International Journal of Heat and Mass Transfer 56 (2013) 238–250

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

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

Universal approach to predicting heat transfer coefficient for condensing mini/micro-channel flow

Sung-Min Kim, Issam Mudawar *

Boiling and Two-Phase Flow Laboratory (BTPFL), Purdue University International Electronic Cooling Alliance (PUIECA), Mechanical Engineering Building, 585 Purdue Mall West Lafayette, IN 47907-2088, USA

ARTICLE INFO

Article history:
Received 19 January 2012
Received in revised form 13 September 2012
Accepted 17 September 2012
Available online 27 October 2012

Keywords:
Two-phase flow
Condensation
Mini-channel
Micro-channel

ABSTRACT

A new universal approach to predicting the condensation heat transfer coefficient for mini/micro-channel flows is proposed that is capable of tackling many fluids with drastically different thermophysical properties and very broad ranges of all geometrical and flow parameters of practical interest. This is accomplished by first amassing a consolidated database consisting of 4045 data points from 28 sources. The database consists of single-channel and multi-channel data, 17 different working fluids, hydraulic diameters from 0.424 to 6.22 mm, mass velocities from 53 to 1403 kg/m^2 s, liquid-only Reynolds numbers from 276 to 89,798, qualities from 0 to 1, and reduced pressures from 0.04 to 0.91. An exhaustive assessment of prior correlations shows only two correlations, that are actually intended for macro-channels, provide relatively fair predictions, while mini/micro-channel correlations generally show poor predictions. Two new correlations are proposed, one for predominantly annular flows, and the second for slug and bubbly flows. This approach shows very good predictions of the entire consolidated database, with an overall MAE of 16.0%. It is shown this accuracy is fairly even 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

The quest for more compact designs in many modern electronic, defense and aerospace applications has lead to unprecedented increases in the amount of heat dissipation per unit volume. Examples of these applications include high performance computers, electrical vehicle power electronics, avionics, and directed energy laser and microwave weapon systems [1,2]. Both single-phase and two-phase cooling solution have been sought, but the single-phase options are dwindling as heat dissipation densities are exceeding the capabilities of the most promising single-phase cooling solutions.

This limitation explains the recent shift to two-phase cooling solutions. By capitalizing upon a liquid coolant's latent heat rather than sensible heat alone, two-phase cooling schemes can deliver orders of magnitude enhancement in heat transfer coefficient compared to their single-phase counterparts. This explains the recent increase in the number of studies addressing two-phase solutions using a variety of cooling schemes, such as spray [3–5], jet [6–9], and micro-channel [2,10–13], as well as means to enhance surface micro-structure [14]. Nonetheless, two-phase solutions do suffer some shortcomings, including the potential for high pressure drop, susceptibility to flow instabilities, and high cost.

Condensers utilizing mini/micro-channels are an important part of the arsenal of two-phase cooling solutions for applications requiring removal of large, concentrated heat loads. Most condensers are designed to operate in the annular flow regime consisting of a thin liquid film that travels along the walls of a flow channel, driven by shear forces exerted by a central vapor core. Using a small channel diameter serves to increase vapor velocity for a given flow rate, which increases the vapor shear stress, resulting in a thinner liquid film. With sufficient conversion of vapor to liquid along the channel, the increase in liquid film thickness eventually leads to a collapse of the annular regime. In a recent study involving condensation of FC-72 along square micro-channels [15], five distinct flow regimes were identified: smooth-annular, wavy-annular, transition, slug, and bubbly. These regimes are depicted in Fig. 1 in a plot of mass flux versus flow quality. The smooth-annular regime consists of a very thin and fairly smooth annular film that is shear driven by the central vapor core. In the wavy-annular regime, the liquid film is thicker and marred by appreciable interfacial waviness. The transition to slug flow is characterized by intermittent bridging of liquid ligaments from the annular film across the vapor core.

* Corresponding author. Tel.: +1 (765) 494 5705; fax: +1 (765) 494 0539.
E-mail address: mudawar@ecn.purdue.edu (I. Mudawar).
URL: https://engineering.purdue.edu/BTPFL (I. Mudawar).

