International Journal of Heat and Mass Transfer 58 (2013) 718–734

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Universal approach to predicting two-phase frictional pressure drop for mini/micro-channel saturated flow boiling

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ARTICLE INFO

Article history:
Received 22 April 2012
Received in revised form 6 November 2012
Accepted 14 November 2012
Available online 23 December 2012

Keywords:
Pressure drop
Flow boiling
Evaporation
Mini-channel
Micro-channel

ABSTRACT

This paper is a part of a recent series of studies by the authors to develop universal predictive tools for pressure drop and heat transfer coefficient for mini/micro-channel flows that are capable of tackling fluids with drastically different thermophysical properties and very broad ranges of all geometrical and flow parameters of practical interest. In this study, a new technique is proposed to predict the frictional pressure gradient for saturated flow boiling. To both develop and validate the new technique, a consolidated database consisting of 2378 data points is amassed from 16 sources. The database consists of 9 working fluids, hydraulic diameters from 0.349 to 5.35 mm, mass velocities from 33 to 2738 kg/m^{2}s, liquid-only Reynolds numbers from 156 to 28,010, qualities from 0 to 1, reduced pressures from 0.005 to 0.78, and both single-channel and multi-channel data. Careful examination of many prior models and correlations shows clear differences in frictional pressure gradient predictions between non-boiling (adiabatic and condensing) versus boiling mini/micro-channel flows that are caused by differences in flow structure, especially droplet entrainment effects. A separated flow technique previously developed by the authors for non-boiling mini/micro-channel flows is modified to account for these differences. The new technique shows very good predictions of the entire consolidated database, evidenced by an overall MAE of 17.2% and even predictive accuracy for different working fluids, and over broad ranges of hydraulic diameter, mass velocity, quality and pressure, and for both single and multiple mini/micro-channels.

1. Introduction

In the early days of electronic device development, tackling heat removal used to be an afterthought since power densities were miniscule and the heat removal could therefore be handled by rather simple natural or forced air convection techniques. As power densities began to escalate appreciably during the 1980s, device developers were confronted with a new reality where the heat removal became an integral part of the design process. The recent developments in applications such as high performance computers, electrical vehicle power electronics, avionics, and directed energy laser and microwave weapon systems, have led to unprecedented increases in power density, rendering obsolete all air cooling and even some of the most aggressive single-phase liquid cooling schemes. These increases necessitated a transition to two-phase cooling schemes, which capitalize upon the coolant's latent heat content to achieve orders of magnitude enhancement in boiling and condensation heat transfer coefficients [1]. Two-phase cooling solutions come in a variety of configurations, including pool boiling [2], spray [3–5], jet [6–9], and mini/micro-channel [2,10–13], as well as surface enhancement techniques [14].

Of the many phase-change cooling options, two-phase mini/micro-channel heat sinks have gained the most popularity among device and system manufacturers because of a number of attributes, including simple construction, compactness, low coolant inventory, and ability to achieve very large heat transfer coefficients. The attractive thermal performance of two-phase mini/micro-channel heat sinks is largely the result of small coolant passage diameter. Unfortunately, small diameter can also be the cause for high pressure drop, which may comprise the efficiency of the entire cooling system. Therefore, the design of high performance mini/micro-channel heat sinks demands accurate predictive tools for both pressure drop and boiling heat transfer coefficient.

Recently, the authors of the present study proposed that pressure drop predictive models and correlations for mini/micro-channel flows must address fundamental differences in flow structure between flow boiling on one hand and condensing and adiabatic flows on the other [15]. As illustrated in Fig. 1(a), this difference is manifest in the existence of entrained droplets in the vapor core for boiling flows and their absence from both condensing and adiabatic flows. For flow boiling in micro-channels, bubbles coalesce very quickly in the upstream region of the channel, causing rapid

