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Working-fluid selection for minimized thermal resistance in ultra-thin vapor chambers

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ABSTRACT

The behavior of a vapor chamber is strongly coupled to the thermophysical properties of the working fluid within. It is well known that these properties limit the maximum power (heat load) at which a vapor chamber can operate, due to incidence of the capillary limit. At this limit, the available capillary pressure generated within the wick structure balances the total pressure drop incurred along the path of fluid flow within the wick. A common figure of merit prioritizes working fluids that maximize this capillary-limited operating power. The current work explores working fluid selection for ultra-thin vapor chambers based on a thermal performance objective, rather than for maximized power dissipation capability. A working fluid is sought in this case that provides the minimal thermal resistance while ensuring a capillary limit is not reached at the target operating power. A resistance-network-based model is used to develop a simple analytical relationship for the vapor chamber thermal resistance as a function of the working fluid properties, operating power, and geometry. At small thicknesses, the thermal resistance of vapor chambers becomes governed by the saturation temperature gradient in the vapor core, which is dependent on the thermophysical properties of the working fluid. To satisfy the performance objective, it is shown that the choice of working fluid cannot be based on a single figure of merit containing only fluid properties. Instead, the functional relationship for thermal resistance must be analyzed taking into account all operating and geometric parameters, in addition to the thermophysical fluid properties. Such an approach for choosing the working fluid is developed and demonstrated.

1. Introduction

Portable electronic device platforms such as smartphones and tablets are trending toward thinner, more compact designs with greater embedded functionality (which in turn leads to more waste heat generation from active components). Due to constraints on power consumption and size, it is not practical to use active air cooling methods, or large heat sinks that enhance heat rejection area, to dissipate heat. It is therefore critical to spread heat generated within the device as uniformly as possible over the entire outer skin, where it must be dissipated by natural convection. A vapor chamber passively spreads heat from a localized heat source to a larger heat rejection surface. The sealed chamber contains a working fluid and is lined on its inner surface with a porous wick. Vapor is generated at the evaporator section. The vapor is driven outward and away from the evaporator, and condenses on the inner surface of the opposing wall. The wick passively pumps the condensed liquid back to the evaporator. Ultra-thin vapor chambers offer a viable heat spreading solution in portable electronic device platforms, and can alleviate hot spots on the surface.

A few studies in the literature have focused on the fabrication of ultra-thin vapor chambers to meet this application need. Aoki et al. [1] fabricated heat pipes with thicknesses of less than 1 mm using a process that simply flattened traditional cylindrical grooved heat pipes. Ding et al. [2] fabricated a titanium-based vapor chamber with a thickness of 0.6 mm, which included a uniform array of microfabricated titanium pillars as the wick structure. Lewis et al. [3] fabricated a flexible heat pipe of 0.5 mm thickness made of copper-cladded polyimide, with a copper mesh wick.

The choice of a working fluid is crucial in the design of such vapor chambers. Given the principle of operation of a vapor chamber (a two-phase thermodynamic cycle), the thermophysical properties of the fluid significantly impact its performance. One conventional ‘figure of merit’ used for guiding the choice of working fluid prioritizes maximizing the operating power. A vapor chamber can operate at a given power only if the capillary pressure available to drive the liquid through the porous wick is larger than the pressure drop; beyond this power level, the vapor chamber will reach the capillary limit and the evaporator will be starved of liq-

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Nomenclature

a_1, a_2	constants in k_{vap} relation [−]
A	factor $\left(\frac{\phi^3}{f(1-\phi)^2}\right)$ [−]
C	arbitrary constant [m $W^{-0.5}$]
d_p	particle diameter [m]
f	factor in Carman–Kozeny relation [−]
F_s	factor of safety [−]
h_{fg}	specific enthalpy of vaporization [kJ kg^{-1}]
k_{vap}	vapor core effective conductance [W K^{-1}]
k_{wick}	wick effective conductivity [W m^{-1} K^{-1}]
K	permeability [m^2]
m	ratio of particle diameter with effective pore radius (d_p/r_{eff}) [−]
$\dot{m}$	mass flow rate [kg s^{-1}]
M_l	liquid figure of merit $\left(\frac{\gamma\rho_l h_{fg}}{\mu_l}\right)$ [W m^{-2}]
$M_{l,min}$	minimum required liquid figure of merit [W m^{-2}]
M_v	vapor figure of merit $\left(\frac{P_v\rho_v h_{fg}^2}{\mu_v R_g T_v^2}\right)$ [W m^{-3} K^{-1}]
n	number of particle diameters along the wick thickness [−]
P	pressure [Pa]
P_v	vapor pressure [Pa]
P_{cap}	capillary pressure [Pa]
Q	power [W]
r	radial coordinate [m]
r_{eff}	effective pore radius [m]
R	radius of vapor chamber [m]
R_e	radius of evaporator [m]
Re	Reynolds number [−]
R_g	gas constant [J kg^{-1} K^{-1}]
t	working thickness [m]
t_{vap}	vapor core thickness [m]
t_{wick}	wick thickness [m]
T	temperature [K]
u_r	radial velocity [m s^{-1}]
U_r	radial velocity scale [m s^{-1}]
z	axial coordinate [m]

