International Journal of Heat and Mass Transfer 75 (2014) 581–591

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental condensing two-phase frictional pressure drop inside mini-channels. Comparisons and new model development

Alejandro López-Belchí *, Fernando Illán-Gómez, Francisco Vera-García, Jose R. García-Cascales

Department of Thermal and Fluids Engineering, Technical University of Cartagena, C/Doctor Fleming s/n, 30202 Cartagena, Murcia, Spain

ARTICLE INFO

Article history:
Received 30 October 2013
Received in revised form 2 April 2014
Accepted 3 April 2014
Available online 6 May 2014

Keywords:
Mini-channels
Two-phase flow multiplier
Frictional pressure gradient
Two phase flow condensation

ABSTRACT

The present paper reports condensing two-phase flow pressure drop inside a mini-channel tube with 1.16 mm inner hydraulic diameter with R1234yf, R134a and R32. According to the available data, most of the models checked capture the trend correctly. Experimental data are analysed to show the influence of saturation temperature, mass velocities, vapour quality and fluid properties in pressure drop. Finally, a new correlation model is presented with a mean absolute relative deviation (MARD) value of 8.32% reducing the best correlation MARD by more than 34%.

1. Introduction

Nowadays, micro and mini-channels are present in many applications ranging from different heat exchangers in process industry to automotive, electronics and domestic applications. Two-phase flow has been applied to a growing number of fields in recent years because of its higher energy efficiency in comparison with single-phase flow. Compactness is a synonym of charge reduction and this is very important in present day refrigeration systems and heat pumps because of the great contribution of HCFC and HFC refrigerants to the direct greenhouse effect. This reduction is also important for natural refrigerants such as hydrocarbons and ammonia for safety reasons[1].

In the early 1980s, Tuckerman and Pease [2] found that the heat transfer coefficient would be enhanced by reducing the tube diameter. From then on, the investigation on heat transfer in mini-channels has been one of the most researched topics in this field.

Condensers utilising mini/micro-channels are especially suited for applications demanding high heat dissipation in a limited volume as the more the tube diameter decreases, the more the ratio of area to volume increases, and the heat transfer increases.

These condensers maintain mostly annular or intermittent flow to take advantage of the large condensation heat transfer coefficients associated with these flow patterns. Decreasing channel diameter increases vapour velocity and the interfacial shear stress, which causes a thinning of the annular film and increases the condensation heat transfer coefficient. Unfortunately, while the heat transfer is empowered by reducing the tube diameter, a higher pressure drop is obtained, which may degrade the overall efficiency of the two-phase system. Therefore, the design of high performance mini-channel condensers requires accurate predictive tools for both pressure drop and condensation heat transfer coefficient.

Two-phase frictional pressure drop has been a research subject for six decades. Many authors relate the two-phase frictional pressure gradient to the single phase pressure gradient through a two-phase multiplier. The first authors to do so were Lockhart and Martinelli [3] who proposed a correlation for isothermal two-phase flow pressure drop. Some years later, Chisholm [4] developed a theoretical analysis of the Lockhart and Martinelli model. This theoretical development coincided with Lockhart–Martinelli experimentally obtained empirical curves. The author also proposed simplified equations for their use in engineering design. Later, Friedel [5], Müller-Steinhagen and Heck [6] developed a simple correlation for two-phase frictional pressure drop prediction in macro-channels. These models are widely used in conventional theory to predict frictional pressure drop in macro-channels, many recent authors have reported the ability of these correlations to estimate with reasonable accuracy the frictional pressure drop in mini-channels [7,8].

There are generally three different kinds of pressure drop models. The first group modifies the Chisholm "C" parameter to best fit experimental data, such as Sun and Mishima [9] and Kim and Mudawar [10]. The second group of authors modifies two-phase flow multiplier and/or develops a correlation that best fits their

* Corresponding author. Tel.: +34 968 32 5994; fax: +34 968 32 5999.
E-mail addresses: alejandro.lopez@upct.es (A. López-Belchí), fernando.illan@upct.es (F. Illán-Gómez), francisco.vera@upct.es (F. Vera-García), jr.garcia@upct.es (J.R. García-Cascales).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.04.003
0017-9310/

