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Boiling heat transfer in a hydrofoil-based micro pin fin heat sink

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Abstract

Flow boiling of R-123 in a hydrofoil-based micro pin fin heat sink was investigated. Average two-phase heat transfer coefficients were obtained over effective heat fluxes ranging from 19 to 312 W/cm^2 and mass fluxes from 976 to 2349 kg/m^2 s. The paper presents a flow map, which divides the data into three flow pattern regions: bubbly, wavy intermittent and spray-annular flows. Heat transfer coefficient trends and flow morphologies were used to infer boiling heat transfer mechanisms. Existing conventional scale correlations for circular tubes resulted in large scatter and were not able to predict the heat transfer coefficients accurately.

Keywords: Pin fin; Microchannels; Cross-flow; Flow pattern; MEMS; Boiling

1. Introduction

Research concerning heat transfer in microsystems has been growing rapidly in the last decade. As part of this endeavor, single-phase flows [1–10] and boiling flows [11–28] have been topics of great interest. Initial studies were dedicated to reveal the thermal and hydrodynamic characteristics of microchannel flows, but recently emerging reports extend this effort to other configurations like pin fins [29–35]. The pin fin shapes employed in these studies were primarily adopted from conventional scale heat sinks like circular [36,37], square [38], diamond [39], and rectangular [40].

Single-phase flow over pin fin heat sinks has been extensively investigated over the years [41–44] and is still a topic of active research [45–57]. Since boiling is often a desired heat transfer mode, it has also been visited in the context of fins. Pin fins are commonly used to enhance pool boiling heat transfer, and various studies have been performed in conventional scale to provide knowledge concerning the boiling phenomenon [58–73]. Honda and co-workers in several recent publications [74–76] utilized successfully micro pin fins to augment the critical heat flux (CHF) conditions in electronic components.

In conventional scale, cross-flow boiling over circular tube bundles has been meticulously studied; collected data and correlations pertaining to large scale systems are available in numerous archival publications [77–100]. Onset of nucleate boiling [78,79], heat transfer coefficients [80–89], critical heat flux conditions [90–94], pressure drop [95–98], and flow morphologies [99,100] have been obtained and correlated, mainly for circular tube bundles. For example, Jensen and Hsu [81] conducted a parametric study of boiling heat transfer in a horizontal tube bundle and reported an increase in local heat transfer coefficient with increasing heat flux, pressure and mass velocity, but found the effect of quality to be minor. Gupta et al. [84] and Gupta [89] studied the effects of heat flux, mass velocity, and tube geometry on local boiling heat transfer of water in small horizontal tube bundles at low velocities. However, the data presented by them were limited to low mass velocities (<9 kg/m^2 s). Chen-type heat transfer coefficient

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Nomenclature

a_1, a_2, a_3	parameters in correlation 8
A_{b}	base area (surface area without pin fins), m^2
$A_{\mathrm{c,fin}}$	fin cross-sectional area, m^2
A_{fin}	total fin surface area, m^2
A_{min}	minimum cross-sectional area, m^2
A_{p}	planform area (surface area of silicon block), m^2
A_{t}	total heat transfer area ($A_{\mathrm{b}} + \eta_f A_{\mathrm{fin}}$), m^2
b_1, b_2, b_3, b_4	constants in correlation 9
Bo	Boiling number based on q''_{w}, $Bo = q''_{\mathrm{w}}/(Gh_{\mathrm{FG}})$
Bo_{ch}	Boiling number based on the average mass velocity, $Bo_{\mathrm{ch}} = q''_{\mathrm{w}}/(G_{\mathrm{av}}h_{\mathrm{FG}})$
c_{p}	specific heat at constant pressure, kJ kg^{-1} °C^{-1}
Cor	correction factor in correlation 6
d	chord thickness, m
d_{h}	channel hydraulic diameter, m
E	enhancement factor
f_{f}	friction factor
F	two-phase Reynolds number factor
g	gravitational constant, m s^{-2}
G	mass velocity based on the minimum cross-sectional area, kg m^{-2} s^{-1}
G_{av}	mass velocity based on the entire cross-sectional area, kg m^{-2} s^{-1}
h_{FG}	latent heat of vaporization, J kg^{-1}
$\bar{h}_{\mathrm{sp}}$	average single-phase heat transfer coefficient at a definite flow rate, W m^{-2} °C^{-1}
$\bar{h}_{\mathrm{tp}}$	average two-phase heat transfer coefficient at a definite flow rate, W m^{-2} °C^{-1}
H	channel height, fin height, m
h_{av}	average heat transfer coefficient at a definite heat flux, W m^{-2} °C^{-1}
j_{G}	superficial gas velocity, Gx/ρ_{G}, m s^{-1}
j_{L}	superficial liquid velocity, $G(1-x)/\rho_{\mathrm{L}}$, m s^{-1}
k_{fin}	thermal conductivity of the fin (silicon), W m^{-1} °C^{-1}
k_{fluid}	thermal conductivity of the fluid, W m^{-1} °C^{-1}
k_{s}	thermal conductivity of the silicon block, W m^{-1} °C^{-1}
L	channel length, m
m	constant
M	number of data points at a fixed mass velocity
$\dot{m}$	mass flow rate, kg s^{-1}
m_{f}	fin parameter in Eq. (2)
M_{t}	total number of data points
MAE	mean absolute error
N_{column}	number of pin fins in a single column
N_{row}	number of pin fins in a single row
N_{t}	total number of pin fins
Nu	Nusselt number
Nu_{ch}	Nusselt number based on the channel hydraulic diameter
$\overline{Nu}$	average Nusselt number at a definite Reynolds number
Nu_{av}	average Nusselt number at a definite heat flux
P	electrical power, W
p_{e}	exit pressure, kPa
P_{fin}	pin fin perimeter, m
Pr	Prandtl number
q''	effective heat flux, W cm^{-2}
q''_{w}	heat flux based on the heat transfer surface area of the device, W cm^{-2}
$\dot{Q}_{\mathrm{loss}}$	heat loss, W
R	electrical resistance, Ω
Re	Reynolds number based on the chord thickness, $Re = Gd/\mu$
Re_{ch}	Reynolds number based on the channel hydraulic diameter, $Re_{\mathrm{ch}} = G_{\mathrm{av}}d_{\mathrm{h}}/\mu$
S	suppression factor
S_{L}	longitudinal pitch, m
S_{T}	transverse pitch, m
t	thickness of the silicon block, m
T	temperature, °C
$\overline{T}$	average surface temperature, °C
T_{e}	exit temperature, °C
$\overline{T}_{\mathrm{heater}}$	average heater surface temperature °C
T_{i}	inlet temperature, °C
U	quantity under consideration
W	channel width, m
x	mass quality
x_{e}	exit mass quality
X_o	bubble growth parameter, m
X_{vt}	Martinelli parameter
We	Weber number, $We = G^2 d/(\sigma\rho)$
We_{ch}	Weber number based on the channel hydraulic diameter, $We_{\mathrm{ch}} = G_{\mathrm{av}}^2 d_{\mathrm{h}}/(\sigma\rho)$

Greek symbols

β	aspect ratio
η_{f}	fin efficiency
ϕ_{L}^2	two-phase friction multiplier
μ	viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
σ	surface tension, N m^{-1}

Subscripts

amb	ambient
av	average
ch	channel
CHF	critical heat flux
e	exit
f	fluid
fin	fin
G	gas
i	inlet
j	index in Eqs. (3) and (4)
L	liquid