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Prediction of subcooled flow boiling pressure drops in small circular tubes

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ABSTRACT

Two-phase pressure drops in a mini-tube, in transition flow and subcooled boiling, are analyzed in the present paper, with the support of an experimental data set provided by ENEA with their BO.E.MI.A. test section. The methodology can be applied to different fluids according to similarity criteria. Single phase, subcooled and saturated conditions have been analyzed. The Reynolds number in the experiments was mainly in the transition zone between laminar and turbulent conditions, therefore a third order interpolation curve of the friction factor has been employed. The methodology is based on the model from Delhaye. The model considers the fluid properties, the energy, mass and momentum conservation equations to predict the ONB and OSV points and a hyperbolic function has been adopted to calculate the non-equilibrium vapor quality in the subcooled boiling region. The best agreement with the ENEA experimental data has been obtained using in the methodology the Chisholm correlation, with 83.59% of the predicted values with an error lower than 30%.

1. Introduction

Extreme engineering applications often require small high-performing solutions. For heating issues, micro-heat exchangers are widely used, as, for example, in the electronic chips cooling where high heat fluxes must be discharged over a small area. One of the simplest arrangements that can be used for the heat removal involves single-phase forced convection that is, however, limited in terms of efficiency. The higher heat transfer coefficients could be achieved only employing a phase transition, and subcooled flow boiling can be considered the best solution for small-scale heat removal equipment.

Due to the small hydraulic diameter used in mini- and micro-exchangers, excessive pressure drop is always a concern, since these devices are typically used in combination with pumps with limited pumping power capability. Another concern is the pressure oscillation due to hydrodynamic instabilities that can appear in subcooled boundaries, You et al. [1], and that can lead up to CHF, Caira et al. [2]. Thus, instabilities must be predicted and prevented to ensure safe operation and good cooling performance. A few published studies discuss pressure drop and hydrodynamic instability of flow boiling in mini/micro-tubes. These concerns are compounded when the fluid flow is in transition between laminar and turbulent flows, where there is no valid and established model.

Jacobi et al. [3] proposed a classification based on the physical size of the channels: micro-channels for a size range 1–100 μm, meso-channels for channel sizes from 100 μm to 1.0 mm, compact channels from 1.0 mm to 6.0 mm and, macro-channels for all channel sizes exceeding 6.0 mm. Instead, Kandlikar et al. [4] proposed a classification based on flow considerations: conventional channels for hydraulic diameters of 3.0 mm or larger, mini-channels for hydraulic diameters of 200 μm to 3.0 mm, micro-channels for hydraulic diameters smaller than 200 μm. The recommendations are valid for both single-phase and two-phase systems. Cheng and Wu [5] proposed criteria based on the Bond number $Bd = g(\rho_f - \rho_g)D^2/\sigma$, to consider the properties of the fluid and, therefore, the gravity and surface tension effects: micro-channel, if $Bd < 0.05$ (significant effect of surface tension); mini-channel, if $0.05 < Bd < 3.0$ (both gravity and surface tension are important); macro-channel, if $Bd > 3.0$ (surface tension has negligible effect).

Pressure drops in saturated flow boiling were largely analyzed at macro-scale, Ould Didi et al. [6] compared seven of the most quoted macro-scale methods in the literature to determinate frictional pressure drop on a 788 points database in two horizontal macro-scale test sections of 10.92 and 12.00 mm diameter for five fluorocarbon refrigerants. They found that the methods of Muller-Steinhagen and Heck [7] and Gronnerud [8] gave the best

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Nomenclature

A	actual value
Bd	Bond number
Bo	Boiling number
C_0	distribution parameter
c_p	specific heat, J/kg K
C	parameter in Lockhart-Martinelli correlation; calculated value
D	tube diameter, m
Fr	Froude number
f	Fanning friction factor
G	mass flux, kg/m^2 s
g	gravitational acceleration, 9.806 m/s^2
H_{lv}	latent heat, J/kg
H	enthalpy, J/kg
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/mK
L	tube length, m
N	number of data points
n	coefficient
Pr	Prandtl number
p	pressure, Pa
Q	heat flux, W/m^2
Re	Reynolds number
S	suppression factor
T	temperature, K
V_g	weighted drift velocity, m/s
We	Weber number
X_{tt}	Lockhart-Martinelli parameter
x	quality
Y	Chisholm correlation coefficient
Z	axial coordinate (stream-wise)

