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Patterning the condenser-side wick in ultra-thin vapor chamber heat spreaders to improve skin temperature uniformity of mobile devices

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ABSTRACT

Vapor chamber technologies offer an attractive approach for passive heat spreading in mobile electronic devices, in which meeting the demand for increased functionality and performance is hampered by a reliance on conventional conductive heat spreaders. However, market trends in device thickness mandate that vapor chambers be designed to operate effectively at ultra-thin (sub-millimeter) thicknesses. At these form factors, the lateral thermal resistance of vapor chambers is governed by the saturation temperature/pressure gradient in the confined vapor core. In addition, thermal management requirements of mobile electronic devices are increasingly governed by user comfort; heat spreading technologies must be designed specifically to mitigate hot spots on the device skin. The current work considers these unique transport limitations and thermal requirements encountered in mobile applications, and develops a methodology for the design of vapor chambers to yield improved condenser-side temperature uniformity at ultra-thin form factors. Unlike previous approaches that have focused on designing evaporator-side wicks for reduced thermal resistance and delayed dryout at higher operating powers, the current work focuses on manipulating the condenser-side wick to improve lateral heat spreading. The proposed condenser-side wick designs are evaluated using a 3D numerical vapor chamber transport model that accurately captures conjugate heat transport, phase change at the liquid–vapor interface, and pressurization of the vapor core due to evaporation. A biporous condenser-side wick design is proposed that facilitates a thicker vapor core, and thereby reduces the condenser surface peak-to-mean temperature difference by 37% relative to a monolithic wick structure.

1. Introduction

A vapor chamber passively transports heat from a localized source to a much larger heat rejection surface. Vapor chambers are used to mitigate the temperature rise of sensitive components in the cooling of electronics by spreading heat away from local hot spots. The sealed vapor chamber (Fig. 1) encloses a working fluid. Vapor is generated at the evaporator section located over the heat source and driven into the rest of the chamber. The vapor condenses on the inner surface of the opposing wall where heat is rejected. A porous wick passively pumps the condensed liquid back to the evaporator. Mobile electronic devices such as smartphones and tablets are trending toward lower thickness and higher functionality, leading to higher heat generation density from active components. It is not practical to use active air cooling methods or embed large, finned heat sinks, due to the size constraints. Thus, to minimize the temperature rise of components and surfaces to be cooled by natural convection, heat must be spread uniformly over the device surface. Ultra-thin vapor chambers may offer a viable solution for passive spreading within mobile devices.

Recent research in vapor chamber design has focused on high-performance commercial and military electronics that require heat spreaders capable of dissipating high heat fluxes (over 500 W/cm^2) from small areas [1]. At such high heat fluxes, the wall superheat typically induces nucleate boiling in the evaporator wicks. Vapor chamber designs for these applications focus on tailoring the evaporator wick to tolerate operation in the boiling regime without suffering from dryout, in order to take advantage of the reduced evaporator thermal resistance that is characteristic of boiling heat transfer. Wick design strategies in the literature have analyzed the ability of wicks to evacuate vapor bubbles generated during boiling in order to avoid dryout and reduce the thermal resistance [2]. This has been achieved through patterning the wick structure [3] or using biporous wicks [4] to enable continuous feeding of liquid to the evaporator under boiling conditions. Alternate strategies aim to reduce the evaporator wick thermal resistance and preserve operation in the evaporative regime (avoiding boiling) using thin

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Nomenclature

V	velocity [m s^{-1}]
x, y, z	Cartesian coordinates [m]
r	radius [m]
u	x-velocity [m s^{-1}]
u_{eff}	effective x-velocity [m s^{-1}]
v	y-velocity [m s^{-1}]
w	z-velocity [m s^{-1}]
P	pressure [Pa]
P_{cap}	capillary pressure [Pa]
K	permeability [m^2]
K_{eff}	effective permeability [m^2]
C_E	Ergun's coefficient [–]
T	temperature [K]
C	specific heat capacity [J kg^{-1} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
k_{eff}	effective thermal conductivity [W m^{-1} K^{-1}]
h_{fg}	enthalpy of vaporization [J kg^{-1}]
A	area [m^2]
m	mass flow rate [kg s^{-1}]
R	gas constant [J kg^{-1} K^{-1}]
Q	power (rate of heat flow) [W]
h	convection coefficient [W m^{-2} K]
t_{wick}	wick thickness [m]
W	groove width [μm]
n	extrapolation coefficient [–]
n_t	number of transient steps between extrapolations [–]
d	sintered copper particle diameter [m]

