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Modulated wick heat pipe

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Abstract

In heat pipes, modulation of evaporator wick thickness provides extra cross-sectional area for enhanced axial capillary liquid flow and extra evaporation surface area, with only a moderate increase in wick superheat (conduction resistance). This modulated wick (periodic stacks and grooves over a thin, uniform wick) is analyzed and optimized with a prescribed, empirical wick superheat limit. A thermal-hydraulic heat pipe figure of merit is developed and scaled with the uniform wick figure of merit to evaluate and optimize its enhancement. The optimal modulated wick for the circular and flat heat pipes is found in closed-form expressions for the viscous-flow regime (low permeability), while similar results are obtained numerically for the viscous-inertial flow regime (high permeability which is also gravity sensitive). The predictions are compared with the experimental result of a prototype (low permeability, titanium/water pipe with the optimal design) heat pipe which gives a scaled figure of merit of 2.2. Good agreement is found between the predicted and measured performance. The maximum enhancement is limited by the pipe inner radius (tapering of the stacks), the wick effective thermal conductivity, and the prescribed wick superheat limit.

Keywords: Modulated wick; Optimal design; Figure of merit; Heat pipe; Critical heat flux; Superheat

1. Introduction

The modulation of heat pipe wick thickness assists axial capillary liquid flow, while limiting the increase in the wick superheat that accompany thicker, uniform wicks [1]. Fig. 1 shows the modulated wick structure with heat and liquid flow paths in the evaporator, evaporation surface (sites) and a prototype modulated wick heat pipe. The thick wick portion of the modulated wick (stacks) decreases the liquid flow resistance, and the thin wick portion (i.e., grooves) reduces the wick superheat. This modulation of the evaporator is used to design high performance heat pipes for microgravity applications [2,3]. The modulated wick has capillary arteries (with an azimuthally regular interval) connected to a thin, uniform wick lining the tube, which feeds liquid to the evaporator. The liquid is vaporized on the entire surface of the modulated wick where the influx heat is exhausted, and moves back to the condenser as vapor phase to make a circulation loop. One method of fabrication uses rectangular-shaped mandrels to create grooves in a thick, uniform wick heat pipe. Due to the rectangular-shaped groove between adjacent stacks and the pipe curvature, each stack has a trapezoidal geometry. When the initial thick wick is deep, this results in a triangle shape, and the height of each stack has the maximum value limited by the base width of the stack. The modulated wick can also be extruded when the base width is below several particle diameters.

Fig. 2(a) and (b) show the enhancement of the critical heat flow rate for the prototype heat pipe tested in this paper. The prototype heat pipe has a $R/\delta = 17.4$, and titanium is used for pipe and working fluid is water. Fig. 2(a) shows the enhancement by the modulated wick heat pipe geometry up to the wick superheat limit. The enhancement

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Nomenclature

A	(cross-section) area (m^2)
C_E	Ergun coefficient
c_p	specific heat (J/kg)
D^d	dispersion coefficient (m^2/s)
g	gravitational acceleration (m/s^2)
Δh_{lg}	enthalpy of vaporization (J/kg)
L	length or height (m)
L_s^*	dimensionless height of stack
K	thermal conductivity (W/m K)
K	permeability (m^2)
$\dot{M}$	mass flow rate (kg/s)
N	number
P	pressure (Pa)
Q	heat transfer rate (W)
Q^*_{CHF}	dimensionless critical heat transfer rate ($=Q_{CHF}/Q_{CHF,u}$)
R	radius of pore or meniscus or bubble (m)
R	pipe radius (m) or thermal resistance (W/K)
R^*	dimensionless radius of pipe ($=R/\delta$)
T	temperature (K)
U	velocity (m/s)
V	specific volume (m^3/kg)
W	width (m)

Greek symbols

α	constant in thermal resistance model
δ	wick thickness (m)
δ'	equivalent wick thickness (m)
φ	angle (deg)
μ	viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

a	adiabatic section
b	bubble
c	capillary or critical or condenser
CHF	critical heat flux
e	evaporator
f	flat heat pipe
g	gas or gap
k	conduction
l	liquid
lg	phase change, or saturation
n	discrete number, normal
p	pore
r	radial
s	surface or stack or solid particle
u	uniform wick
v	vapor
w	wick
$\perp$	lateral

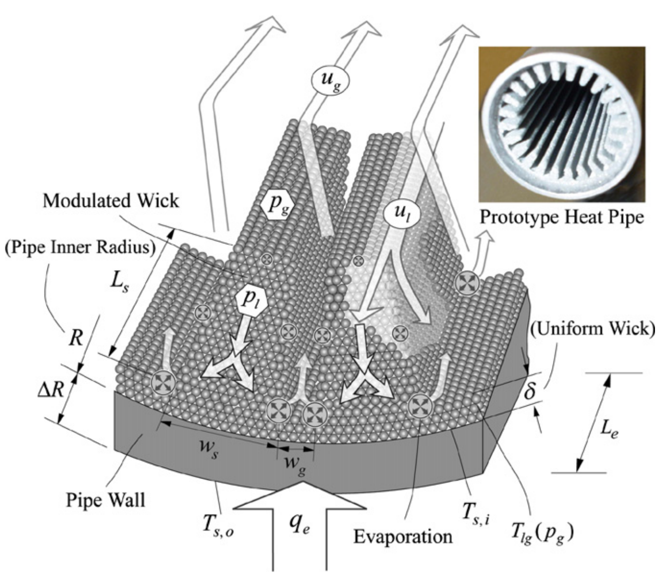

Fig. 1. Schematic of the modulated wick geometry in the evaporator, and the liquid/vapor flow paths and evaporation surface (sites). The photograph of the prototype modulated wick heat pipe is also shown.

of a flat heat (very large radius) pipe is also shown as an asymptotic upper limit. The critical heat flow rate (dryout limit) for modulated wick heat pipe Q_{CHF} is scaled using that for non-modulated (i.e., thin, uniform) wick $Q_{CHF,u}$, while wick superheat is normalized by the maximum allowable (a prescribed value) wick superheat. The enhancement is attributed to a decrease in the liquid flow resistance by expanding cross-sectional area of the modulated wick until the axial liquid pressure drop reaches the capillary limit. The critical heat flow rate enhances as the pipe radius increases, since a tapered stack geometry (this is in part dictated by fabrication) becomes rectangular, reaching the flat heat pipe ($R/\delta \rightarrow \infty$) limit. Hereafter, $R^* = R/\delta$. The maximum predicted enhancement of the prototype heat pipe (with a wick thermal conductivity $\langle k \rangle = 4.4$ W/m K) is $Q_{CHF}/Q_{CHF,u} = 4.3$, since the critical heat flow is also controlled by an effective thermal resistance. Fig. 2(b) shows further enhancement is possible with larger wick effective thermal conductivity. For the prototype (circular) heat pipe geometry, using titanium–water, the enhancement is $Q_{CHF}/Q_{CHF,u} = 3.1$, while it can increase up to $Q_{CHF}/Q_{CHF,u} = 7$ by a copper–water combination. Hereafter, $Q^*_{CHF} = Q_{CHF}/Q_{CHF,u}$.

Here, we study the modulated heat pipe without curvature effect proposed in [1] to arrive at the optimal wick structure design. The pipe curvature affects the liquid flow cross-sectional area as well as the wick thermal resistance.