International Journal of Heat and Mass Transfer 100 (2016) 98–110

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Condensation heat transfer in rectangular microscale geometries

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ARTICLE INFO

Article history:
Received 19 July 2015
Received in revised form 21 March 2016
Accepted 23 March 2016
Available online 6 May 2016

Keywords:
Condensation
Heat transfer
Microchannel
Annular
Intermittent

ABSTRACT

Heat transfer coefficients during condensation of refrigerant R134a in small hydraulic diameter ($100 < D_h < 160$ μm) rectangular ($1 < AR < 4$) channels are presented. A novel technique to accurately determine condensation heat duty and heat transfer coefficient in such microscale geometries at small Δx is used. Models in the literature that were developed for larger tubes are shown to under predict the data. A new model that accounts for the flow mechanisms during condensation at such small scales, and takes into account the effect of G, x, T_{sat}, D_h and AR, is developed. The model predicts 94% of the data in the intermittent, transition and annular flow regimes within ±25%.

1. Introduction

Microchannels are increasingly being used by numerous industries to miniaturize heat transfer equipment, improve energy efficiency, and minimize heat transfer fluid inventory. A fundamental understanding of condensation at the microscales will yield far reaching benefits for the automotive and HVAC&R industries, and others that need miniaturized components, such as portable personal cooling devices, hazardous duty and high ambient air-conditioning, and medical devices.

Garimella et al. [1] reported measurements and a unified model for intermittent and annular flow pressure drops during condensation of refrigerant R134a in small hydraulic diameter ($100 < D_h < 160$ μm) rectangular ($1 < AR < 4$) channels for a wide range of conditions ($300 < G < 800$ kg m^{-2} s^{-1}, $0 < x < 1$; $30 < T_{sat} < 60$ °C). It was found that pressure drop and heat transfer coefficient increased with increasing vapor quality, increasing mass flux and decreasing saturation temperature. The pressure drop model of Garimella et al. [1] relied on an annular flow factor (AFF) that accounted for the relative predominance of annular or intermittent flow in these channels.

In this paper, a substantial amount of additional heat transfer data are introduced and a new heat transfer model is proposed based on the data and using the insights on flow mechanisms and their influence on pressure drop reported in Garimella et al. [1].

2. Prior work

Models for horizontal, in-tube condensation have primarily considered idealized gravity and shear-driven mechanisms and the relative importance of the two. Gravity driven models are most important in stratified and wavy flow regimes. As the channel diameter decreases, surface tension forces become increasingly important and the gravity driven stratified and wavy flow regimes become less prevalent, as evidenced by the condensation flow visualization studies of Coleman and Garimella [2,3]. Thus, modeling of condensation heat transfer in the shear-dominated annular and intermittent flow regimes are of primary importance.

Shear-based annular flow models generally relate the interfacial shear stress to the analogous heat transfer across the condensate film. This approach was first introduced by Carpenter and Colburn [4] and later adapted by other researchers [5,6] with modifications made in the determination of the interfacial shear. Chen et al. [7] developed a general purpose annular flow correlation starting with asymptotic limits, and blending them through simple combinations of the terms at the respective limits. Several researchers have also used a two-phase multiplier approach, similar to that commonly used in two-phase pressure drop models. When used in the heat transfer models, the two-phase multiplier is applied to the corresponding single-phase heat transfer coefficient. It should be noted that shear-based models also use two-phase multipliers to determine the interfacial shear stress, and thus the two approaches are equivalent to each other.

Several researchers, including, Dobson and Chato [8], Cavallini et al. [9], and Thome et al. [10], have analyzed condensation data