Greek symbols

α	void fraction
Γ	volumetric flow rate, m^3/s
μ	dynamic viscosity, Pa s
ξ	convergence parameter
ρ	density, kg/m^3
σ	surface tension, N/m
φ	two-phases multiplier

Subscripts

conv	convective
eq	equilibrium
F	friction
H	heated
in	inlet
lam	laminar
lo	liquid only
l	liquid
out	outlet
ΔP	pressure drop
sat	saturated
sub	subcooled
SP	single-phase
TP	two-phase
turb	turbulent
t	total
v	vapor
vo	vapor only
w	wall
z	axial

Acronyms

MAPE	Mean Average Percentage Error
MPE	Mean Percentage Error
ONB	Onset Nucleate Boiling point
OSV	Onset Significant Void point
PDB	Partial Developed Boiling region
FDB	Full Developed Boiling region

predictions. Ribatski el al. [9] compared twelve prediction methods and found as the most effective the macro-scale method proposed in [7]. However, they showed how none of the analyzed methods can be classified as a design tool for microscale tubes.

In micro-scale Zhang and Webb [10], Kuwahara et al. [11] obtained good predictions of their data for R134a by using the Friedel [12] correlation. Also, Lazarek and Black [13] studied the problem obtaining good forecasts by using a value of $C = 30$ in the generalized Chisholm [14] and Lockhart–Martinelli [15] correlations. Along this direction, Qu and Mudawar [16], Lee and Mudawar [17] and Lee and Garimella [18] developed flow boiling pressure drop models based on their experimental data developed in microchannel heat sinks. Mishima and Hibiki [19] obtained reasonably good predictions for their frictional pressure drop data by correlating the Chisholm [14] parameter in the Lockhart–Martinelli [15] correlation as a function of the tube diameter. Bowers and Mudawar [20,21] analyzed flow boiling pressure drop of refrigerant R-113, using a homogenous equilibrium model, in both mini and micro-channel obtaining a good agreement. Two-phase hydrodynamic instabilities in parallel mini/micro-channels were addressed by Kandlikar et al. [22] and Hetsroni et al. [23]. Tran et al. [24] studied flow boiling pressure drop of three different refrigerants in single tubes and for a single rectangular channel. Kim and Mudawar [25] developed a model, using a database of 2378 experimental points, that takes into account six dimensionless parameters to calculate the Lockhart–Martinelli *C* parameter.

Both macro-scale and micro-scale correlations have been used in the literature to develop models for heat transfer and pressure drops in mini-channels, and mainly in laminar or turbulent conditions. The pressure drops in a mini-channel in single and two-phase transition flow are analyzed in the present paper, with the support of experimental data provided by ENEA in their BO.E.MI.A. test section [26]. The main aim of the work is to provide a comprehensive methodology to predict pressure drops for small circular tubes, in transition flow and subcooled boiling condition, valid for many fluids according to similarity criteria, due to the lack of specific models in these conditions.

2. The BO.E.MI.A. experimental facility

The BO.E.MI.A. experimental facility (BOiling Experiments in MIcrochannel Apparatus) was built at the ENEA Laboratory of Chemical and Thermo-Fluid Dynamic Processes for Energy. It consists of a tube of 1.016 mm (internal diameter) and wall thickness 0.57 mm; two different total lengths have been used, 100 or 200 mm: The working fluid is the refrigerant FC-72 (perfluorohexane C6F14). The facility can operate at pressures up to 10 bar and a volumetric flowrate from 6 to 552 ml/min. An upstream electrical pre-