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Feasibility study of a vapor chamber with a hydrophobic evaporator substrate in high heat flux applications

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ABSTRACT

A novel vapor chamber was fabricated to assess the feasibility of combining hydrophobic and hydrophilic wettabilities in the evaporator to optimize thermal performance. The proposed vapor chamber included a separate layer of hydrophilic sintered copper powder wick that was pressed in intimate contact with a hydrophobic evaporator substrate with a water contact angle around 140°. The contact between the wick layer and the evaporator was provided by sixteen posts implemented on the condenser, which pushed the wick layer toward the evaporator. The thermal performance was evaluated based on the thermal resistance, source temperature, and temperature uniformity across the condenser. Results were compared with those of a baseline vapor chamber that was fabricated by sintering hydrophilic copper particles on a hydrophilic copper evaporator substrate. The wick size and the copper powders used to fabricate the wick structure were the same in both vapor chambers. Overall, the performance of the proposed vapor chamber was lower than that of the baseline vapor chamber, possibly due to microscale gaps between the wick layer and the evaporator substrate. However, the concept of using a hydrophilic wick to force liquid in contact with a hydrophobic evaporating surface could enable a new family of vapor chambers with low thermal resistance, if more efficient techniques for improving the mechanical contact between the wick layer and the evaporator are introduced through further detailed research. If successful, the fabrication cost of vapor chambers would be reduced as well, by using prepared wick structures, which do not require high-temperature sintering processes on evaporators.

1. Introduction

Rapid shrinkage in the size of electronic devices along with increases in their power have necessitated developing compact thermal management solutions to remove large amounts of heat from electronic devices, maintain the maximum temperature of the devices below acceptable limits, and improve the temperature uniformity across the devices. While such requirements cannot be met by active cooling systems due to their external power and space requirements, two-phase passive cooling systems are appropriate thermal management solutions for today's shrinking electronic devices.

A vapor chamber is one of the most efficient passive two-phase cooling devices to spread heat from a localized heat source to a much larger area. The low profile form factor and low thermal resistance of vapor chambers make these thermal management solutions intriguing and suitable for spreading heat within small-size electronic devices. Fig. 1 describes the basic operation of a vapor chamber. Basically, a vapor chamber is a compact and sealed metal enclosure that is partially filled (charged) with an appropriate amount of working fluid, and consists of three main components as (i) the evaporator, (ii) the wick structures, and (iii) the condenser. Heat is transferred from a localized heat source to the evaporator, and evaporates the working fluid. The resulting vapor pressure drives the vapor outward and away from the evaporator to the condenser where the vapor condenses. Then, the liquid (condensed vapor) is pumped to the evaporator through capillary forces generated by the wick structure [1,2]. The wick structures provided by posts facilitate operation of the vapor chamber against gravity. The cycle repeats itself as long as a temperature gradient exists between the evaporator and condenser portions of the vapor chamber.

Research on vapor chambers has received considerable attention, and there are a significant number of studies on to how to improve thermal performances of vapor chambers. Wong et al. [3] designed a novel vapor chamber by replacing the conventional wicked condenser wall with a plate that included fine parallel grooves. Ji et al. [4] proposed a copper foam as the wick structure and achieved the heat flux of 216 W/cm^2 with the minimum thermal resistance of 0.09 K/W. Li et al. [5] demonstrated improved temperature uniformity on the condenser of the vapor chamber with a copper foam as the wick structure. Tang

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Nomenclature

d_{col}	Diameter of copper column (excluding wicks) on the condenser (m)
d_p	Post diameter (m)
H_{in}	Distance from the evaporator to the condenser, without wick structures (m)
H_p	Post height (m)
K	Thermal conductivity of the vapor chamber enclosure (W/mK)
L_e	Evaporator length (m)
L_s	Pedestal length (m)
L_{VC}	Vapor chamber length (m)
m_l	Mass of water (kg)
q	Heat flux (W/cm^2)
Q_{input}	Electrical input heat (W)
$R_{s\text{-}ref}$	Source thermal resistance (K/W)
R_t	Total thermal resistance (K/W)
R_{VC}	Interior thermal resistance of the vapor chamber (K/W)
$R_{w,c}$	Thermal resistance due to the envelope wall at the condenser (K/W)
$R_{w,e}$	Thermal resistance from the heat source to the evaporator (K/W)
t_c	Condenser thickness (m)
t_e	Thickness of evaporator substrate (m)
t_s	Distance from the pedestal hole to the exterior side of evaporator (m)
t_{wick}	Evaporator wick thickness (m)
$T_{c,\text{avg}}$	Average temperature at the exterior side of condenser (K)
T_i	Inlet water temperature to the cold plate (K)
T_o	Outlet water temperature from the cold plate (K)
T_{ref}	Reference temperature (inlet temperature to the cold plate) (K)
T_s	Source temperature at the pedestal (K)
$\dot{V}$	Volume flow rate (m^3/s)
Greek symbols	
η	Fill ratio
ρ_l	Water density (kg/m^3)