Nomenclature

C	Chisholm parameter
D	hydraulic diameter (m)
f	friction factor
G	mass velocity (kg/m^2 s)
h	enthalpy (J/Kg K)
k	uncertainty coverage factor
$\dot{m}$	mass flow rate (kg/s)
MRD	mean relative deviation
$MARD$	mean absolute relative deviation
p	pressure (Pa)
$\dot{Q}$	power (W)
$Re = GD/\mu$	Reynolds number
u	uncertainty
$\dot{v}$	volumetric flow (m^3/s)
x	vapour quality (kg/kg)
z	length (m)
$[x]$	evaluated at x conditions

Greek symbols

α	void fraction
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
ϕ	two-phase frictional multiplier
X	Lockhart–Martinelli parameter

Subscripts

A	A type uncertainty
ac	acceleration
acc	accessories
ave	average
B	B type uncertainty
C	combined
$cont$	contraction
$crit$	critical
E	expanded
$evap$	evaporator
exp	expansion
$expr$	experimental
f	frictional
g	gravitational
gas	vapour
go	gas only
h	hydraulic
hot	hot
in	inlet
liq	liquid
lo	liquid only
$meas$	measured
mom	momentum
out	outlet
$pred$	predicted
red	reduced
ref	refrigerant
tp	two-phase
ts	test section
$tube$	section tube
w	water

data. The following authors develop a new multiplication factor: Cavallini et al. [11], Zhang and Webb [12], Müller-Steinhagen and Heck [6] and Friedel [5]. Finally, the third group develops a completely new model to predict two-phase pressure drop, like Garimella et al. [13], based on flow patterns or Cavallini et al. [14] with superficial gas or liquid velocity. In most cases, they try to include the effect of the refrigerant, the thermodynamic conditions, the geometry, the surface tension, refrigerant flow pattern, etc.

The main goal of this study is to characterise two-phase pressure drop inside mini-channels during condensation and develop a new correlation to predict pressure drop.

This paper is organised as follows. The installation is briefly described and the type of tube used in the experiments presented. The methodology followed to determine the pressure drop in the tubes is explained. The results obtained for pressure drop inside the multiport tubes with R1234yf, R134a and R32 are presented. The influence of reduced pressure, mass velocity, and vapour quality in frictional pressure drop is analysed in the paper, the experimental results are compared with those provided by the open literature and conclusions are finally drawn.

2. Experimental apparatus

An experimental installation for the study of condensation processes inside tubes has been constructed at the Technical University of Cartagena, Spain.

The test rig used is depicted in Fig. 1. It consists of the primary (refrigerant) loop and three auxiliary loops: two cooling water loops and one hot water loop. Only the primary loop has been represented in Fig. 1.

The sub cooled refrigerant from the condenser (1) flows into a tank (2). There is a controlled gear pump (3) connected to this tank, magnetically coupled to its variable speed electric motor.

When operating the installation for condensation measurements, the fluid is pumped through the Coriolis-effect mass flow metre (4) and the evaporator (5) where the refrigerant is vaporised up to a desired vapour quality. The previously mentioned Coriolis-effect flow metre also allows taking refrigerant density and mass flow rate readings.

After passing through the evaporator, the two-phase mixture flows through a ten centimetre copper tube to the inlet header (6). Uniform two-phase flow is assumed to be developed in the copper section before entering the measuring section through the inlet header. This is an approximation but it is a common practice (e.g., [12,15–17]). These references show experimental test sections similar to the section tested.

In the test section (7) the refrigerant is partially condensed with the variation of vapour quality in all tests lower than 0.08. The fluid exits the test section through the outlet header (8) and then enters the condenser (1) from which point the same cycle will repeat.

Two thermal baths are used in the condensation test: the first provides hot water used in the evaporator heated by Joule effect; the second feeds the measuring section and the condenser after the test section. The temperature of these two circuits can be set to different values thanks to two mixing valves.

The test section inlet pressure is controlled by energy removal in the condenser. The main tank is a two-phase reservoir and vapour phase pressure is used to control the system pressure. The amount of refrigerant charge is enough to avoid vapour phase to be suctioned by the pump. A control system guarantees steady state conditions and ensures that measurements are properly made.

The interested reader can find a study about possible non-uniform flow in multiport mini-channels tubes in López-Belchí et al. [18]. That aforementioned study reports that non-uniform condensation is not at all random and pressure drop values in multi-port tubes is not affected by possible non-uniform distribution.