International Journal of Heat and Mass Transfer 123 (2018) 172–191

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Investigation of subcooled and saturated boiling heat transfer mechanisms, instabilities, and transient flow regime maps for large length-to-diameter ratio micro-channel heat sinks

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ARTICLE INFO

Article history:
Received 29 September 2017
Received in revised form 31 January 2018
Accepted 5 February 2018

Keywords:
Micro-channel
Subcooled flow boiling
Saturated flow boiling
Two-phase heat sink
Two-phase instabilities
Dryout

ABSTRACT

This study investigates the interfacial behavior and heat transfer mechanisms associated with flow boiling of R-134a in a micro-channel test module. The test module features 100 of 1×1 mm^2 square micro-channels. Large length of micro-channels used (609.6 mm) is especially important to capturing broad axial variations of both flow and heat transfer behavior. The fluid is supplied to the test module in subcooled state to enable assessment of both the subcooled boiling and saturated boiling regions. The study employs a combination of temperature measurements along the test module and high-speed video to explore crucial details of the flow, including dominant flow regimes, flow instabilities, and downstream dryout effects. It is shown that, unlike macro-channel flows, where flow regimes can be clearly demarcated, flow regimes in micro-channels are associated with transient fluctuations that are induced by flow instabilities. The dominant flow behavior and associated dryout effects are characterized with the aid of a new transient flow regime map and a dryout map, respectively. Two sub-regions of the subcooled boiling region, partially developed boiling (PDB) and fully developed boiling (FDB), are examined relative to dominant interfacial and heat transfer mechanisms, and a previous correlation is identified for accurate prediction of the heat transfer coefficient for both PDB and FDB. The saturated boiling region is shown to consist of three separate sub-regions: nucleate boiling dominated for qualities below 0.3, combined nucleate and convective boiling for qualities between 0.3 and 0.5, and convective boiling dominated for qualities above 0.5. Above 0.5, dryout effects begin to take effect, causing a gradual decline in the heat transfer coefficient followed downstream by a more severe decline. A previous correlation is identified for prediction of the heat transfer coefficient in the saturated boiling region.

1. Introduction

1.1. Two-phase cooling potential and features of two-phase mini/micro-channel cooling

Rapid escalation in heat dissipation in modern electronics and power applications, coupled with a quest for smaller and more lightweight packaging, has created a pressing need for more effective cooling solutions. Despite many innovative improvements to both air and single-phase liquid cooling, these cooling schemes have largely fallen short of maintaining acceptable device temperatures. These shortcomings have shifted interest among thermal system designers to two-phase cooling schemes, which capitalize on the coolant's both sensible and latent heat to greatly enhance cooling performance compared to single-phase cooling schemes [1].

Over the past three decades, investigators at the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL) and several other researcher groups have examined a broad variety of two-phase cooling solutions, the most basic of which are capillary-driven devices (heat pipes, capillary pumped loops, and loop heat pipes) [2–4] and pool boiling thermosyphons [5–7]. For applications demanding more superior cooling performance, a variety of pump-driven schemes have also been proposed, including falling film [8,9], channel flow boiling [10,11], mini/micro-channel flow boiling [12–15], jet-impingement [16–19], and spray [20–26].

Of the different two-phase cooling schemes, those employing mini/micro-channel cooling have received particular attention because of a number of thermal and system attributes. Their key

