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Effects of sintered structural parameters on reducing the superheat level in heat pipe evaporators

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ABSTRACT

For applications involving high heat density and low heat load, this study investigates the correlation among superheat, evaporative heat transfer, and the sintered structural parameters of heat pipe evaporators. In the experiments, structural parameters, such as powder size, powder shape, and structural thickness, all influence evaporative heat transfer performance. To measure the evaporative heat flux at low superheat levels, this study developed an advanced facility integrated with a temperature data acquisition system, a low heat loss chamber, a directly sintered design, and a pressure controllable environment. Among the combinations of the structural parameters, evaporation could occur stably at the superheat of only 1.90 K when the structural parameters are composed of 45-μm dendritic powder and 751-μm thickness, moreover, the evaporative heat flux could still achieve 8.91 W/cm^2 at this superheat level. To enhance evaporative heat transfer and lower corresponding superheat, this study suggests that an improved result can be attained by having a powder shape of inter-pores, smaller powder size, and thinner structural thickness. However, these parameters are constrained by practical applications, such as the effects of permeability, capillary effect, and dry-out prevention. In conclusion, the total amount of thin film, working fluid level in structure, and effective thermal conductivity may be the factors affecting evaporative heat transfer and corresponding superheat in evaporators.

1. Introduction

Heat pipes have been widely applied to solve various cooling problems, including heat recycling in heavy industries, cooling solutions for power conversion, performance improvement of integrated circuits (ICs), and life ensuring of light-emitting diodes (LEDs). A large amount of latent heat exchange effectively provides superior heat transfer ability. Furthermore, the ability of heat dissipation has recently attracted attentions because of high heat density and low heat load applications, such as high-power LEDs, which generate a small amount of heat through a small heat transfer area. For example, the heat density of a 1 W LED mounted on a metal core printed circuit board (MCPCB) with 12.57 mm^2 heat transfer area is approximately 79,554 W/m^2, which requires heat pipes to work under conditions of small temperature differences.

A heat pipe consists of evaporator, adiabatic, and condenser sections. The performances of the adiabatic and condenser sections are correlated with the exterior heat exchange and the capillary effect. The capillary effect drives transportation of working fluid back to the evaporator. In low heat load applications, the working fluid is consumed slowly in evaporators. The effects of wick permeability are less crucial at this low flow rate of working fluid. Moreover, to achieve the ability of low superheat level heat transfer, thin-film evaporation in the evaporator is essential in high-performance heat pipes [1]. Combined with the mechanism of thin-film evaporation, thin working fluid films easily absorb heat and change phases, which in turn allow heat pipes to operate under less temperature differences, and reduce thermal resistances of cooler modules.

For anti-gravity purposes, internal surfaces of heat pipes are covered with wick structures. Wang and Catton [2] indicated that these structures not only improve capillary effect for the working fluid supply but also significantly increase the evaporative surface area and improve evaporative heat transfer. Wang et al. [3] developed a model with idealized structural geometries to investigate thin film properties. In this model, heat transfers from heat sources to working fluid through solid structures. Among the interface areas between structures and working fluid, the thin films at tipped meniscuses are the major contributor of heat flux [4,5]. These thin films contribute more than 50% of the overall heat flux and 90% of the interfacial temperature decrease.

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Nomenclature

A	heat flow area of meter bar
T	temperature
T_1	temperature at position 1
T_2	temperature at position 2
T_3	temperature at position 3
T_c	structural temperature of cold side
T_{c1}	temperature at position 1 of cold meter bar
T_{c2}	temperature at position 2 of cold meter bar
T_h	structural temperature of hot side
T_{h1}	temperature at position 1 of hot meter bar
T_{h2}	temperature at position 2 of hot meter bar
T_{base}	temperature at the base of sintered structure
$T_{\text{saturated}}$	saturated temperature
k	thermal conductivity
L	distance
$L_{\text{base-1}}$	distance between positions T_{base} and T_1
L_{1-3}	distance between positions T_1 and T_3
L_h	distance between positions T_{h1} and T_{h2}
L_{he}	distance between positions T_h and T_{h1}
L_c	distance between positions T_{c1} and T_{c2}
L_{ce}	distance between positions T_c and T_{c1}
Q	total heat flow through meter bar
U	uncertainty

Subscripts

base	base position of sintered structure
base-1	position base and position 1
e	effective thermal conductivity

Typical wick structures consist of grooves, meshes, or sintered powder. At the same structural porosity, the more and smaller pores produce more contact interfaces between working fluid and solid structures, thus promoting the length and total area of thin film simultaneously. The sintered powder structures provide many small pores, which characteristic is related to powder parameters and sintering processes. Because these small pores exist, the mechanism of thin-film evaporation occurs obviously in sintered powder structures. The characteristics of higher fluid pumping effect and lower conductive thermal resistance also indicate that sintered powder structures [6] are suitable to be used as the wick structure of heat pipes.

