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Theoretical model for local heat transfer coefficient for annular flow boiling in circular mini/micro-channels

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ABSTRACT

This study examines two-phase heat transfer characteristics associated with annular flow boiling in circular mini/micro-channels with circumferentially uniform heat flux. A theoretical control-volume-based model is developed based on the assumptions of smooth interface between the annular liquid film and vapor core, and uniform film thickness around the channel's circumference. Droplet entrainment and deposition effects are incorporated in the model with the aid of new correlations for initial liquid droplet quality at the onset of annular flow, and deposition mass transfer coefficient, respectively. The model also accounts for interfacial suppression of turbulent eddies due to surface tension with the aid of an eddy diffusivity model specifically tailored to shear-driven turbulent films. The model shows excellent predictive capability against 149 convective boiling dominant data points for saturated flow boiling in circular mini/micro-channels, evidenced by an overall mean absolute error of 16.5%, with 91.3% and 98.0% of the data falling within ±30% and ±50% error bands, respectively.

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1. Introduction

Recent advances in applications such as high performance computers, electrical vehicle power electronics, avionics, and directed energy laser and microwave weapon systems have led to unprecedented challenges in removing large amounts of heat from very small areas [1–8]. While a variety of two-phase cooling schemes, including pool boiling [9–11], jet [12–15], spray [16–19], surface enhancement [20–22], and hybrid cooling techniques that combine the benefits of different schemes [23,24] have been considered for these applications, two-phase mini/micro-channel devices have been especially favored for their compactness, relative ease of fabrication, high heat dissipation to volume ratio, and small coolant inventory.

Studies on flow boiling in mini/micro-channels have resulted in different approaches to predicting pressure drop and heat transfer coefficient. The vast majority of these studies are based on Lockhart–Martinelli-type [25] separated flow models for pressure drop [26–30], and semi-empirical correlations for heat transfer coefficient [31–34]. However, these methods have been validated only for specific flow configurations and relatively narrow ranges of operating conditions. In pursuit of 'universal' predictive tools that are applicable to different working fluids and broad ranges of operating conditions, a series of studies have been conducted at the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL), which involve systematic consolidation of world databases for mini/micro-channels, and development of universal predictive tools for pressure drop [35,36], heat transfer coefficient [37,38], and dryout incipience quality [39], following very closely a methodology that was adopted earlier to predict flow boiling critical heat flux (CHF) for water flow in tubes [40–42].

Another effective method to predicting pressure drop and heat transfer coefficient for annular two-phase flow in mini/micro-channels is the control-volume-based approach. Because annular flow consists of predominantly two separated phases – vapor core and annular liquid film – it lends itself better to theoretical modeling than dispersed flow regimes such as bubbly and slug flows. Fig. 1 shows a schematic of the convective boiling dominant regime that is associated with saturated inlet conditions and terminated with dryout. In a recent study by the authors [38,39], convective boiling was identified as one of two dominant heat transfer mechanisms for saturated flow boiling in mini/micro-channels. For this convective boiling dominant regime, bubbly and slug flow occupy a small portion of the channel length, while annular flow spans a significant fraction. Gradual evaporation and thinning of the annular liquid film cause the heat transfer coefficient to increase along the channel length. With a sufficiently high wall heat flux or sufficiently long channel, dryout of the

