows along multi-hole material back to evaporator under capillary force then. Thus, heat is transferred from one end to the other through such cycles.



1-Evaporator; 2-Liquid; 3-Adiabatic section; 4-Vapor; 5-Sintered wick; 6-Condenser; 7-Container; 8-Trapezium-grooved wick

Fig.1. Schematic diagram for working principle of circular micro heat pipe with a sintered wick on trapezium-grooved-wick substrate

Mathematical Modeling for Capillary Limit of Micro Heat Pipes with Compound Structure of Sintered Wick on Trapezium-grooved Substrate

Capillary limit is the maximum heat quantity transferred by the cycles of working fluid under the capillary-pressure head generated between capillary wick and working fluid in a micro heat pipe. Therefore the formula deduced by Chi on the assumption that heat load is uniformly distributed in evaporator and condenser for vapor flow in incompressible and laminar state, can be adopted for mathematical modeling of capillary limit, that is,

$$Q_{ca,\max}=\frac{\dfrac{2\sigma}{r_c}-\rho_l g d_v\cos\phi\pm\rho_l g l\sin\phi}{\left(F_l+F_v\right)l_{eff}} \tag{1}$$

where: r_c, effective capillary radius, is defined as the value that enables $2/r_c$ to obtain the maximum possible value of $(1/R_1+1/R_2)$ in wicks. As for a micro heat pipe with the compound structure of a sintered wick on trapezium-grooved-wick substrate, shown in Fig.1, r_c is mainly determined by its sintered wick, and its meniscus is a circle, $R_1=R_2$, so

$$\frac{2}{r_c}=\frac{1}{R_1}+\frac{1}{R_2}=\frac{2}{R_1}=\frac{2}{R_2}\quad\Rightarrow\quad r_c=R_1=R_2 \tag{2}$$

The model shown in Fig.2 can be referred to calculate the array of copper powders when the wick is sintered with no lucite powders being added, and the effective capillary radius of the micro heat pipe is as follows,

$$r_c=\frac{2}{3}\cdot 2r_s\sin\frac{\pi}{3}-r_s=\left(\frac{2}{\sqrt{3}}-1\right)r_s=0.1547r_s \tag{3}$$

It can be deduced from fig.2(b) that the number of copper powders on each circle is 2π(R+r$_s$)/2r$_s$, and from Fig.2(a), the center distance between adjacent layers of copper powders in axial direction is 2r$_s$sin(π/3). Therefore, void fraction for the sintered wick of a micro heat pipe is:

$$(4)\qquad \varepsilon_1 = 1 - \frac{\dfrac{2\pi(R+r_s)}{2r_s}\cdot\dfrac{l}{\left(2r_s\sin\dfrac{\pi}{3}\right)}\cdot\dfrac{4}{3}\pi r_s^3}{2\pi(R+r_s)\cdot 2r_s\cdot l} = 1-\frac{\pi}{3\sqrt{3}} = 39.54\%$$

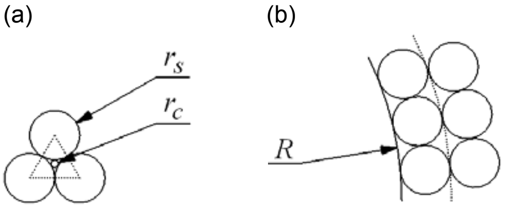


Fig.2 Schematic diagram for calculating effective capillary radius of wick sintered without lucite powders

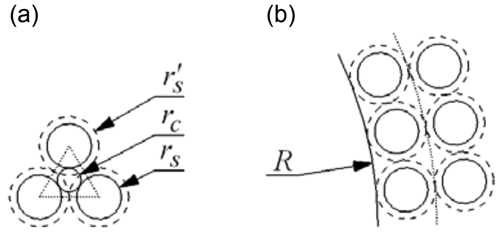


Fig.3 Schematic diagram for calculating effective capillary radius of wick sintered with lucite powders

When sintered with lucite powders, the array of copper powders in wick can be calculated through the model in Fig.3. From Fig.3 (b), it can be calculated that the number of copper powders on each circle is 2π(R+r$_s$′)/2r$_s$′, and from Fig.3(a), the center distance between adjacent layers of copper powders in axial direction is 2r$_s$′sin(π/3).Therefore, void fraction for a sintered wick is:

$$(5)\qquad \varepsilon_1 = 1 - \frac{\dfrac{2\pi(R+r_s')}{2r_s'}\cdot\dfrac{l}{\left(2r_s'\sin\dfrac{\pi}{3}\right)}\cdot\dfrac{4}{3}\pi r_s^3}{2\pi(R+r_s')\cdot 2r_s'\cdot l} = 1-\frac{\pi}{3\sqrt{3}}\left(\frac{r_s}{r_s'}\right)^3$$

