INTERNATIONAL JOURNAL OF REFRIGERATION 59 (2015) 1–13

Available online at www.sciencedirect.com

ScienceDirect

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

Pressure drop during near-critical-pressure condensation of refrigerant blends

Ulf C. Andresen [a], Srinivas Garimella [b,*], Biswajit Mitra [c], Yirong Jiang [d], Brian M. Fronk [e]

[a] Shell Oil Company, New Orleans, LA 70139, USA
[b] Sustainable Thermal Systems Laboratory, George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[c] Chiller Development Program, Carrier Corporation, Charlotte, NC 28269, USA
[d] Thermo King, Minneapolis, MN 55420, USA
[e] School of Mechanical, Industrial and Manufacturing Engineering, Oregon State University, Corvallis, OR 97331, USA

ARTICLE INFO

Article history:
Received 31 December 2014
Received in revised form 4 July 2015
Accepted 14 July 2015
Available online 21 July 2015

Keywords:
Two-phase
Pressure drop
Condensation
Microchannel
Critical pressure

ABSTRACT

This paper presents the results of an experimental study on pressure drop during condensation of refrigerant blends R404A and R410A at near-critical pressures inside tubes of $0.76 \le D \le 9.4$ mm. Local frictional pressure gradients were measured at reduced pressures (P_r) of 0.8 and 0.9 for the mass flux range $200 \le G \le 800$ kg m^{-2} s^{-1}, in small quality increments. The data were compared with adiabatic and diabatic two-phase pressure drop correlations from the literature. These correlations were not able to adequately predict the pressure drop over the range of tube sizes and mass fluxes under consideration here at high reduced pressures. A new correlation for pressure drop is introduced, which accounts for property variations and microchannel effects. The correlation predicts 85% of the data within ±25%, with an average deviation between model predictions and data of ±14%.

Chute de pression durant la condensation de mélanges de frigorigènes à proximité de la pression critique

Mots clés : Diphasique ; Chute de pression ; Condensation ; Microcanal ; Pression critique

* *Corresponding author.* Sustainable Thermal Systems Laboratory, George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA. Tel.: +1 404 894 7479; Fax: +1 404 894 8496.
E-mail address: sgarimella@gatech.edu (S. Garimella).
http://dx.doi.org/10.1016/j.ijrefrig.2015.07.016

Nomenclature

A	area (m^{-2})
B	constant in Chisholm (1973) correlation
C	phase coupling constant (Chisholm (1967))
D	diameter (mm)
Fr	Froude number (–)
G	mass flux (kg m^{-2} s^{-1})
J_G	dimensionless vapor velocity (Cavallini et al. (2002))
L	length (mm)
N_{conf}	confinement number (–)
P	pressure (kPa)
P_r	reduced pressure (–)
$\dot{Q}$	heat duty (W)
Re	Reynolds number (–)
T	temperature (°C)
V	velocity (m s^{-1})
x	quality
X	Martinelli parameter (–)

Greek symbols

α	void fraction (–)
Φ	two-phase multiplier (–)
ρ	density (kg m^{-3})
Γ	dimensionless Chisholm (1973) parameter
μ	dynamic viscosity (kg m^{-1} s^{-1})
ψ_H	homogeneous flow multiplier (–)
ψ_S	separated flow multiplier (–)

Subscripts

f	frictional pressure drop
in	test section inlet
L	liquid phase
LO	liquid-only
out	test section outlet
sat	saturated
sec	secondary coolant heat exchanger
test	test section
V	vapor phase

1. Introduction

The HVAC&R industry has updated air-conditioning and refrigeration systems to utilize HFCs (hydrofluorocarbons) in response to environmental concerns and the pertinent legislation. In high-temperature lift vapor compression applications, HFC blends R404A and R410A have replaced the previously used working fluids. R404A is a near-azeotropic mixture of R125, R143a and R134a (44/52/4% by mass) with properties similar to CFC R502, whereas R410A is an azeotropic mixture of equal proportions by mass of R32 and R125 with properties similar to those of HCFC R22. The critical temperature and pressure of R404A are 72.05 °C and 3729 kPa, respectively, while the corresponding values for R410A are 71.36 °C and 4903 kPa, respectively. In comparison, the critical temperature and pressure for R22 are 96.15 °C and 4990 kPa, respectively. Thus, at the high heat rejection temperatures in high-temperature-lift space-conditioning and water heating systems, the operating pressures of these blends approach, and even exceed, the critical pressure. Thus, despite the design and adoption of equipment using these replacement fluids by various equipment manufacturers, an understanding of the underlying two-phase flow phenomena and their impact on pressure drop and heat transfer has lagged.

For condenser design, it is necessary to accurately model pressure drop. In horizontal channels, the two-phase condensation pressure drop is strongly coupled to the local flow regime and the fluid properties. At near critical pressures ($0.8 \le P_r \le 1$), the vapor dome narrows and the difference between the saturated liquid and vapor properties decreases, with the ratio between the two approaching unity at the critical point. Pressure drop during condensation of refrigerants in this operating range is not well understood, particularly in small diameter channels. Thus, this study measures the local pressure drop for R404A and R410A condensing in horizontal channels with $0.76 \le D \le 9.4$ mm in small quality increments in the mass flux range $200 \le G \le 800$ kg m^{-2} s^{-1}. Then, the results are compared with the limited correlations in the literature and the degree of agreement is evaluated. Finally, a new model for prediction of condensation pressure drop of high-pressure refrigerants is introduced and validated for the experimental conditions of interest.

2. Prior work

The pressure drop during condensation arises from shear stresses imposed by the surrounding tube wall, the interaction of the two phases, and a deceleration component due to the change in density during condensation. As the low-density vapor condenses to a higher-density liquid, the overall flow velocity decreases, resulting in an increase in static pressure. The deceleration pressure change acts opposite to the frictional pressure drop, reducing the overall measured pressure drop.

One of the most common methods of modeling pressure drop is through the two-phase multiplier approach, where the two-phase pressure drop is related to that of a single phase flow. Examples include the Lockhart and Martinelli (1949), Chisholm (1967) and Friedel (1979) correlations. Lockhart and Martinelli (1949) developed a widely used correlation for two-phase pressure drop by relating the Martinelli parameter, X, to the liquid and gas two-phase multipliers. The Martinelli parameter is the square root of the ratio of the pressure drop in the pipe if the liquid phase flowed alone to the pressure drop if the gas phase flowed alone. Their investigation included data for adiabatic two-phase flow in horizontal tubes for air, benzene, kerosene, water and various oils in round tubes ranging from 1.49 to 25.83 mm. The pressure drops were correlated based on whether the liquid flow and gas flow were laminar or turbulent. Chisholm (1967) developed a correlation (Eq. (1)) for the two-phase multiplier, which showed good agreement with the study of Lockhart and Martinelli (1949). The constant C accounts for the pressure drop arising from the coupling between the liquid and vapor phases and is a function of the flow regime (i.e., laminar or turbulent) of the liquid and vapor phases.

$$\Phi_L = \left(1 + \frac{C}{X} + \frac{1}{X^2}\right)^{1/2} \quad (1)$$