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Comprehensive experimental investigation of two-phase heat transfer and pressure drop with propane in a minichannel

*Davide Del Col**, *Matteo Bortolato*, *Stefano Bortolin*

Dipartimento di Ingegneria Industriale, Università degli Studi di Padova, Via Venezia 1, 35131 Padova, Italy

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ABSTRACT

The use of hydrocarbons as natural refrigerants inside small diameter channels allows charge minimization and therefore it may be an interesting option in the refrigerating and heat pump technology. The aim of the present experimental work is to fully characterize the thermal performance of propane (R290) in minichannels by measuring frictional pressure drop, condensation and flow boiling heat transfer coefficients inside a circular cross section horizontal minichannel with an internal diameter of 0.96 mm and a rough inner surface. Measurements of frictional pressure drop during adiabatic two-phase flow have been performed at mass velocity ranging between 200 and 800 kg m^{-2} s^{-1}. Local heat transfer coefficients have been measured during condensation and during flow boiling in the mass velocity range from 100 to 1000 kg m^{-2} s^{-1}. The present database, including frictional pressure gradient, condensation and vaporization heat transfer coefficients, is compared against predicting correlations available in the open literature.

Etude générale expérimentale du transfert de chaleur diphasique et de la chute de pression de propane dans un minicanal

Mots clés : Minicanaux ; Propane ; Ecoulement en ébullition ; Condensation ; Chute de pression

1. Introduction

Nowadays, there is an increasing interest in refrigerants possessing low global warming potential (GWP) because of a higher attention to environmental problems and climatic changes leading to a growing number of regulations and laws promulgated by the main international organizations. The search for alternatives primarily focuses on the use of natural refrigerants in heat pump and air conditioning equipment or in industrial processes, because the direct effect on the anthropogenic global warming due to atmospheric emissions

* *Corresponding author*. Tel.: +39 049 8276891; fax: +39 049 8276896.
E-mail address: davide.delcol@unipd.it (D. Del Col).
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Nomenclature

a_0, …, a_M	coefficients of the water temperature fitting equation
Bo	boiling number [/]
Co	confinement number [/]
c	specific heat [J kg^{-1} K^{-1}]
d_h	hydraulic diameter [m]
e_P	percentage deviation = 100 ($y_{CALC}-y_{ExP}$)/y_{ExP} [%]
e_R	average deviation = (1/N_P) Σe_P [%]
|e_R|	absolute mean deviation = (1/N_P) Σ|e_P| [%]
f	friction factor [/]
f_{opt}	optimum value of the pair frequency in Eq. (20) [Hz]
G	mass velocity [kg m^{-2} s^{-1}]
g	gravitational acceleration [m s^{-2}]
h	specific enthalpy [J kg^{-1}]
$h_{LV} = h_V - h_L$	latent heat of vaporization [J kg^{-1}]
HTC	heat transfer coefficient [W m^{-2} K^{-1}]
J_G	dimensionless gas velocity = $x\,G/(g\,d_h\,\rho_V\,(\rho_L-\rho_V))^{0.5}$
L_{MS}	distance between pressure ports [m]
$\dot{m}$	mass flow rate [kg s^{-1}]
n	number of reading during acquisition
n_f	exponent in Eq. (20) [/]
N_P	number of data points [/]
q'	local heat flux [W m^{-2}]
q'_{ref}	reference heat flux in Eq. (20) [W m^{-2}]
R^2	R square coefficient of determination [/]
R^2_{adj}	adjusted R square coefficient of determination [/]
Ra	arithmetic mean deviation of the assessed profile according to EN ISO 4287:1998/A1 [μm]
Re	Reynolds number [/]
s	standard deviation for a measured parameter
T	temperature [K]
t	temperature [°C]
u_A	type A uncertainty
u_B	type B uncertainty
u_c	combined experimental uncertainty
We	Weber number [/]
x	thermodynamic vapor quality [/]
y(z), y_1, y_2	fitting function for water temperature as a function of z
z	axial position [m]

Greek symbols

Δp	pressure drop [Pa]
ΔT	temperature difference [K]
θ	directly measured quantity
ε	effective roughness in Churchill (1977) correlation [m]
μ	dynamic viscosity [Pa s]
ξ	quantity expressed as function of uncorrelated inputs
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
σ_N	standard deviation (prediction method) = [Σ $(e_p-e_R)^2/(N_P-1)]^{1/2}$ [%]

Subscripts

CALC	calculated
EXP	experimental
in	inlet
L	saturated liquid
LIQ	liquid phase
LO	liquid only
MS	measuring sector
out	outlet
PS	pre-sector
ref	refrigerant
sat	saturation
sub	subcooled
V	saturated vapor
VAP	vapor phase
wall	wall
wat	water

is almost completely avoided. In particular, hydrocarbons show good materials compatibility and desirable thermodynamic and transport properties, which can also reduce the indirect effect on anthropogenic global warming. Among hydrocarbons, propane is regarded as a long term alternative refrigerant and its employment in the refrigeration applications represents an interesting opportunity as the physical properties are close to those of R22. The GWP over 100 years is lower than 3 for propane, while it is equal to 2100 and for R410A and around 1400 for R134a.

Because of flammability and very low ignition concentration, charge minimization is a major design objective for the equipment when using hydrocarbons as refrigerants. From the previous experience, it appears that the estimated charge of unitary air conditioners is expected to be mainly trapped in the heat exchangers. In particular, Harms et al. (2003) estimated the charge in three unitary air conditioners from 9 kW up to 26 kW using R22 and R407C; they found that the computed charge in the condenser may vary from 30% to 70% of the total amount, while the charge in the evaporator is lower (around 20%). Similar results have been obtained by Corberan and Martinez (2008) for a water-to-water propane heat pump using plate heat exchangers: 50% of the total charge is expected in the condenser, while about 20% should be trapped in the evaporator.

In this regard, minichannel technology appears to be a very good opportunity to minimize the charge without significant performance loss. Hoehne and Hrnjak (2004) experimentally studied the performance of a refrigeration system with a cooling capacity between 1 kW and 2 kW provided with air-to-propane minichannel heat exchangers. The hydraulic diameter of the tubes was 0.75 mm for the evaporator and 1.1 mm for the condenser. As compared to the traditional refrigeration system provided with fin and tube heat exchangers, the minichannel technology enabled the reduction of the internal volume and the charge of propane was decreased from 200 g to less than 130 g, while maintaining the same capacity and coefficient of performance. Cavallini et al. (2010) presented the experimental