That is,

$$(6)\qquad r_s' = \frac{1}{\sqrt{3}}\left(\frac{\pi}{1-\varepsilon_1}\right)^{\frac{1}{3}} r_s$$

So, effective capillary radius for a micro heat pipe with a sintered wick on trapezium-grooved-wick substrate is as follows,

$$(7)\qquad r_c = \frac{2}{3}\cdot 2r_s'\sin\frac{\pi}{3} - r_s = \left(\frac{2}{3}\left(\frac{\pi}{1-\varepsilon_1}\right)^{\frac{1}{3}} - 1\right) r_s$$

It can be deduced from Equation (4) and (5) that the minimum value for sintered-wick's void fraction is 39.54%. According to the experiments by Beijing Research Institute of Chemical Industry, void fraction of a micro heat pipe can amount to 70% if the wick is sintered with lucite powders, and its effective capillary radius is related to both void fraction and copper powders' size.

F$_l$ is acquired after considering fluid-flow pressure loss in different wicks and passages, so

$$(8)\qquad F_l = \frac{\mu_l}{KA_W\rho_l h_{fg}}$$

Where, permeability for the sintered wick of a compound wick is defined as follows,

$$(9)\qquad K_1 = \frac{r_s^2\cdot\varepsilon_1^3}{37.5(1-\varepsilon_1)^2}$$

For the trapezium grooves of a compound wick, its permeability is defined by the following equation,

$$(10)\qquad K_2 = \frac{2\varepsilon_2\cdot r_{hl}^2}{f_l\,\mathrm{Re}_l}$$

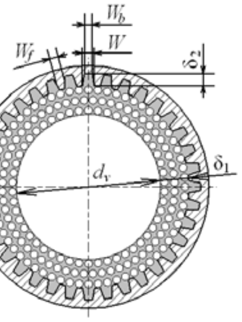


Fig.4 Schematic diagram for cross section of compound wick

As shown in Fig.4, for the trapezium grooves of the compound wick, it can be deduced that,

$$(11)\qquad \varepsilon_2 = \frac{n(W+W_b)\delta_2}{2\left(\pi\left(\dfrac{d_v}{2}+\delta_1+\delta_2\right)^2 - \pi\left(\dfrac{d_v}{2}+\delta_1\right)^2\right)} = \frac{n(W+W_b)}{2\pi(d_v+2\delta_1+\delta_2)}$$

$$(12)\qquad r_{hl} = \frac{2A_l}{C_l} = \frac{(W+W_b)\delta_2}{W_b+\sqrt{(W-W_b)^2+4\delta_2^2}}$$

The value of f$_l$Re$_l$ can be obtained from Fig.5, and when W≤2δ$_2$, α=W/2δ$_2$; when W>2δ$_2$, α=2δ$_2$/W.

As shown in Fig.4, for the sintered section of the compound wick, its cross-section area A$_{W1}$ is calculated as follows,

$$(13)\qquad A_{W1} = \pi\left(\frac{d_v}{2}+\delta_1\right)^2 - \pi\left(\frac{d_v}{2}\right)^2 = \pi(d_v+\delta_1)\delta_1$$

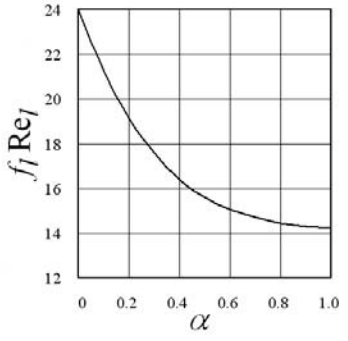


Fig.5 Drag coefficient in trapezium grooves in laminar-flow state

For the trapezium grooves of the compound wick, its cross-section area A$_{W2}$ is as follows,

$$(14)\qquad A_W = \pi\left(\frac{d_v}{2}+\delta_1+\delta_2\right)^2 - \pi\left(\frac{d_v}{2}+\delta_1\right)^2 = \pi(d_v+2\delta_1+\delta_2)\delta_2$$

So,

$$(15)\qquad F_l = \frac{\mu_l}{\left(\dfrac{\left(3\sqrt{3}r_s'^3-\pi r_s^3\right)^3(d_v+\delta_1)\delta_1}{112.5\sqrt{3}\pi r_s^4 r_s'^3} + \dfrac{n(W+W_b)^3\delta_2^3}{\left(W_b+\sqrt{(W-W_b)^2+4\delta_2^2}\right)^2 f_l\,\mathrm{Re}_l}\right)\rho_l h_{fg}}$$

