Thermal performance of sintered miniature heat pipes

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Abstract Investigation has been carried out on the thermal performance of sintered miniature heat pipes with 3 mm outer diameter. In the theoretical analysis, the influence of wick structure parameters is determined by using the theory of capillary limitation. As a result, the degree of importance is found to be as follows: porosity, powder diameter and thickness of wick structure. In the experiments, heat pipes with sintered dendritic copper powder wicks were fabricated and tested. The maximum heat transfer rate is about 13 W with an effective heat pipe length of 20 cm. By adopting the formulae developed for both sintered spherical powder and fiber and adjusting their proportion, the agreement between experimental results and prediction is found to be quite good in the tested operation temperature range.

List of symbols

- **A** area
- **C** constant
- **d** diameter
- **k** thermal conductivity
- **L** length (m)
- **p** pressure
- **Q, q** heat transfer rate
- **R** thermal resistance
- **Re** Reynolds number
- **μ** absolute viscosity
- **r_{h,v}** hydraulic radius of vapor flow pass
- **r_s** pore radius
- **T_v** vapor temperature
- **ψ** angle
- **λ** latent heat of vaporization
- **ε** wick porosity
- **ρ** density
- **σ** surface tension

Subscripts

- **a** adiabatic section
- **c** condenser
- **e** evaporator
- **eff** effective
- **g** gravity
- **l** liquid
- **v** vapor
- **o** outer
- **i** inner
- **w** wick

1 Introduction

Efficient cooling of electronic components is of vital importance to the successful operation of modern electronic devices. The amount of heat generated in these electronic devices must be dissipated in order to maintain the operating temperature limit. Heat pipes as a cooling strategy have demonstrated to be a promising alternative to traditional cooling schemes and offer the possibility of high local heat transfer rates. As an example, the total heat that generates from the current CPU and other components in notebook computer can be amounted in excess of 30 W. With this amount of heat, the conventional cooling using fin heat sink and/or fan may not be a feasible solution without compromising the size and weight of notebook computer. Heat pipes with an outer diameter of about 3–4 mm have been demonstrated to be able to solve the problem in the cooling of notebook computer (Nguyen, 1998).

According to the concept of micro heat pipe proposed by Cotter (1965), a heat pipe with a hydraulic diameter on the order of 10 μm is considered to be a micro heat pipe. Traditionally, if the hydraulic diameter of a heat pipe is on the order of 1 mm, it is referred to as a miniature heat pipe. A comprehensive review of micro/minature heat pipes and their limitations was given by Cao et al. (1993). Detailed descriptions and modeling for micro/minature heat pipes can also be found from Faghri (1995). Miniature heat pipes have the characteristics of conventional heat pipes and are capable of handling higher heat transfer rate than the micro heat pipes.

There can be found three typical types of wick structures for miniature heat pipes. These include axially grooved, wrapped screen and sintered metal powder. In an experimental study, Huang et al. (2000) conducted performance tests with commercially available miniature heat pipes with different wick structures. They found that the...
heat pipes with sintered powder wicks have the best thermal performance among the three. Although there are some studies about the design and performance test of sintered wick heat pipes, for example Pruzan et al. (1991), they are mostly limited to the discussion of heat pipes with a larger diameter. No systematic investigations have been carried out concerning the parametric study of sintered wick structure for miniature heat pipes. Therefore the present study attempted to investigate the thermal performance of miniature heat pipes with sintered copper powder wick structure. Emphasis was put on the study of wick structure. In the theoretical analysis, the influence of wick structure parameters was determined by using the theory of capillary limitation. In the experiments, heat pipes with different sintered copper powder wicks were fabricated and tested. Based on the experimental results, prediction formulae for miniature heat pipes with sintered dendritic power wick were proposed.

**Theoretical analyses of the heat transfer limitations**

Theoretical analyses of the heat transfer limitations were firstly carried out for copper-water miniature heat pipes with sintered spherical copper powder wick. The heat pipes have an outer diameter of 3 mm (tube wall thickness is 0.3 mm) and a length of 200 mm. The heat transfer limitations include boiling, viscous, sonic, entrainment and capillary limitations. The predictive relations can be found from Faghri (1995) or Peterson (1994). The calculated heat transfer limitations are illustrated in Fig. 1 as a function of operating temperature, which is also the temperature at the adiabatic section of the heat pipe. As can be seen, the actual heat transfer limit is always the capillary limit. This means also that the maximum capillary pressure which heat pipes can achieve must be greater than or equal to the summation of all kinds of pressure drop. Considering the effect of gravity, the balance equation in heat pipes can be expressed as follows:

\[
\Delta P_c \geq \Delta P_l + \Delta P_v + \Delta P_g
\]  

(1)

After some mathematical manipulation, the capillary limitation for heat pipes with sintered spherical powder wick can be expressed as:

\[
q \leq \frac{2\sigma /0.41r_g - \rho g d_0 \cos \theta \pm \rho g L \sin \theta}{37.5(1 - \varepsilon)^2 \mu_1/r_g^2 \varepsilon^3 A_w \lambda \rho_1 + C(f \Re_v \mu_v/2(\varepsilon_{h,v})^2 A_v \rho_v \lambda/L_{eff}}
\]  

(2)

Besides the maximum heat transfer rate, thermal resistance is also important in the evaluation of the thermal performance of heat pipes. After an order of magnitude analysis, the total resistance can be written as:

\[
R = \frac{\ln(d_0/d_1)}{2\pi} \left( \frac{1}{L_{c}k_p} + \frac{1}{L_{c}k_p^2} + \frac{1}{L_{c}k_{eff}} + \frac{1}{L_{c}k_{eff}^2} \right)
\]  

(3)

The variation of the maximum transfer rate with wick thickness is shown in Fig. 2. The powder diameter is the curve parameter. In this example, the porosity is fixed at 50% and the operating temperature 60 °C. An optimum wick thickness around 0.5 mm appears for each of the three powder diameters. Optimum values occur due to the influence of wick thickness on both liquid and vapor flows. A larger powder diameter results in an increased maximum heat transfer rate. The thermal resistance increases monotonically with increasing wick thickness.

The effect of porosity on the maximum heat transfer rate is shown in Fig. 3 with the maximum heat transfer rate plotted against powder diameter for two wick thickness. As revealed, porosity has a profound influence on the