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.086
0017-9310/

Nomenclature

AR	aspect ratio
AFF	annular flow factor
Cp	specific heat (J kg^{-1} K^{-1})
d	depth of microchannels (m)
D	diameter (m)
f	function of, friction factor
G	mass flux (kg m^{-2} s^{-1})
h	condensation heat transfer coefficient (W m^{-2} K^{-1})
J, j	superficial velocity (m s^{-1})
k	conductivity (W m^{-1} K^{-1})
L	length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
N	number of parallel channels, number of segments in heat transfer analysis
N_{UC}	number of unit cells
Nu	Nusselt Number = hD/k
P	pressure (kPa)
Pr	Prandtl number = $\mu\, Cp/k$
Q	heat duty (W)
q''	heat flux (W m^{-2})
R	thermal resistance (K W^{-1})
Re	Reynolds number = $\rho VD/\mu$
SLR	slug length ratio
T	temperature (°C, K)
t	thickness (m), time (s)
U	average velocity (m s^{-1})
V	volume (m^3), velocity (m s^{-1})
W, w	width (m)
x	quality, length parameter
z	length parameter

Greek symbols

α	void fraction, thermal diffusivity ($k/\rho Cp$)
β	homogenous void fraction
δ	film thickness (m)
Δ	change, difference
λ	eigen values
μ	dynamic viscosity (kg m^{-1} s^{-1})
ρ	density (kg m^{-3})
ε	emissivity
η	fin efficiency
σ	surface tension (N m^{-1})

Subscripts and superscripts

0	minimum
ave	average
B	bubble
CL	critical lower
CU	critical upper
Cu	copper
exp	experimental
f	film, film/bubble section
fric	frictional
g	gas phase
h	hydraulic
i	segment or node number
in	inlet
l, L	liquid, lower, laminar
out	outlet/exit
refg	refrigerant
s	slug
sat	saturation
TS	test section
v	vapor
w	water, wall
X	differential with respect to $x = \frac{\partial}{\partial x}$
XX	second order differential with respect to $x = \frac{\partial^2}{\partial x^2}$

from multiple researchers and developed heat transfer models spanning a wide range of mass fluxes, diameters, and fluids. The models attempt to account for flow-regime-specific heat transfer and pressure prop mechanisms. Most of these correlations classify the data into stratified/wavy or annular flows. Heat transfer models for intermittent and mist flow regimes have still not been successfully developed in these studies. Soliman [11] proposed a quasi-homogeneous model for the mist flow regime.

Only a few researchers have reported heat transfer measurements and models for tubes of $D < 3$ mm. Webb and coworkers [12–16] conducted experiments to determine heat transfer coefficients in extruded aluminum tubes with multiple parallel ports of $D_h < 3$ mm. They attempted several different approaches to model the heat transfer coefficients including shear stress and equivalent mass flux models, but a reliable model that predicts and explains the variety of trends seen in these results has not yet been developed. Yang and Webb [15] explicitly account for surface tension forces in microchannels (with microfins) by computing the drainage of the liquid film from the microfin tips and the associated heat transfer enhancement when the fin tips are not flooded. Wang et al. [17,18] also proposed an analytical treatment for microchannels with $D \sim 1$ mm that account for the combined influence of surface tension, shear and gravity in the condensation process.

Garimella and Bandhauer [19] conducted heat transfer experiments in small diameter tubes ($0.4 < D_h < 4.9$ mm). They specifically addressed the experimental difficulty of accurately determining condensation heat transfer coefficients due to the high heat transfer coefficients and low mass flow rates in microchannels by developing a novel thermal amplification technique. Bandhauer et al. [20] reported that during the condensation process, as the refrigerant quality decreases, the flow changes from mist to annular to intermittent flow with large overlaps in these types of flows. They developed an annular flow based model, because most of their data were either in the annular flow regime or in transition between the annular flow regime and other regimes. They noted that many of the available shear-driven models, though sound in formulation, led to poor predictions because of the inadequate calculation of shear stresses using pressure drop models that were not applicable to microchannels. Thus, their model is based on boundary layer analyses analogous to the development by Traviss et al. [6], but with the shear stress being calculated from the ΔP models of Garimella et al. [21] developed specifically for microchannels. Their model also indirectly accounts for surface tension through a surface tension parameter in the ΔP used for the shear stress calculation to yield accurate microchannel heat transfer predictions over a wide range of conditions.

3. Experimental methodology and results

Evaluation of condensation heat transfer coefficient in rectangular channels was originally presented for a single geometry (200×100 μm, $AR = 2$) in a study by Agarwal and Garimella [22]. In the present study, a considerable amount of additional data over