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.11.045

Nomenclature

Bd	Bond number
Bd^*	modified Bond number
Bo	Boiling number, q''_H/Gh_{fg}
C	parameter in Lockhart–Martinelli correlation
D	tube diameter
D_h	hydraulic diameter
Fr	Froude number
f	Fanning friction factor
G	mass velocity
g	gravitational acceleration
h_{fg}	latent heat of vaporization
J_f	superficial liquid velocity, $J_f = G(1-x)/\rho_f$
J_g	superficial vapor velocity, $J_g = Gx/\rho_g$
L	length
MAE	mean absolute error
N	number of data points
N_{conf}	Confinement number
P	pressure
P_{atm}	atmospheric pressure
P_{crit}	critical pressure
P_F	wetted perimeter of channel
P_H	heated perimeter of channel
P_R	reduced pressure, $P_R = P/P_{crit}$
ΔP	pressure drop
q''_H	heat flux based on heated perimeter of channel
Re	Reynolds number
Re_f	superficial liquid Reynolds number, $Re_f = G(1-x)D_h/\mu_f$
Re_{fo}	liquid-only Reynolds number, $Re_{fo} = GD_h/\mu_f$
Re_g	superficial vapor Reynolds number, $Re_g = GxD_h/\mu_g$
Re_{go}	vapor-only Reynolds number, $Re_{go} = GD_h/\mu_g$
Su	Suratman number
v	specific volume
v_{fg}	specific volume difference between saturated vapor and saturated liquid
We	Weber number
X	Lockhart–Martinelli parameter
x	thermodynamic equilibrium quality
z	stream-wise coordinate

Greek symbols

α	void fraction
β	channel aspect ratio ($\beta < 1$)
θ	percentage predicted within ±30%
λ	mean absolute error
μ	dynamic viscosity
ξ	percentage predicted within ±50%
ρ	density
$\bar{\rho}$	mixture density
σ	surface tension
ϕ	two-phase multiplier; channel inclination angle

Subscripts

A	accelerational
exp	experimental (measured)
F	frictional
f	saturated liquid
fo	liquid only
G	gravitational
g	saturated vapor
go	vapor only
k	liquid (f) or vapor (g)
$pred$	predicted
sat	saturation
tp	two-phase
tt	turbulent liquid-turbulent vapor
tv	turbulent liquid-laminar vapor
vt	laminar liquid-turbulent vapor
vv	laminar liquid-laminar vapor

transition to annular flow, and liquid shattered from upstream forms small droplets that are entrained in the vapor core [16]. This behavior is evident from video images in Fig. 1(b), which show micro-channel walls sheathed with a thin liquid film, with droplets clearly entrained in the vapor core [17]. However, recent images of annular condensing flow in micro-channels, which are also depicted in Fig. 1(b), show no evidence of droplet entrainment in the vapor core [15]. Clearly, different predictive tools must be developed for pressure drop in boiling flows compared to those for condensing and adiabatic flows.

Researchers have used different approaches with various levels of complexity to predict flow boiling pressure drop in mini/micro-channels [18–33]. These approaches can be grouped mostly into two general categories, those that are based on the homogeneous equilibrium model [34–40] and those that utilize semi-empirical correlations [41–57].

But there are also a few theoretical models for two-phase pressure drop. Being the most prevalent in mini/micro-channels, annular flow has been the target of more theoretical modeling efforts than all other flow regimes combined. These modeling efforts rely mostly on the control volume approach, where conservation relations are applied separately to the liquid and vapor phases. This approach has shown great versatility in tackling a wide variety of two-phase flow configurations, including pool boiling [58,59], vertical separated flow boiling along short walls [60,61] and long heated walls [62–65], in addition to annular condensation in mini/micro-channels [66].

Only a few prior studies have explored the development of a generalized predictive approach for flow boiling pressure drop in mini/micro-channels that is suitable for all possible flow boiling regimes [54–57]. In fact, no accurate predictive tools presently exit that can tackle a wide range of working fluids, mass velocities, pressures, and channel diameters. The development of this type of predictive tool is the primary motivation for a series of studies that have been initiated at the Purdue University Boiling and Two-Phase Flow Laboratory (PU-BTPFL), which involve systematic consolidation of world databases for condensation and flow boiling in mini/micro-channels, and development of universal predictive tools for both pressure drop and heat transfer coefficient, following very closely a methodology that was adopted earlier at PU-BTPFL to predict flow boiling critical heat flux (CHF) for water flow in tubes [67–70].

Recently, the authors of the present study used this approach to develop a universal predictive tool for pressure drop in condensing and adiabatic mini/micro-channel flows [71], which showed high accuracy in predicting data spanning very broad ranges of all key flow parameters. The present study follows the same systematic methodology to develop a universal approach to predicting pressure drop for flow boiling in mini/micro-channels. To accomplish this goal, flow boiling pressure drop databases are amassed from 16 sources into a single consolidated database. The database is compared to predictions of previous homogeneous equilibrium models and semi-empirical correlations for both macro-channels and mini/micro-channels. A new universal correlation for