Experimental Thermal and Fluid Science 72 (2016) 112–124

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Flow boiling characteristics of R134a and R245fa mixtures in a vertical circular tube

Gholamreza Bamorovat Abadi, Eunkoo Yun, Kyung Chun Kim *

School of Mechanical Engineering, Pusan National University, San 30, Jangjeon-dong, Geumjeong-gu, Busan 609-735, Republic of Korea

ARTICLE INFO

Article history:
Received 25 August 2015
Received in revised form 28 October 2015
Accepted 3 November 2015
Available online 10 November 2015

Keywords:
Refrigerant mixtures
Heat transfer coefficient
Flow boiling
High speed visualization

ABSTRACT

Considerable attention has recently been given to making new refrigerant mixtures for applications such as organic Rankine cycles (ORCs). In this study, the flow boiling of a mixture of R134a and R25fa was visualized. Mixtures at different molar fractions ranging from pure R245fa to a molar concentration up to 50% R245fa–50% R134a were chosen. The ranges of mass flux and heat flux were 300–800 kg/m^2 s and 1–69 kW/m^2, respectively. A circular glass tube with a 3-mm inner diameter and 200-mm length was used. In each case, different flow regimes were recognized, such as bubbly flow, slug flow, and annular flow. Throat-annular flow was observed in limited cases but not in all mixtures. The heat transfer coefficient in each case was analyzed carefully. Degradation of the heat transfer coefficient due to the mass transfer resistance is discussed, and the heat transfer coefficient of the mixtures is shown to be lower than that of the original pure refrigerants. The heat transfer coefficient data were compared to predictive methods in the literature, and a modified version of correlations is proposed for the mixture of R134a and R245fa.

1. Introduction

Pure refrigerants maintain a constant temperature during a phase change at a constant pressure, whereas some of their mixtures do not. For example, zeotropic mixtures experience a temperature glide during a phase change under constant pressure. Refrigerant mixtures do not have the same concentration in the liquid and vapor phases, which is a well-known phenomenon [1] that has mostly been considered a disadvantage for refrigeration cycles. However, with the introduction of organic Rankine cycles (ORC), it has been proven that the temperature glide of zeotropic mixtures can be an advantage [2–4].

Many have performed visualization studies on pool boiling and flow boiling of R134a and R245fa as pure refrigerants [5–11]. Saisorn et al. conducted flow boiling visualization experiments on R134a refrigerant in a horizontal circular channel with a 600-mm length and an inner diameter of 1.75 mm [12]. They published the flow pattern and local heat transfer coefficient data for R134a and visualization of different flow regimes. They reported five different flow regimes, including slug flow, throat-annular flow, churn flow, annular flow, and annular-rivulet flow in a range of mass and heat fluxes, vapor qualities, and saturation pressures. Their heat transfer results were also compared with existing prediction methods. Later, they compared their experimental data with their previous data from the flow boiling of R134a in a vertical mini channel to examine the effect of the flow direction [13]. They reported that the flow regimes and heat transfer coefficient depend on the flow direction under their experimental conditions.

Tibiriçá et al. used R134a and R245fa to visualize flow boiling in a 2.3-mm inner-diameter tube [14]. They characterized the heat coefficient distribution of these refrigerants as a function of the vapor quality. In their experiment, the mass velocity, heat flux, and vapor quality ranges were 50–700 kg/m^2 s, 5–55 kW/m^2, and 0.05–0.99, respectively. The heat transfer coefficient strongly depended on the mass and heat fluxes as well as the vapor quality of the refrigerant.

Yin et al. visualized the flow boiling of R134a in a horizontal circular duct with an inner diameter of 6.35 mm [15]. They examined the onset of nucleate boiling (ONB), during which there was strong hysteresis. They characterized the bubble behavior and its frequency on the wall. They concluded that if subcooling is increased, the heat transfer would be much better.