For F_v, the Vapor-flow's frictional coefficient deduced by Chi after considering vapor pressure drop from dynamic pressure change and compressibility impact can be employed. F_v is related to vapor-flow's working condition, i.e., Re_v (vapor Reynolds number) and M_v (Mach number)

$$\mathrm{Re}_v = \frac{2r_{hv}Q}{A_v\mu_v h_{fg}} \tag{16}$$

For a circular micro heat pipe, $R_{hv}=d_v/2$, so

$$\mathrm{Re}_v = \frac{4Q}{\pi d_v\mu_v h_{fg}} \tag{17}$$

$$M_v = \frac{Q}{A_v\rho_v h_{fg}\sqrt{\gamma_v R_v T_v}} = \frac{4Q}{\pi d_v^2\rho_v h_{fg}\sqrt{\gamma_v R_0 T_v / M}} \tag{18}$$

if $Re_v \leqslant 2300$, $M_v \leqslant 0.2$, then

$$F_v = \frac{8\mu_v}{A_v r_{hv}^2\rho_v h_{fg}} = \frac{128\mu_v}{\pi d_v^4\rho_v h_{fg}} \tag{19}$$

if $Re_v \leqslant 2300$, $M_v > 0.2$, then

$$F_v = \frac{8\mu_v}{A_v r_{hv}^2\rho_v h_{fg}}\left(1+\frac{\gamma_v-1}{2}M_v^2\right)^{-1/2} = \frac{128\mu_v}{\pi d_v^4\rho_v h_{fg}}\left(1+\frac{\gamma_v-1}{2}M_v^2\right)^{-1/2} \tag{20}$$

if $Re_v > 2300$, $M_v \leqslant 0.2$, then

$$F_v = \frac{0.038\mu_v}{A_v r_{hv}^2\rho_v h_{fg}}\left(\frac{2r_{hv}Q}{A_v h_{fg}\mu_v}\right)^{3/4} = \frac{0.608\mu_v}{\pi d_v^4\rho_v h_{fg}}\left(\frac{4Q}{\pi d_v h_{fg}\mu_v}\right)^{3/4} \tag{21}$$

if $Re_v > 2300$, $M_v > 0.2$, then

$$F_v = \frac{0.038\mu_v}{A_v r_{hv}^2\rho_v h_{fg}}\left(\frac{2r_{hv}Q}{A_v h_{fg}\mu_v}\right)^{3/4}\left(1+\frac{\gamma_v-1}{2}M_v^2\right)^{-3/4} = \frac{0.608\mu_v}{\pi d_v^4\rho_v h_{fg}}\left(\frac{4Q}{\pi d_v h_{fg}\mu_v}\right)^{3/4}\left(1+\frac{\gamma_v-1}{2}M_v^2\right)^{-3/4} \tag{22}$$

So, for a circular micro heat pipe with the compound structure of a sintered wick on trapezium-grooved-wick substrate, mathematical model for its capillary limit is established as follows,

$$Q_{ca,\max} = \frac{\dfrac{2\sqrt{3}\sigma}{2r_s' - \sqrt{3}r_s} - \rho_l g d_v\cos\phi \pm \rho_l g l\sin\phi}{\left(\mu_l \middle/ \left(\left(\left(\dfrac{\left(3\sqrt{3}r_s'^3 - \pi r_s^3\right)^3(d_v+\delta_1)\delta_1}{112.5\sqrt{3}\pi r_s^4 r_s'^3} + \dfrac{n(W+W_b)^3\delta_2^3}{\left(W_b+\sqrt{(W-W_b)^2+4\delta_2^2}\right)^2 f_l\,\mathrm{Re}_l}\right)\rho_l h_{fg}\right) + F_v\right) l_{eff}\right)} \tag{23}$$

where: F_v is determined by Re_v and M_v.

In above equations, $Q_{ca,max}$-capillary limit of micro heat pipe (W); W- groove's top-width (m); W_b- groove's bottom-width (m); W_f- average width of groove ribs (m); δ_1-sintered thickness (m); δ_2-groove's depth (m); r_s-radius of copper powder (m); n-number of grooves; l_{eff}-effective length of micro heat pipe (m); l-total length of micro heat pipe (m); h_{fg}-latent evaporation heat of working fluid (J/kg); ρ_l-liquid density of working fluid (kg/m^3); ρv-vapor density of working fluid (kg/m^3); μ_v-vapor viscosity of working fluid (N•s/m^2); μ_l-liquid viscosity of working fluid (N•s/m^2); σ-liquid surface tension of working fluid (N/m); γ_v-specific heat ratio of vapor (for one-atom vapor, γ_v is 5/3; for double-atom vapor, γ_v is 7/5; and for multiple-atom vapor, γ_v is 4/3); R_v-gas constant for vapor of working fluid (J/kmol•K); R_0-universal gas constant (J/kmol•K); T_v-operating temperature of micro heat pipe (K); M-relative molecular mass of working fluid (g/mol); r_{hl}- hydraulic radius of the wick (m); r_{hv}-hydraulic radius of vapor cavity (m); r_c-effective capillary radius of the wick (m); d_v-diameter of vapor cavity in micro heat pipes (m); A_v-cross-sectional area of vapor cavity in micro heat pipe (m^2); g-acceleration of gravity (N/kg); Φ-inclined angle of micro heat pipe, i.e., the included angle between micro heat pipe and horizontal plane when mounted; F_l-frictional coefficient of liquid; F_v-frictional coefficient of steam-flow; R_1, R_2-principal curvature radius of meniscus (m); A_W-cross-sectional area of the wick(m^2); K-permeability of the wick; ε-permeability of the wick; $f_l Re_l$-drag coefficient in laminar flow; Re_v-Reynolds number of vapor; M_v - Mach number.

