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Experimental study of evaporative heat transfer in sintered powder structures at low superheat levels

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ABSTRACT

Evaporation at the evaporator of a heat pipe plays an important role in its overall heat transfer performance, especially at low superheat levels. Used sintered powder structures as wicks, this study investigated the correlations between superheat levels and heat fluxes. The parameters included powder sizes of 45 μm, 75 μm, 150 μm, and powder shapes of spherical, dendritic. A two-part measurement in this study consisted of effective thermal conductivity and evaporative heat transfer. For the experiment of evaporative heat transfer, an apparatus consisting of a thermal guard test chamber, a direct sintering design, a pressure control loop, and a data acquisition system was used to measure heat fluxes and corresponding superheat levels. The effective thermal conductivity measurement showed that smaller powder sizes achieved higher effective thermal conductivities for both powder shapes. Spherical powder structures achieved twice the effective thermal conductivity of dendritic powder ones for each powder size. Furthermore, the evaporative heat transfer measurement showed that the heat fluxes increased proportionally with the superheat between 2 and 6 K. At the same superheat level, structures of smaller powder size and dendritic powder shape achieved higher heat fluxes. In conclusion, the effect of thin-film evaporation may be the primary factor affecting evaporative heat transfer among these structural parameters.

1. Introduction

Heat pipes are widely used in cooling solutions that demand high heat transfer performance or heat dissipation ability. The heat dissipation ability has recently attracted attention in high heat density cooling applications such as high-power light-emitting diodes (LED), which generate a small amount of heat through an extremely small heat transfer area. Thus, heat pipes must operate under conditions with low superheat levels.

Heat pipes consist of evaporator, adiabatic and condenser sections. At the saturated temperature, the working fluid enclosed in heat pipes absorbs and releases heat through a phase-change mechanism. A large amount of latent heat provides superior thermal conductivity ability. In heat pipes, wick structures are often used to help transport the working fluid from the condenser to the evaporator. Wang and Catton [1] indicated that these structures not only improve the capillary effect of working fluid transportation, but also significantly increase the evaporative surface area and improve evaporative heat transfer.

Common wick structures include grooves, meshes, and sintered powder. Sintered powder structures have the most pores and the largest evaporative surface area, greatly enhancing the mechanism of thin-film evaporation. Moreover, sintered powder structures have [2] a high capillary ability and a low conductive thermal resistance. Through the structure, heat transfers into the working fluid, and then the working fluid changes from liquid to gaseous phase. This process contributes dominant portions of entire thermal resistance in the evaporator. To increase the heat transfer performance and reduce the superheat level of the evaporator, this study compared the parameters of sintered powder structures, including the powder size and shape.

According to the heat conduction model [3] of a grooved wick, the micro region of working fluid surface is at the tip of the interface area between the structure and working fluid. The working fluid near the interface has a meniscus shape that is governed by surface tension forces and adhesion forces. Sartre et al. [4] developed a thin-film evaporation model for a micro heat pipe. They indicated that most of heat transfers through the micro region of working fluid meniscus in the evaporator. The heat transfer rate is high in the micro region, leading to a significant temperature decrease.

Wang et al. [5,6] developed a numerical model with an idealized structural geometry to investigate the thin-film characteristics in evaporative heat transfer. In their model, heat transfers from the solid structure to the working fluid. The thin liquid film

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Nomenclature

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

Subscripts

etc	effective thermal conductivity
eht	evaporative heat transfer

at the tip of the meniscus contributes the majority of the heat flux, including more than 50% of the overall heat flux and 90% of the interfacial temperature decrease. Hohmann and Stephan [7] used temperature-sensitive liquid crystals (TLC) to measure the temperature distribution of an evaporating liquid meniscus. Their experimental results are similar to the previous numerical models, in which the tip of the meniscus leads to a significant temperature decrease and evaporative rate.