Greek symbols

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

Subscript

l	liquid phase
v	vapor phase
vap	vapor core domain
$wick$	wick domain

uid. This figure of merit is derived by equating the capillary pressure and the pressure drop incurred, which results in a single grouping of thermophysical liquid properties [4] given by

$$M_l = \frac{\gamma\rho_l h_{fg}}{\mu_l}. \quad (1)$$

A higher value for this figure of merit indicates that the vapor chamber can operate at a larger power prior to reaching the capillary limit. A high surface tension yields a higher capillary pressure, while higher density and latent heat reduce the liquid volume flow rate (for a given power input); a lower viscosity leads to a lower pressure drop in the wick. Other less common vapor chamber operational limits include a sonic limit [5] where high vapor velocities lead to choked flow, or an entrainment limit [5] where liquid is entrained into the vapor flowing in the opposite direction by shear forces, starving the evaporator of liquid flow. Along with these phenomenological limits, there are additional practical constraints on working fluid selection. A high fluid vapor pressure at the operating temperature may breach mechanical limits on the pressure that can be supported by the vapor chamber walls. The working fluid also must be chemically compatible with other materials used to construct the vapor chamber.

Recent technology development has focused on vapor chamber designs for high-performance electronics requiring the dissipation of high heat fluxes (over 500 W/cm^2) [6]. The thermal resistance of such vapor chambers, as well as of more conventional vapor chambers with a comparatively thick form factor, is dominated by the resistance across the wick at the evaporator. The design of such vapor chambers typically focuses on the evaporator wick, and aims to reduce thermal resistance in the evaporative [9,10] or boiling regimes [7,8]. The thermophysical properties of the fluid have a comparatively smaller effect on the thermal resistance in these vapor chamber designs compared to the capillary limit. Fluid selection can therefore be based on the liquid figure of merit alone to maximize the operating power for such thick high-heat-flux dissipating vapor chamber devices.

The thermal resistance of vapor chambers becomes dominated by the temperature gradient in the vapor core as the thickness is reduced. An ultra-thin vapor core induces a high pressure gradient, and hence a high saturation temperature gradient. This thermal resistance is governed by the fluid thermophysical properties. Such a high temperature gradient along the vapor core leads to a high temperature variation along the condenser surface. Patankar et al. [11] experimentally observed this variation in temperature along the condenser surface when characterizing the performance of ultra-thin vapor chambers; the vapor chamber resistance changed with operating temperature due to changes in the thermophysical properties with temperature. Yadavalli et al. [12] analyzed the performance limitations of a thin heat pipe using a resistance-network-based model. In the limit of low power (where the capillary limit is not of concern), the authors developed a figure of merit based on the thermophysical fluid properties that affect the vapor core thermal resistance, given as

$$M_v = \frac{P_v\rho_v h_{fg}^2}{\mu_v R_g T_v^2}. \quad (2)$$

A higher value for this figure of merit corresponds to a lower thermal resistance in the vapor core.

While these two prevailing figures of merit are useful in the extreme cases where the exclusive concern is either maximizing total heat dissipation power (M_l) or minimizing vapor chamber thickness (M_v), a more practical design objective is to select a working fluid that provides the minimal thermal resistance while ensuring that the capillary limit is not reached at the target operating power for a given vapor chamber size. These figures of merit are also developed using modeling frameworks that intrinsically assume that the vapor chamber design is held constant when comparing across fluids; however, this may not be an appropriate comparison if the design could be tuned to take advantage of favorable characteristics unique to each candidate fluid. For example, the overall thickness may be constrained, but the vapor chamber wick

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