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Nomenclature

A	area
A^+	constant in Eq. (47)
A_{ch}	cross-sectional area of channel
$A_{f,*}$	flow area of liquid control volume
Bo	Boiling number, $q''_H/(Gh_{fg})$
C	liquid droplet concentration in vapor core
Ca	Capillary number, $\mu_f G/(\rho_f \sigma)$
c_p	specific heat at constant pressure
D	tube diameter
D_h	hydraulic diameter
$D_{h,c}$	hydraulic diameter of vapor core
e	liquid droplet quality
e_0	initial liquid droplet quality at onset of annular flow
F	function
f	Fanning friction factor; liquid film quality
G	mass velocity
h	heat transfer coefficient
h_{fg}	latent heat of vaporization
K	Von-Karman constant
k	deposition mass transfer coefficient; thermal conductivity
l^+	dimensionless turbulent mixing length
MAE	mean absolute error
$\dot{m}$	mass flow rate
P	pressure
P_{crit}	critical pressure
P_F	wetted perimeter
$P_{f,y}$	local perimeter
$P_{f,\delta}$	interfacial perimeter
P_H	heated perimeter
P_R	reduced pressure, P/P_{crit}
Pr	Prandtl number
Pr_T	turbulent Prandtl number, $\varepsilon_m/\varepsilon_h$
q''	heat flux at distance y from channel wall
q''_H	heat flux based on heated perimeter of channel
q''_w	uniform circumferential heat flux for circular tube
Re	Reynolds number
Re_c	effective Reynolds number of vapor core, $\rho_H(u_c - u_i)D_{h,c}/\mu_g$
Re_F	liquid film Reynolds number, $4\rho_f u_{f,m}\delta/\mu_f$
Re_f	superficial liquid Reynolds number, $G(1-x)D_h/\mu_f$
Re_{fo}	liquid-only Reynolds number, GD_h/μ_f
Re_G	vapor core Reynolds number, $\rho_g u_c D_{h,c}/\mu_g$
T	temperature
T^+	dimensionless temperature
u	velocity
u^+	dimensionless velocity
u^*	friction velocity
$u_{f,m}$	mean liquid film velocity
v	specific volume
W	deposition rate
We	Weber number, $G^2 D_h/(\rho_f \sigma)$
x	vapor quality
x_0	vapor quality at onset of annular flow
x_c	effective vapor quality in vapor core
x_e	thermodynamic equilibrium quality
X_{tt}	Lockhart–Martinelli parameter based on turbulent liquid-turbulent vapor flows
y	distance perpendicular to channel wall
y^+	dimensionless distance perpendicular to channel wall, yu^*/ν_f
z	stream-wise distance

Greek symbols

Γ_d	deposition mass transfer rate per unit channel length
Γ_{fg}	evaporation mass transfer rate per unit channel length
δ	thickness of annular liquid film
δ^+	dimensionless thickness, $\delta u^*/\nu_f$
ε_h	eddy heat diffusivity
ε_m	eddy momentum diffusivity
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density
ρ_H	homogeneous density of vapor core
σ	surface tension
τ	shear stress

Subscripts

avg	average
c	vapor core
cb	convective boiling dominant heat transfer
e	entrained liquid
exp	experimental (measured)
f	saturated liquid; liquid film
fo	liquid only
g	saturated vapor
i	interfacial
nb	nucleate boiling dominant heat transfer
pred	predicted
sat	saturation
tp	two-phase
w	wall

annular film ensues at a location downstream where the heat transfer coefficient begins to decrease appreciably.

The control-volume-based approach proved effective in predicting a variety of two-phase flow configurations, including pool boiling [10,11], separated flow boiling [43–48], and flow boiling in micro-channel heat sinks [49]. Recently, the authors of the present study also used this approach to construct a new model for annular condensation in mini/micro-channel flows [50].

Nonetheless, several fundamental challenges remain when attempting to develop an accurate model for annular flow boiling. These include interfacial instabilities, interfacial mass, momentum and heat transfer, and turbulence within the annular film. Two other sources of difficulty are droplet entrainment and droplet deposition. Entrainment refers to tiny liquid droplets breaking off the crests of waves and driven along with the vapor core. Deposition refers to droplets from the vapor core falling back upon the film interface. As indicated by Qu and Mudawar [51], the annular regime in flow boiling is initiated far upstream in a micro-channel, with an abundance of entrained droplets that are formed mostly by shattering of liquid from the micro-channel's upstream bubbly and slug flows.

The primary goal of the present study is to develop a theoretical control-volume-based model for annular flow boiling in mini/micro-channels. To assess the accuracy of the model, convective boiling dominant heat transfer data for saturated flow boiling in circular mini/micro-channels are compiled from six sources [52–57] as indicated in Table 1. Since two heat transfer regimes exist for flow boiling in mini/micro-channels, nucleate boiling dominant

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