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Two-phase frictional pressure drop in horizontal micro-scale channels: Experimental data analysis and prediction method development

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ABSTRACT

An investigation was conducted on the effects of fluid refrigerant and channel geometry on the frictional pressure drop during two-phase flow inside microchannels. Experimental results for two-phase frictional pressure drop were obtained for the refrigerants R134a, R1234ze(E), R1234yf and R600a in a circular channel and for R134a in square and triangular channels. The experiments were performed for mass velocities from 100 to 1600 kg m^{-2} s^{-1}, saturation temperatures of 31 and 41 °C, and vapor qualities from 0.05 to 0.95. The experimental data have been analyzed focusing on the effects of the geometry and fluid on the two-phase pressure drop. Then, the data were compared with the most quoted predictive methods from the literature. Based on the broad database obtained, a new method for prediction of the two-phase frictional pressure drop was proposed. The new method provided accurate predictions of the database, predicting 89% of the results within an error band of ±20%.

Chute de pression frictionnelle diphasique dans les canaux horizontaux à micro-échelle : Analyse des données expérimentales et développement d’une méthode prédictive

Mots clés : Écoulement diphasique ; Effet de la géométrie ; Chute de pression ; Ébullition convective ; Microcanaux

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Nomenclature

A	area [m^2]
C_C	area ratio vena contracta [dimensionless]
dp/dz	pressure drop gradient [kPa m^{-1}]
D	diameter [m]
f	friction factor [dimensionless]
G	mass velocity [kg m^{-2} s^{-1}]
i	enthalpy [J kg^{-1}]
K	singular pressure drop coefficient [dimensionless]
k	momentum correction factor [dimensionless]
L	length [m]
M	mass flow rate [kg s^{-1}]
p	pressure [kPa]
P	electrical power [W]
Ra	arithmetic mean roughness [μm]
Re	Reynolds number [dimensionless]
Rt	maximum roughness height [μm]
x	vapor quality [dimensionless]
z	position along the tube [m]

Greek letters

α	void fraction [dimensionless]
β	energy momentum coefficient [dimensionless]
η	parcel of data predicted within a certain error band [%]
λ	empirical coefficient [dimensionless]
μ	dynamic viscosity [Pa·s]
ρ	density [kg m^{-3}]
ς	aspect ratio for rectangular channels [dimensionless]
σ_A	area ratio of contraction/expansion [dimensionless]
ω	empirical coefficient [dimensionless]

Subscripts

1ϕ	single-phase
2ϕ	two-phase
Ac	accelerational
con	contraction
exp	expansion
Eq	equivalent
f	frictional
in	inlet
int	internal
I	irreversible
H	hydraulic
L	liquid
$L0$	two-phase mixture as liquid
G	vapor
LG	difference between vapor and liquid properties
$G0$	two-phase mixture as vapor
out	outlet
ph	pre-heater
$pred$	predicted
R	reversible
sat	saturation
ts	test section
vs	visualization section

1. Introduction

In the past years, several experimental studies concerning two-phase pressure drop were performed and, as consequence, new predictive methods were proposed with most of them based on restricted experimental databases. However, as pointed out by Ribatski (2013), there are still differences among data from independent laboratories that can be related to several aspects, e.g. different surface roughness, channel dimension uncertainties, channel obstructions, inappropriate data reduction procedures and the presence of thermal instabilities (see also Ribatski et al., 2007).

According to the comprehensive literature review by Tibiriçá and Ribatski (2013), almost 97% of the studies concerning single-channels were performed for circular cross sections, especially, due to the easiness to obtain them in the market in different diameters. However, the two-phase flow behavior in a circular microchannel may be significantly different from non-circular cross-sectional geometries (square, rectangular, triangular, etc.) due to factors like aspect ratio and a possible accumulation of liquid in the corners with the subsequent decreasing of the liquid film thickness in the region between consecutive vertices. It is also important to emphasize that the characteristic dimension of the channel that should be adopted to predict frictional pressure drop during two-phase flows in non-circular channels is still not clear in the literature.

Microchannel array heat sinks evaluated in the literature are generally formed by rectangular microchannels. This fact is evidenced by the study of Tibiriçá and Ribatski (2013). According to these authors, 87% of studies concerning multichannel configurations were performed for rectangular cross sections covering a wide range of aspect ratios and only 9% for triangular cross sections. It is important to mention that experimental data for pressure drop in microchannel arrays may be affected by instabilities, local restrictions, maldistribution and back flow, just to name a few effects. Therefore, all these phenomena that are typical of the array geometry make isolation of the frictional pressure drop caused by the two-phase flow along the channel difficult. For this reason, the present authors believe that pressure drop experimental data obtained for microchannel arrays are not suitable to be used in the development of predictive method with generic claims.

It should be mentioned that the majority of studies concerning the evaluation of the two-phase pressure drop in small diameter channels was performed for HFC refrigerants (see Kim and Mudawar, 2014). In 1997, the Kyoto Protocol has established the gradual replacement of HFCs by refrigerants with global warming potential (GWP) less than 150. In this context, a new demand was generated for fluids that could substitute the HFCs. According to Calm (2008) and Mota-Babiloni et al. (2014), the potential substitutes for HFCs are natural refrigerants (hydrocarbons, CO_2 and ammonia), hydrofluoroolefins (HFOs) and mixtures of HFCs and HFOs.