Hanlon and Ma [8] presented numerical analyses and experiments indicating that the thin-film evaporation mechanism occurred at the upper surface of a horizontally oriented wick structure. Thin working fluid films absorb heat and change phase easily, which are essential enhancing the evaporative heat transfer and achieving low superheat ability. Their numerical results showed that reducing the powder size could enhance the evaporative heat transfer. Furthermore, selecting an appropriate structural porosity could promote thin-film evaporation at the upper surface of a sintered powder structure.

Ranjan et al. [9,10] presented a micro-scale model with idealized powder shapes and arrangements to compare the evaporative heat transfer between powder shapes under saturated vapor conditions. Various powder shapes, including parallel rectangular ribs, horizontal parallel cylinders, vertically aligned cylinders, and packed spheres, represent the wicks commonly used in heat pipes, such as rectangular grooves, wire mesh, vertical micro-wires, and sintered powder structures, respectively. They indicated that the thin-film region of the liquid meniscus contributed most of the evaporative heat transfer. Their numerical results showed that the closely packed spheres had the highest evaporative heat transfer performance. A higher heat flux resulted from a smaller porosity as the thin-film area increased. The heat flux did not change significantly with various powder shapes. However, this closely packed arrangement maximized flow resistance and reduced permeability.

Davis and Garimella [11] built a thermosyphon chamber to measure the thermal resistance of a sintered copper powder structure. De-ionized water was used as the working fluid. They sintered three specimens in various powder sizes. The structure of a powder size ranging from 106 to 150 μm achieved lower thermal resistance than either 45-to-75-μm powder or 250-to-355-μm powder. They concluded that the thermal resistance decreased sharply to 0.01 K/W under higher input powers. Moreover, an optimum porosity and powder size could help achieve the lowest thermal resistance.

Weibel et al. [12] developed a method to measure the heat flux and thermal resistance in sintered powder wicks with working fluid feeding. They sintered spherically shaped powders sized 45–75 μm, 106–150 μm, and 250–355 μm. Each powder size was prepared for three levels of structural thickness approximately 600, 900, and 1200 μm after sintering. When using de-ionized water as the working fluid, experimental results showed that the specimen of 106-to-150-μm powder size and 1200-μm structural thickness had the lowest thermal resistance. An optimum powder size and porosity minimized the thermal resistance because of the increased heat transfer area and the decreased vapor flow resistance.

Wong et al. [13] simulated a flat plate heat pipe to investigate the evaporative resistance of sintered powder structures. They used de-ionized water as the working fluid, and their experimental results showed that the specimen of fine spherical powder had lower thermal resistance than that of coarse spherical powder or irregular powder. On the contrary, the effective thermal conductivity measurements of these structures showed that the specimen of fine spherical powder had a lower effective thermal conductivity than that of coarse spherical powder. Thus, they concluded that the effective thermal conductivity of sintered structures might not influence evaporation significantly. Using the visualization technique, they found that no nucleate boiling occurred when the heat flux was smaller than 100 W/cm^2. Thin-film evaporation is the major phase-changing mechanism below this 100 W/cm^2 heat flux level.

Wong et al. [14] prepared heat pipes with water, methanol, and acetone to compare the performance of various working fluids. The wicks in the heat pipes were sintered hybrid copper screens of 100 and 200 meshes. Their experimental results showed that the maximum heat flux of water was far greater than that of methanol and acetone. Using the visualization technique, they observed that the thinnest water layer had the greatest effect on the experimental results. And for water, evaporation occurred stably at the corresponding superheat level of 3 K.

Kang et al. [15] developed a micro heat pipe fabrication and measurement method. They indicated that heat pipe performance should not only be determined by the heat flux, but also by the corresponding superheat level. Researchers have recently used superheat and thermal resistance as evaluating indices. For applications involving high heat density and low heat load, working at a low superheat level with adequate heat flux ability is more practical.

According to previous studies, sintered powder structural parameters, including powder size and powder shape, all affect