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Experimental investigation of vapor chambers with different wick structures at various parameters

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ABSTRACT

In this study, copper water vapor chambers (VCs) with two wick structures (copper foam and copper powder) are manufactured. An air-cooled test rig is designed to investigate the thermal performance. For copper-foam-based VCs (CFVCs), samples with filling rates ranging from 50% to 190% are manufactured; for copper-powder-sintered VCs (CPVCs), copper powders with particle sizes ranging from 66 ± 9 μm to 265 ± 85 μm are sintered. The VC samples are tested at heat loads ranging from 60 W to 200 W under 20 mm × 20 mm heating area; CFVC with 120% filling rate and CPVC with 66 ± 9 μm particle size are also tested at heat loads ranging from 60 W to 140 W under 10 mm × 10 mm heating area, to evaluate the effect of heating area. Response time, temperature uniformity of the condenser zone, and thermal resistance are used as performance indicators. Results show that CFVCs exhibit good temperature uniformity and that CPVCs exhibit low thermal resistance. CFVCs with moderate filling rates ranging from 90% to 120% outperform those with other filling rates; CPVCs with fine-particle powders outperform those with coarse-particle powders. Furthermore, an increased heating area enhances the performance.

1. Introduction

The thermal management of electronic components has become one of the key points in component design because of increasing heat flux. Centralized heat can deteriorate component performance and reliability. In general, heat should be spread to a large surface area for effective heat removal [1]. Heat pipes are now widely used to transfer high heat flux from a centralized heat source to a large heat sink. However, heat pipes generally transport heat in one dimension. Two-dimensional heat transfer is more common in electronic components. Another phase-change heat transfer device, namely, vapor chamber (VC), is developed for this requirement. VCs can swiftly spread heat from a hot spot to a large condenser area [2] and facilitate heat removal. Given the low thermal resistance and good temperature uniformity of VCs, this type of heat transfer device is commonly used in high heat flux components such as LEDs, CPUs, and hard disk drives [3].

A VC is a vacuum device with a wick structure and charged with a two-phase working fluid. In general, the bottom plate serves as the evaporator and the top plate serves as the condenser, i.e., gravity-assisted mode. The liquid at the evaporator zone absorbs heat and evaporates into vapor. Vapor condenses at the condenser zone and releases latent heat. The condensed liquid is recycled back to the evaporator zone through the wick structure. The wick structure provides capillary pressure for the fluid circulation and ensures the stabilized thermal performance. Various wick structures with different materials, morphologies, and geometries have been developed for VCs to enhance performance. Wang and Peterson [4] conducted experimental and analytical investigation on sintered copper screen mesh VC. The heat transfer capacity was influenced by the wire diameter, mesh number, layer number, tilt angle and compact coefficient of the wick. The parameters were optimized to enhance the performance. The best prototype can reach 123 W and 19.1 W/cm^2. Chen et al. [5] compared the performance of aluminum VCs with radial grooved and sintered powder wick structures. Their results indicated that lower thermal resistance and better temperature uniformity coexisted in the sintered powder wick because of the larger capillary pressure. However, grooved VC was easier to manufacture and cost lower than sintered powder VC. Ji et al. [6] developed copper-foam-based VCs (CFVCs) for high heat flux applications. Copper foam wick structure

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Nomenclature

A	area, m^2
d	diameter, mm
m	mass, g
Q	heat load, W
R	thermal resistance, K/W
T	temperature, °C
V	volume
x	distance, mm

