International Journal of Heat and Mass Transfer 98 (2016) 285–298

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Measured and predicted frictional pressure drop for boiling zeotropic mixed refrigerants in horizontal tubes

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form 1 March 2016
Accepted 1 March 2016

Keywords:
Frictional pressure drop
Joule–Thomson
Zeotropic
Mixed gas
Mixture
Non-azeotropic

ABSTRACT

Zeotropic mixtures are widely used in mixed refrigerant Joule–Thomson cryocoolers for various applications such as cryoprobes. Within the Joule–Thomson cycle, multicomponent mixtures exist in a two-phase condition throughout a large portion of the system. Frictional pressure drop correlations for zeotropic refrigerants operating at these conditions are necessary for designers to optimize these systems; however, there are limited experimental data on the two-phase pressure drop of these mixtures available in the open literature.

This paper provides experimental data for the frictional pressure drop exhibited by a set of multicomponent zeotropic mixtures boiling in small channels over temperatures ranging from 100 K to room temperature along with the sensitivity of frictional pressure drop to parameters such as mass flux, pressure, tube diameter, and mixture composition. The measured data are compared to several pressure drop correlations available in the literature and the Awad and Muzychka (definition 1) correlation (Awad and Muzychka, 2008) was able to predict the frictional pressure drop over the range of experimental data considered, with an Absolute Average Deviation (AAD) of 17%. The second best correlation is Sun and Mishima (2009) with an AAD of 18%. In addition, the Cicchitti et al. (1959), Müller-Steinhagen and Heck (1986) and Mishima and Hibiki (1996) correlations also show reasonable agreement with the experimental data. Based on our data, the Awad and Muzychka (definition 1) (Awad and Muzychka, 2008) homogeneous model is recommended for prediction of pressure drop because this correlation agrees with 81% of our data with a relative absolute error lower than 25%.

1. Introduction

Utilization of heat exchangers with small tubes or mini-channels using two-phase flow has become more popular because they are able to transfer higher heat flux in a smaller space than traditional heat exchangers. As the channel size is reduced, the surface area to volume ratio increases which reduces both material and fluid requirements. The advantage of using small tubes in heat exchangers is even more significant if two-phase-flow occurs throughout the heat exchanger because of its higher heat transfer coefficient; however, the reduction in channel size increases the frictional pressure drop; thereby, creating parasitic effects to the refrigeration system. Designers often seek to optimize their systems by balancing the advantages and drawbacks of using two-phase flow in small channels; consequently, accurately predicting both the pressure drop and heat transfer coefficient is essential.

The refrigerants of interest in this study are zeotropic mixtures that maintain two-phase conditions over a temperature range of more than 80 K when the evaporating pressure is held constant. The evaporating pressure considered corresponds to bubble and dew point temperatures located on the range from 100 K to room temperature. All of the refrigerants analyzed are multicomponent mixtures, consisting of two, three, four and five components. Finally, the experimental measurements were made using small tubes with diameters that ranged between 0.5 and 1.5 mm.

These zeotropic refrigerant mixtures are used widely on mixed refrigerant Joule–Thomson systems in various applications such as cryoprobes and they are finding increasing use in traditional vapor compression cycles as well. The most important and largest component of a Joule–Thomson system is the heat exchangers and the circulating refrigerant remains mostly in the two-phase region within the heat exchanger. Although frictional pressure drop correlations for multi-phase and multi-component fluid

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.010
0017-9310/

Nomenclature

AAD	average absolute deviation
B	Chawla coefficient
B	Chisholm coefficient
Bo	Bond number
C	Chisholm parameter
Cp	specific heat
D	diameter
e	Chawla coeffcient
Eo	Eotvos number
f	friction factor
Fr	Froude number
g	gravitational acceleration
G	mass flux
H	Cavallini coefficient
htc	heat transfer coefficient
ID	inner diameter
k	thermal conductivity
L	length
La	Laplace number
Nu	Nusselt number
p	pressure
P	pressure
Pr	Prandtl number
$\dot{Q}''$	heat flux
R	surface roughness
Re	Reynolds number
relrough	relative roughness
RMS	root mean square
T	temperature
x	thermodynamic quality
X	Lockhart–Martinelli coefficient
We	Weber number
z	length