Thus it can be deduced from Equation (23) that when working fluid, operating temperature and effective length have been fixed, a micro heat pipe's capillary limit is related to the following factors: diameter of vapor cavity; the top-width, bottom-width, depth and the number of the grooves in trapezium-grooved-wick substrate; the size of copper powders, void fraction, sintered thickness in its sintered wick; working condition of vapor flow.

Performance Analysis of Capillary Limit

The performance testing is conducted under the following experimental conditions: micro heat pipes being horizontally placed; H_2O as working fluid; operating temperature of evaporator section being 60□; the lengths of evaporator, adiabatic and condenser sections being 50mm, 85mm and 100mm respectively; external diameter of the pipes 6mm; the thinnest wall thickness 0.2mm; trapezium grooves in sector structure with top-width 0.3mm and depth 0.25mm, and the thickness of the thinnest part between grooves being no less than 0.05mm; the wicks sintered with no lucite powders being added. Micro heat pipes with a trapezium-grooved wick, a sintered wick, and the compound wick of a sintered wick on trapezium-grooved-wick substrate are tested respectively to study their capillary limit performances. The experimental results are shown in Fig.6: Curve 1 shows capillary limit for a micro heat pipe with a trapezium-grooved wick having grooves of optimal structural parameters; Curve 2, 4, 6, 8 and Curve 10 demonstrate the relationships between capillary limit and sintered thickness for micro heat pipes with sintered wicks when particle sizes of copper powders are less than 80μm, in the range of 80-110μm, 110-140μm, 140-170μm, 170-200μm, respectively; Curve 3, 5, 7, 9 and Curve 11 demonstrate the relationships between capillary limit and sintered thickness for micro heat pipes having the compound structure of a sintered wick on trapezium-grooved-wick substrate when its grooves are of optimal structural parameters and particle sizes of copper powders are less than 80μm, in the range of 80-110μm, 110-140μm, 140-170μm, 170-200μm, respectively.

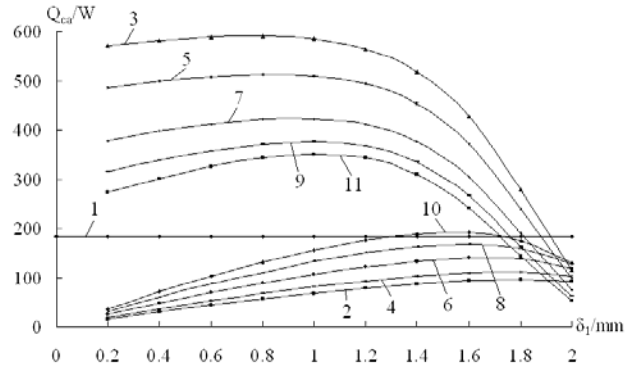


Fig. 6 Relationship between Capillary Limits and Wick Structures

Conclusion

For a micro heat pipe with a simplex sintered wick, choosing appropriate particle size of copper powders and sintered thickness can help obtain capillary limit superior to that of micro heat pipe with a simplex trapezium-grooved wick having optimal groove structures, and there exists an optimal sintered thickness that makes capillary limit obtain optimum value.

For a micro heat pipe with a compound wick having the structure of a sintered wick on trapezium-grooved-wick substrate, its capillary limit is evidently superior to that of a micro heat pipe with a simplex grooved wick or a simplex sintered wick. Capillary limit for a micro heat pipe with a simplex sintered wick increases with particle size of copper powders, whereas for a heat pipe with the compound structure of a sintered wick on trapezium-grooved-wick substrate, its capillary limit decreases with particle size of copper powders. Therefore, how to reduce backflow resistance of working fluid is crucial to increasing capillary limits. Furthermore, in order to avoid the grooves being filled, copper powders of the particle size larger than groove's top-width should be selected.

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