Greek symbols

ε	porosity,%
Δ	difference
δ	thickness, mm
ξ	filling rate,%

Subscripts

avg	average
bp	bottom plate
c	condensation
dry	dry sample
cw	condenser wick
e	evaporation
ew	evaporator wick
h	heat source
l	liquid
max	maximum
p	plate
s	spread
sat	saturated
tp	top plate
v	vapor
vc	vapor chamber
w	wick
wet	wet sample
λ	conduction

has large porosity and high permeability. Thus, the use of this structure can achieve high temperature uniformity. A new parameter called surface thermal resistance was defined to characterize temperature uniformity on the condenser and evaporator. Heat transfer limit was not reached at the heat flux of 216 W/cm^2. Ju et al. [7] reported that several hybrid wick structures, including vertical columnar arteries, converging lateral arteries, and biporous powder structures. They combined distributed high-permeability liquid supply structures with thin evaporation layers to achieve low thermal resistance and high heat transfer capacity Comparable thermal performance with 350 W/cm^2 critical heat flux and 0.075 K/W cm^2 was attained. The effect of particle size was also assessed. The optimal particle size of 59 μm was proved to have the best performance. Chang et al. [8] devised loop-type vapor chamber with 0.5 mm interior height. The composite wick structure of the evaporator was constructed by the 0.05 mm deep parallel/staggered square grooves with a copper woven wire mesh sintered above the staggered grooves. The performance was investigated in vertical/horizontal orientations. The flow phenomenon within the wick structure were observed by a CCD system. Vapor chamber performed better at vertical orientation, especially at high-heat-flux condition. It worked at a heat flux of 632 W/cm^2. Sigurdson et al. [9] fabricated a titanium thermal ground plane. The groove wick was coated by nanoporous Titania to enhance wettability. Moreover, multi-scale wicks were combined by laser welding. This new thermal ground plane was able to work at a heat load of 1 kW. Furthermore, some researchers also conducted hydrophilic/hydrophobic treatment and coating on the wick structures to enhance wettability [10,11].

The performance of VCs is also determined by the filling rate of the working fluid. In general, heat transfer at the evaporator zone is achieved by conduction through the liquid layer and evaporation. Thus, evaporation resistance is dominated by the effective conductivity of the wick, together with the thickness of the evaporating film [12]. Chen and Chou [13] investigated flat plate heat pipes with various filling rates. Excess liquid leads to liquid retention and thick liquid film at the evaporator zone. High evaporation resistance can be attained accordingly. By contrast, insufficient liquid easily induces partial dry out. Maximum heat flux can be largely reduced. They also considered that phase change only take place at a sufficiently high heat load. At a low heat load, flat plate heat pipes act like Al heat sink and transfer heat mainly by conduction. Attia and El-Assal [14] investigated vapor chambers with different working fluid at different filling rates. For water, the optimal filling rates are 10% and 30%. At exceed filling rate, heat transfers firstly by conduction through thick liquid film. The effective thermal conductivity can be reduced remarkably. Chen et al. [15] used nanofluids as working fluid and investigated the effects of filling rate. Both too high and too low filling rates can increase thermal resistance. The flat heat pipes perform best at the optimal filling rate. Therefore, obtaining an optimal filling rate is necessary to enhance the thermal performance. For accurate filling, Ababneh et al. [16] proposed a novel charge station and investigated the filling rate error during charging and vacuuming. Small amount of fluid can be lost during vacuuming.

The heating area significantly affects performance because of the existence of spreading resistance in VCs. On one hand, Tang et al. [17] investigated the resistance against different heating areas. The equivalent resistance was used to measure the performance. The VC performed better under small heat source than under large heat source because of the decreased evaporation resistance. Furthermore, concentrated heating mode performed better compared with the disperse mode because heat spreading was reduced. On the other hand, Wong et al. [12] considered that thermal resistance can be reduced by increasing the heating area. Sideward conductive spreading was obvious under a small heating area. The two distinct statements are both reasonable. However, a systematic measurement is required to verify the rationality.

Although VCs have been frequently investigated in many aspects, integrated measurements of VCs with different parameters are lacking. This study aims to exhibit the thermal performance of VCs with various parameters, including wick structure, filling rate, particle size of copper powder, and heating area, and attain the optimal parameters for application. VCs sintered with copper powder wicks and copper foam wicks are fabricated. The filling rates range from 50% to 190%. The particle sizes of the copper powders are vary from 66 ± 9 μm to 265 ± 85 μm. The effects of the heating area are also evaluated. The response time, temperature uniformity on the condenser surface, and thermal resistance are compared.