Greek symbols

ρ	density [kg m^{-3}]
ϕ	porosity [–]
μ	dynamic viscosity [Pa s]
σ	accommodation coefficient [–]
γ	surface tension [N m^{-1}]

Subscripts

i	wick–vapor interface
0	reference
solid	solid properties
liquid	liquid properties
vapor	vapor properties
wick	wick properties
s	condenser surface
m	mean
amb	ambient

Superscripts

$''$	per unit area

nanostructure arrays [5,6] or thin monoporous copper particles with arterial liquid return paths [7,8].

The requirements of vapor chambers for mobile thermal management are in stark contrast to these high-power-density applications. For mobile applications, vapor chambers must be ultra-thin, on the order of less than 1 mm, and typically operate at significantly lower power inputs and heat fluxes. At such thicknesses and heat fluxes, the thermal resistances across the vapor chamber wall and wick are very low while the lateral temperature gradient in the confined vapor core governs the heat spreading resistance [9]. Boiling is not likely to occur in the evaporator wick. Thus, the design focus for mobile applications must shift away from the evaporator wick structure and toward the layout of the wick and vapor domains. There is a fledgling body of literature that has investigated the design of ultra-thin heat pipes or vapor chambers. Aoki et al. [10] fabricated heat pipes with thickness less than 1 mm by simply flattening traditional cylindrical grooved heat pipes. Ding et al. [11] developed a titanium-based vapor chamber with a thickness of 0.6 mm that included a uniform array of microfabricated titanium pillars as the wick structure. Oshman et al. [12] fabricated a 1 mm-thick heat pipe with a hybrid copper mesh and micropillared wick encased in a liquid–crystal polymer chamber. Lewis et al. [13] fabricated a 0.5 mm-thick flexible heat pipe made of copper-cladded polyimide, with a copper mesh wick. In each of these studies, the wick was designed to allow dissipation of the maximum possible power and/or minimum evaporator-to-condenser thermal resistance at an ultra-thin form factor.

A unique objective of the vapor chamber design process for mobile applications is condenser-side surface temperature uniformity, in contrast to a sole objective of reducing evaporator temperature. The condenser surface is in close proximity to the user's skin and may not propagate hotspots generated within the device. Overly high device skin temperature is often the factor which forces limits on mobile electronic device performance, rather than the junction temperatures [14].

The current work focuses on the design of ultra-thin vapor chambers for improved condenser-surface temperature uniformity; consideration of this application-driven design constraint is

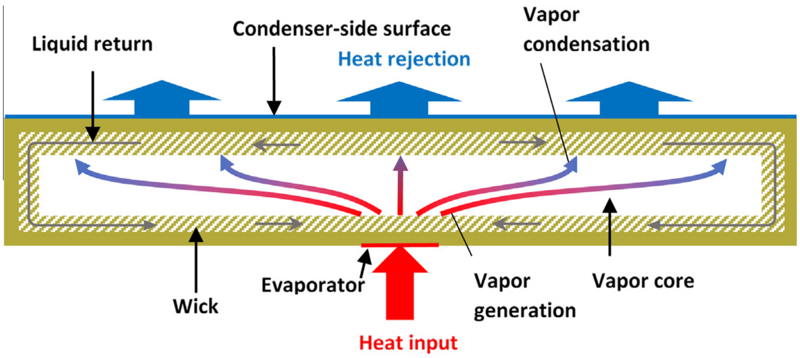

Fig. 1. Schematic diagram of vapor chamber operation.