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Two-phase heat transfer and pressure drop of propane during saturated flow boiling inside a horizontal tube

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ABSTRACT

Comprehensive heat transfer coefficient and pressure drop data of the two-phase saturated flow boiling for propane were obtained in a smooth horizontal tube at conditions covering mass fluxes from 62 to 104 kg m^{-2} s^{-1}, heat fluxes from 11.7 to 87.1 kW m^{-2}, and saturated temperatures from −35.0 to −1.9 °C. Results indicate that heat transfer coefficients increase with mass and heat flux. For saturation temperature and vapor quality, distinct variation trends were observed depending on different test conditions. The heat transfer experimental data were compared with five well-known correlations. Among those, Liu–Winterton correlation shows the best agreement with a mean absolute relative deviation less than 10%. For two-phase frictional pressure gradients, the influences of saturation temperature, mass flux and vapor quality were also presented. The predicted method of Müller-Steinhagen & Heck correlation gives the best fit to the data with a mean absolute relative deviation less than 20%.

Transfert de chaleur diphasique et chute de pression du propane pendant l'ébullition en écoulement saturé à l'intérieur d'un tube horizontal

Mots clés : Propane ; Ebullition enácoulement ; Transfert de chaleur ; Chute de pression ; Schéma d'écoulement ; Corrélation

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Nomenclature

Bo	boiling number
C_p	specific heat capacity (J kg^{-1} K^{-1})
D	inner diameter of the tube (mm)
g	gravity (m s^{-2})
G	mass flux (kg m^{-2} s^{-1})
h	heat transfer coefficient (kW m^{-2} K^{-1})
H_{lv}	latent heat (J kg^{-1})
L	length of the pressure drop test section (mm)
m	mass flow rate (kg s^{-1})
p	pressure (kPa, MPa)
q	heat flux (W m^{-2})
Q	thermal power (W)
Re	Reynolds number
T	temperature (K)
x	vapor quality

Greek symbol

ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
$\lambda_{30\%}$	percentage of experimental points predicted within ±30%

Subscripts

cal	calculated value
exp	experimental value
frict	frictional pressure drop
in	inlet of the test section
l	liquid phase
mom	momentum pressure drop
out	outlet of the test section
sat	saturation state
sub	subcooled state
v	vapor phase
w	wall

1. Introduction

The increasing awareness of the environmental protection has led to a demand for natural refrigerants in the refrigeration and air conditioning industries. Hydrocarbons (HC's), in particular like propane (R290), are well known as excellent refrigerants. It has been verified to be used as a long term alternative refrigerant both as a pure refrigerant or a major component for several mixed refrigerants due to its good cooling performance and its less impact on the environment (Blanco et al., 2005; Cavallini et al., 2010; Fernando et al., 2004; Jung et al., 2000; Lee et al., 2012; Navarro et al., 2005). With the substitution of old refrigerants by new environmentally friendly ones, characteristics of the heat transfer coefficients are of great significance, as well as the two-phase frictional pressure drop features.

For recent decades, researches of boiling characteristics on natural refrigerants have become more active (Thome, 1996). Some experiments on pool boiling of propane have been undertaken (Shen et al., 1997). However, relevant experimental data about flow boiling heat transfer and pressure drop characteristics of pure propane in tubes are still not enough.

A number of studies of mixtures with propane as a component were reported (Thome et al., 2008). Zou et al. (2010) presented saturated flow boiling heat transfer coefficients in a horizontal tube of the binary mixtures of R170/R290. The degradation of mixtures increases as increasing the heat flux and decreases as the vapor quality or the mass flux increases. The influence of saturation pressure is unapparent, while the mass flux does have a significant effect. A modified correlation was developed based on their previous pool boiling heat transfer database, which shows an acceptable agreement with the experimental data for predicting the heat transfer coefficients of both pure refrigerants and mixtures. Grauso et al. (2011) conducted an experimental study on flow boiling of CO_2 and propane mixtures in a smooth horizontal tube with an internal diameter of 6 mm. The results confirm a strong degradation of heat transfer respect to the ideal heat transfer coefficient for mixtures. Results show the heat transfer coefficients are only slightly dependent on the mass flux and the working temperature, while strongly influenced by the heat flux.

A few researches on pure propane two-phase flow boiling characteristics were reported. Watel and Thonon (2002) conducted an experimental study on propane flow boiling during a vertical upflow inside a compact serrated plate-fin exchanger. The experimental conditions reflect those occurring in industrial applications. An analysis of measured convective boiling heat transfer coefficients, without nucleate boiling, shows the separate effects of quality, mass flux, and pressure. Lee et al. (2005) presented experimental results of heat transfer characteristic and pressure gradients of such hydrocarbon refrigerants as R290, R600a, R1270 and HCFC refrigerant R22 during evaporating inside horizontal tubes. Similar results were observed that the local evaporating heat transfer coefficients and pressure drop of hydrocarbon refrigerants were higher than those of R22. Moreover, in their study, the average evaporating heat transfer coefficient increases with the mass flux, and a peak point appears at 0.85 as for the influence of vapor quality. As for the influence of vapor quality on the pressure drop, a highest value of pressure drop is shown at 0.6 quality point. Compared with existing correlations, the heat transfer coefficient experimental results are well matched with Shah's correlation, Kandlikar's correlation and Gungor–Winterton's correlation. Choi et al. (2009) reported the convective boiling pressure drop and heat transfer experiments of propane in horizontal smooth minichannels with inner diameters of 1.5 mm and 3 mm. The experimental results show that pressure drop is a function of mass flux, inner tube diameter, surface tension, density and viscosity. A new pressure drop correlation was developed on the basis of the Lockhart–Martinelli method as a function of the two-phase Reynold number and Webber number. Mass flux, heat flux and saturation temperature have an effect on the heat