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.02.020
0017-9310/

Nomenclature

A_{base}	total base area of heat sink
Bo	boiling number, $Bo = (q''_H/Gh_{fg})$
C	empirical coefficient
c_p	specific heat at constant pressure
D_b	bubble detachment diameter
D_h	hydraulic diameter
G	mass velocity
g	gravitational acceleration
G_c	critical mass velocity
h	enthalpy; heat transfer coefficient
$\bar{h}$	average heat transfer coefficient
H_{ch}	micro-channel height
h_{fg}	latent heat of vaporization
h_{sub}	enthalpy of subcooling, $h_{sub} = h_{sat} - h$
H_{tc}	distance between thermocouple and bottom wall of micro-channel
j	superficial velocity
Ja^*	modified Jakob number, $Ja^* = c_{p,f}\Delta T_{sub,in}/h_{fg}$
$j_{g,cor}$	superficial velocity of vapor corrected relative to air
k	thermal conductivity
k_s	thermal conductivity of solid
L_{ch}	micro-channel length
L_{sp}	length of single-phase region
m	fin parameter; empirical exponent
$\dot{m}$	total mass flow rate of heat sink
MAE	mean absolute error (%)
n	empirical exponent
Nu	Nusselt number
N_{pch}	phase change number
N_{sub}	subcooling number
p	pressure
Pr	Prandtl number
q''	heat flux
q^*	dimensionless heat flux
q_B''	heat flux based on total base area of heat sink
q_H''	heat flux based on heated area of micro-channel
Re	Reynolds number
Su	Suratman number
T	temperature
t	time
$T_{b,f}$	bulk liquid temperature
T_w	micro-channel wall temperature
$T_{w,b}$	bottom wall temperature of micro-channel
v	specific volume
V_b	bulk fluid velocity
v_{fg}	specific volume difference between vapor and liquid
W_{ch}	micro-channel width
We	Weber number
We^*	modified Weber number
W_w	half-width of copper sidewall separating micro-channels
x	vapor quality
x_e	thermodynamic equilibrium quality
X_{tt}	turbulent-turbulent Lockhart-Martinelli parameter
z	axial coordinate

Greek symbols

α	void fraction
β	channel aspect ratio
η	fin efficiency
θ	percentage predicted within ±30%
μ	dynamic viscosity
ν	kinematic viscosity
ξ	percentage predicted within ±50%
ρ	density
σ	surface tension
ψ	dimensionless heat transfer rate
ψ_0	dimensionless heat transfer rate corresponding to $x_e = 0$

Subscripts

3	three-sided heating
4	four-sided heating
avg	average
b	bottom of micro-channel
cor	correlation for uniform circumferential (circular or four-sided) heating
devel	developing flow
exp	experimental
f	liquid
g	vapor
in	micro-channel inlet
k	liquid (f) or vapor (g)
lam	laminar flow
max	maximum
out	micro-channel outlet
pred	predicted
sat	saturation
sc	subcooled boiling
sp	single phase
sub	subcooling
tc	thermocouple
turb	turbulent flow
w	micro-channel wall
z	local properties along axial direction

thermal advantage is the ability to dissipate fairly high heat fluxes while maintaining relatively low device temperatures [27]. They are also very compact and lightweight, and require low flow rates and minimal coolant inventory. Other lesser known advantages are their versatility, including adaptability to pump-free loops [28,29], and flexibility of incorporation into hybrid cooling modules that combine the merits of mini/micro-channel flow boiling with those of jet impingement [30–32].

However, two-phase mini/micro-channel heat sinks also pose several challenges. Most of these challenges are associated with the use of small hydraulic diameter to enhance the two-phase heat transfer coefficient. For a given coolant flow rate, small hydraulic diameters are generally associated with high pressure drop. This may lead to appreciable compressibility, which results from large variations in specific volumes of the vapor and liquid with axially decreasing pressure. Another concern is increased flashing, which is the result of large variations in enthalpies of the vapor and liquid with axially decreasing pressure. For high mass velocities, the combined effects of compressibility and flashing increase the likelihood of two-phase choking, which is reflected in the following relation for critical mass velocity corresponding to a two-phase Mach number equal to unity [33].

$$G_c = \left\{ -\left[x\frac{dv_g}{dp} + (1-x)\frac{dv_f}{dp} - \frac{v_{fg}}{h_{fg}}\left(\frac{dh_f}{dp} + x\frac{dh_{fg}}{dp}\right)\right]\right\}^{-0.5}. \qquad (1)$$

These concerns were first addressed by Bowers and Mudawar [34], who compared cooling performances of two heat sinks, one featuring 2.5-mm mini-channels and the other 0.51-mm micro-channels, using R-113 as working fluid. They showed that, while