et al. [6] achieved low thermal resistances by designing a multi-artery vapor chamber. Ju et al. [7] proposed efficient vapor chambers incorporating hybrid wicks consisting of a low thermal resistance evaporator and efficient liquid supply structures, and dissipated heat fluxes over 350 W/cm^2 over a heating area of 1 cm^2. Peng et al. [8] proposed a leaf-vein-like fractal architecture as the wick structure to improve the thermal performance of the vapor chamber. Also, extensive research has been performed to develop more efficient vapor chambers by focusing on other aspects of the vapor chamber rather than the wick structure, such as leveraging dropwise condensation on the condenser [9,10], selecting the working fluids [1], using phase change materials [11], integrating cooling devices on the condenser [12], and fabrication of vapor chambers by using materials with low coefficients of thermal expansion [13].

In recent high-performance commercial and military electronics that require heat spreaders with capabilities of dissipating high heat fluxes (over 500 W/cm^2 from an area smaller than 1 cm^2), the wall superheat induces nucleate boiling in the evaporator wicks [14,15]. The performance of boiling heat transfer is best characterized by two main thermal performance parameters, the heat transfer coefficient (HTC) which reflects the vapor chamber's primary thermal resistance at a given level of superheat, and the critical heat flux (CHF), which reflects the heat flux limit of operation before device failure [16]. In a vapor chamber, the thermal resistance that is proportional to the inverse of HTC is a commonly used performance parameter instead of HTC. It has been widely accepted that surfaces with homogeneous wettability typically do not simultaneously enhance CHF and HTC, as such, while a homogeneously hydrophilic surface delays the CHF by rewetting the surface, it delays nucleate boiling incipience and reduces the HTC at superheat temperatures inferior to the onset of nucleate boiling. In this mode, the best optimization strategies involve thinning the wick and relying on evaporation as the mode of evaporating liquid. On the other hand, while a uniformly hydrophobic surface exhibits earlier onset of nucleate boiling and enhances the HTC at low superheat temperatures, it reduces the CHF due to pronounced bubble coalescence on the surface [17,18].

Generally, the sintered powder wick is the most widely used wick structure in industrial production due to its ability to generate higher capillary pressure compared with other types of wick structures such as micro-grooved wicks and screen mesh wicks [6,19]. This type of wick structure is a homogeneously hydrophilic material, and is fabricated by sintering metal particles with high thermal conductivity, mostly copper and aluminum, on copper and aluminum evaporator substrates, respectively. However, both native copper and aluminum surfaces in chemical equilibrium with their working fluids are considered hydrophilic materials [20]. Therefore, this study is performed to investigate the thermal performance of hydrophobic materials in the evaporator regions of vapor chambers.

In the present study, the feasibility of a hydrophobic evaporator substrate to enhance nucleation sites and, in turn, enhance heat transfer coefficients (i.e. decrease thermal resistance) in a vapor chamber is investigated for high heat fluxes. The capillary pressure is provided by a layer of hydrophilic sintered copper powder wick that is firmly pressed into the hydrophobic evaporator. The wick layer is pushed in place toward the evaporator by implemented posts on the condenser, in order to minimize the gap between the wick layer and the substrate. The

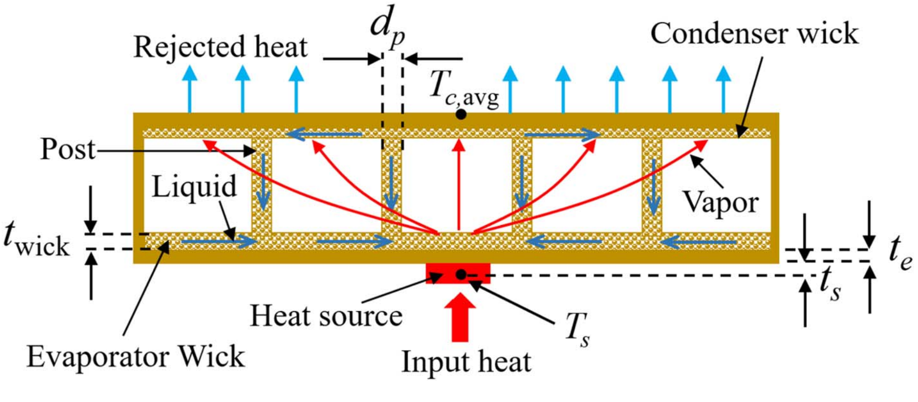

Fig. 1. Schematic of the basic operation of a vapor chamber.