Davis and Garimella [7] built a thermosyphon chamber with sintered structure to simulate a flat plate heat pipe. Using deionized water as the working fluid, the structure of 106–150 μm powder sizes had greater apparent heat transfer coefficients than did those of 45–75 μm and of 250–355 μm. Using the same working fluid, Weibel et al. [8] developed a novel facility to simulate a flat plate heat pipe, selecting spherical powder to prepare specimens of 45–75 μm, 106–150 μm, and 250–355 μm in powder size. Each powder size was prepared to three levels of structural thicknesses, approximately 600 μm, 900 μm, and 1200 μm after sintering process. The specimen of 106–150 μm powder size and 1200-μm thickness had the lowest thermal resistance.

Based on the pressure decrease throughout porous structures, Wang and Peterson [9] developed an analytical model to simulate evaporators of flat plate heat pipes. Their results showed that increasing the structural thickness increased the superheat level and conductive resistance, but it simultaneously enhanced critical heat flux. Ranjan et al. [10] presented a model of idealized powder shapes and arrangements to compare the influence of powder shapes, such as parallel rectangular ribs, horizontal parallel cylinders, vertically aligned cylinders, and spheres, on thin-film evaporation. Their numerical data showed that the area of thin film increased with the decreasing porosity. Closely packed spheres had the highest evaporative heat transfer performance. Minimizing the structural thickness reduced the thermal resistance, which caused by the poor effective thermal conductivity of the porous structures.

Wong et al. [11] developed a simulated operating flat plate heat pipe to investigate the thermal resistance of sintered powder structures. Selecting deionized water as the working fluid, they showed that a specimen made of fine spherical powder had lower thermal resistance than a coarse powder did. However, the structure of fine spherical powder had a lower effective thermal conductivity than did the structure of coarse powder. The effective thermal conductivity of sintered structures might not be the major factor influencing evaporation and boiling. They also indicated [12] that the maximal heat flux for water was far greater than those of methanol and acetone, which might be caused by the evaporating water layers being the thinnest. The evaporation of water activated at superheat of over 3 K in the evaporator of a sintered hybrid mesh screen structure, which was composed of 100 and 200 mesh screens to form a structural thickness of 0.26 mm.

Hanlon and Ma [1] proposed a study by considering conductive resistance through wicks. Their numerical results showed that reducing the powder size could enhance the evaporative heat transfer. Moreover, they concluded that when the thin film regions were maximized, it could reach the highest evaporating heat transfer coefficient. Ranjan et al. [13] developed a microscale model of thin-film evaporation in ideally arranged structures. Heat flux did not change significantly with various powder shapes. However, heat flux decreased with increasing porosity because of the reduction of thin-film amount.

According to previous studies, sintered powder properties, such as powder size, powder shape, and structural thickness all influence evaporative heat transfer in evaporators. Kang et al. [14] proposed that performances of heat pipes should not be determined according to heat flux only, but also according to the corresponding superheat at a certain level of heat flux. Reducing superheat and maintaining sufficient heat flux are practical for occasions of high heat density and low heat load. To obtain and compare the heat fluxes of sintered powder structures at low superheat levels, this study presents a novel facility that integrates a temperature data acquisition system, a low heat loss chamber, a directly sintered design, and a pressure controllable environment. Various sizes and shapes of powder were fabricated into sintered structures. Correlating with superheat, heat fluxes at these structures were measured. These experimental results suggest that structural parameters can enhance the evaporative heat transfer and reduce the corresponding superheat in the evaporator of heat pipes.

2. Experimental methods

Fig. 1 shows a diagram of the experimental design. The powder structure was directly sintered on a heat flux meter bar. In this design, heat transfers from the 300-W main heater to the heat flux meter bar, the sintered powder structure, and working fluid, thus constituting the main heat transfer path. The heat flux and temperatures were measured at the meter bar. Outside the main heat