Subscripts

avg	average
c	critical
c	Chawla coefficient
*c*1	Chawla coefficient
*c*2	Chawla coefficient
exp	experimental
Fr	Froude
H	hydraulic
h	homogeneous
int	interphase
l	liquid
lo	liquid only
mixt	mixture
RMS	root mean square
tt	turbulent liquid/turbulent vapor
v	vapor
vo	vapor only
2*ph*	two-phase

Greek letters

α	void fraction
Δ	difference
Δ	delta
μ	viscosity
ρ	density
σ	surface tension
ϕ	two-phase friction multiplier
Γ	physical properties coefficient
Ω	Chen coefficient

operating at the conditions described here are an important tool for designers, there is little information in the open literature that discusses this topic and validates the models with experimental data.

Some reported studies such as Ould Didi et al. [6], Greco and Vanoli [7], Jung and Radermacher [8] and Sami and Duong [9] include pressure drop information for zeotropic mixtures with small temperature glides and nearly-azeotropic mixtures that change phase at temperatures close to room temperature in conventional channels. Ould Didi et al. [6] report two-phase frictional pressure drop data measured in horizontal tubes (D_H = 10.92 and 12.00 mm) while evaporating five refrigerants (R-134a, R-123, R-402a, R-404a and R-502) as a function of mass flux (100–500 kg/m^2-s) and thermodynamic quality (0.04–1.0). Ould Didi et al. concluded that Müller-Steinhagen and Heck [4] and Gronnerud [10] methods provide the best predictions for their data. Greco and Vanoli [7] describe an experimental study of the frictional pressure drop for boiling R-22, R-507, R-404A, R-134a, R-407C and R-410A in a horizontal tube (D_H = 6 mm). The pressure drop is provided as a function of mass flux (280–1080 kg/m^2-s) while the evaporating pressure is fixed at 7.0 bar. Chawla's [11] friction correlation shows the best-fit to their experimental data.

Jung and Radermacher [8] report pressure drop data collected during boiling of pure and mixed refrigerants of R-22, R-114, R-12, and R-152a in a horizontal test section. The heat flux and mass flux vary from 10–45 kW/m^2 and 230–720 kg/m^2-s, respectively. Jung and Radermacher reported good correlation between the Lockhart and Martinelli parameter and pressure drop with both pure and mixed refrigerants. Also, Jung and Radermacher proposed a correlation that predicts their experimental data with a mean deviation of 8.4%. Sami and Duong [9] present empirical data for a boiling mixture R-22/R-114 in the annuli of a horizontal enhanced surface tubing evaporator with 17.3, 28.6 and 32.3 mm for the inner, envelope and an outer diameters, respectively. Heat flux ranged between 5 and 25 kW/m^2 while the mass flux varied between 180 and 290 kg/m^2-s at a pressure of 570 kPa. A correlation is proposed to predict pressure drop of their R-22/R-114 (zeotropic refrigerant) mixture.

One of the few studies that involve conditions similar to those described here is reported by Baek et al. [12]. They report pressure drop data during boiling for what they called "macro heat exchangers" (D_H = 1.58 mm) and "micro heat exchangers" (D_H = 0.34 mm) installed in a mixed refrigerant Joule–Thomson system using two-phase zeotropic mixtures as a function of mass flux. A four component mixture formed by Argon, R-14, R-23 and R-218 (0.26/0.21/0.21/0.32 M composition) and a five component mixture formed by Argon, R-14, R-23, R-218 and R-134a (0.34/0.22/0.10/0.15/0.19 M composition) were tested over a temperature range between 70 and 210 K and an evaporating pressure of 200 kPa. The pressure drop that is reported takes into account the pressure difference between the inlet and the outlet of the heat exchangers. Baek et al. [12] concluded that the frictional pressure drop for the zeotropic mixtures tested while operating at cryogenic temperatures can be predicted with the Qu and Mudawar [13] and Sami and Duong [9] correlations for macro and micro heat exchangers, respectively. However, their global measurement of the frictional pressure drop does not allow a fundamental understanding of two-phase frictional pressure drop phenomenon