0017-9310/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.09.032

Nomenclature

Bo	Bond number
C	coefficient in Lockhart–Martinelli parameter
C_1, C_2	empirical coefficients
c_p	specific heat at constant pressure
D	tube diameter
D_h	hydraulic diameter
Fr	Froude number
Fr^*	modified Froude number
f	Fanning friction factor
G	mass velocity
g	gravitational acceleration
Ga	Galileo number
h	heat transfer coefficient
h_{fg}	latent heat of vaporization
Ja	Jakob number
J_g^*	dimensionless superficial vapor velocity
Ka	Kapitza number
MAE	mean absolute error
N	number of data points
N_1–N_5	empirical exponents
Nu	Nusselt number
P	pressure
P_{crit}	critical pressure
P_R	reduced pressure, $P_R = P/P_{crit}$
Pr	Prandtl number
Pr_T	turbulent Prandtl number
q''	heat flux
q''_w	heat flux based on micro-channel's cooled perimeter
Re	Reynolds number
Su	Suratman number
T_δ^+	dimensionless boundary layer temperature
u^*	friction velocity
v	specific volume
We	Weber number
We^*	modified Weber number
X	Lockhart–Martinelli parameter
x	thermodynamic equilibrium quality
Δx	quality change
y^+	dimensionless distance normal to the wall, $yu^*/_f$
z	stream-wise coordinate

Greek Symbols

β	channel aspect ratio ($\beta < 1$)
δ	thickness of condensing film
δ^+	dimensionless thickness of condensing film, $\delta u^*/_f$
ε_m	eddy momentum diffusivity
θ	percentage predicted within ±30%
μ	dynamic viscosity
ν	kinematic viscosity
ξ	percentage predicted within ±50%
ρ	density
σ	surface tension
τ_w	wall shear stress
ϕ	two-phase multiplier

Subscripts

3	based on three-sided heat transfer in rectangular channel
4	based on four-sided heat transfer in rectangular channel
ann	annular flow
cir	based on uniform circumferential cooling
exp	experimental (measured)
f	saturated liquid
fo	liquid only
g	saturated vapor
go	vapor only
non-ann	slug and bubbly flow
$pred$	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
w	wall

Achieving very high condensation heat transfer coefficients is by no means the sole concern in arriving at an acceptable cooling scheme. Unfortunately, decreasing channel diameter in pursuit of a higher heat transfer coefficient also increases the condenser's pressure drop, which may compromise overall thermal efficiency. Therefore, the design of a high performance mini/micro-channel condenser demands predictive tools for both pressure drop and condensation heat transfer coefficient. The present study concerns prediction of the condensation heat transfer coefficient.

Studies on two-phase condensing flow in mini/micro-channels [16–43] have resulted in different approaches to predicting the condensation heat transfer coefficient. The vast majority of these studies involve the use or development of semi-empirical correlations [39,41,44–53]. However, these methods have been validated only for specific flow configurations and relatively narrow ranges of operating conditions. Of the different condensation regimes, annular flow has received the most attention. 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 slug and bubbly flows. One method that has shown great promise in modeling annular flow is the control volume approach, where conservation relations are applied separately to the liquid and vapor phases. This approach proved effective in modeling other two-phase flow configurations,

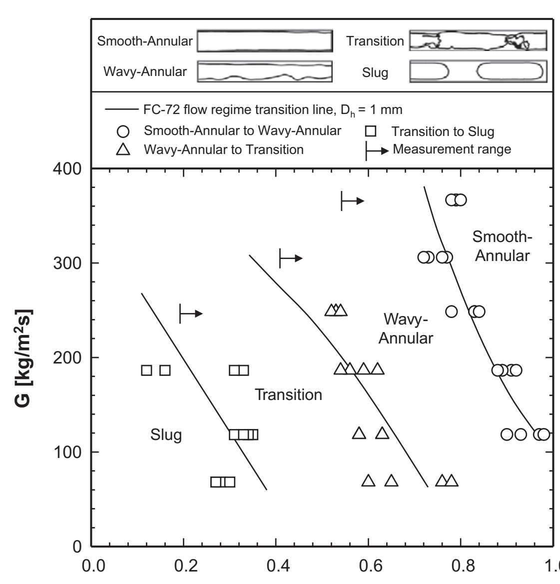

Fig. 1. Two-phase flow regime boundaries for condensation of FC-72 in square micro-channels with D_h = 1 mm [15].