R134a has also been the subject of flow boiling experiments in other studies. Owhaib et al. performed flow boiling visualization of R134a in a vertical circular mini channel with a 1.33-mm diameter [16]. They examined the flow pattern and dryout of the liquid film at various mass and heat fluxes. They concluded that when the mass flux is low, the location of the fluid front fluctuates, and a thin

* Corresponding author.
E-mail address: kckim@pusan.ac.kr (K.C. Kim).

http://dx.doi.org/10.1016/j.expthermflusci.2015.11.006
0894-1777/

Nomenclature

T	temperature (K)
G	mass flux (kg/m^2 s)
P	test section perimeter (m)
z	distance from inlet of test section (m)
q	heat flux (W/m^2)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
C_p	specific heat (J/kg K)
A	cross sectional area (m^2)
x	vapor quality (–)
X	liquid phase mole fraction
Y	vapor phase mole fraction
ρ	density (kg/m^3)
β	mass transfer coefficient (m/s)
p	pressure (kPa)
d	diameter (m)
μ	viscosity (Pa s)
X_{tt}	Martinelli parameter
Re	Reynolds number
Pr	Prandtl number
σ	surface tension (N/m)
$\tilde{\rho}$	density (kmol/m^3)
$\tilde{h}_{fg}$	latent heat of evaporation (J/kmol)
P_r	reduced pressure
M	molecular weight (g/mol)
q_{vol}	volumetric heat flux (W/m^3)
h_{fg}	latent heat of evaporation (J/kg)
$\dot{m}$	mass flow rate (kg/s)
Q	heat transferred (W)

Subscripts

i,in	inlet
o,out	outlet
sat	saturation
1	more volatile component
2	less volatile component
id	ideal
l	liquid
cr	critical
lo	liquid only
v	vapor
tp	two phase
vo	vapor only
nb	nucleate boiling
fc	forced convective boiling
pre	predicted value
exp	experimental value

film is formed between waves created in the tube. However, when the mass flux is high, the location of the liquid front is more stable.

R245fa is a relatively new refrigerant that has attracted attention recently because of its great performance in ORC. Although its global warming potential might not be appealing, it has no ozone depletion potential and is non-toxic. In addition to Tibiriçá et al. [14], Charnay et al. used R245fa as a refrigerant in their flow boiling experiment at high saturation temperatures [17] and medium saturation temperatures [18]. They published optical techniques and experimental results for the flow pattern characterization of R245fa [19]. They characterized the flow patterns and transitions of flow regimes at different saturation temperatures and mass and heat fluxes in a horizontal circular tube with a 3-mm diameter. They reported four main flow regimes: intermittent flow, annular flow, dryout, and mist flow. Charnay et al. [17] found the flow type to be closer to the micro-scale type at high saturation temperatures. Another study reported that at saturation temperatures of 60 °C and 80 °C, the heat transfer coefficient does not vary with the vapor quality or mass velocity when the flow is intermittent but is dependent on the heat flux [18]. In addition, in annular flow, if the vapor quality or mass velocity increases, the heat transfer coefficient also increases. Hence, nucleate and convective boiling occur concomitantly.

The behavior of R134a and R245fa under a variety of conditions is predictable, but the behavior of their binary mixtures is not completely understood. Binary mixtures in ORC applications have the potential to improve efficiency and power output by reducing irreversibility in heat exchangers with phase changes. Unlike pure refrigerants, which have a straight horizontal phase-change line in their T–s diagram, zeotropic binary mixtures experience a temperature glide in their phase change and can be adjusted to follow the heat source temperature line with a constant distance, which reduces the irreversibility compared to pure refrigerants. Before using such a mixture in an ORC power generation system, the flow boiling needs to be investigated. The present paper discusses the flow boiling visualization results for binary mixtures of R245fa–R134a under various conditions and molar fractions along with the heat transfer characteristic data of the mixture.

2. Experimental setup

2.1. Refrigerant loop

Fig. 1(a) shows the experimental setup used in this study. The setup was a closed loop consisting of a reservoir tank behind a pump to ensure smooth flow. The gear pump has a 170-W motor with a frequency controller. Immediately after the pump is a positive displacement flowmeter with a digital indicator. A preheater precedes the test section to control the inlet temperature of the flow. Parallel to the test section is a bypass pipe with a controllable valve to adjust the mass flow in the test section. Because it is a closed loop, an orifice was used after the test section and before the condenser to produce a pressure difference in the system, which is necessary for the pump to work properly. Next to this, there is a condenser in the form of a plate heat exchanger connected to an air-cooled chiller. The fluid cools down, condenses, and returns to the reservoir tank, thus completing one loop.

Pressure transducers and K-type thermocouples were installed around the loop to monitor and control the pressure and temperature during the experiment. These measurement devices and the digital output of the flowmeter were connected to a data acquisition system that was monitored by a customized LABVIEW program.

2.2. Refrigerants

The properties of the pure fluids and mixtures with different molar concentrations are summarized in Table 1. Fig. 2 shows the properties of the mixture as a function of composition, and Fig. 3 shows the temperature–composition diagram for R245fa/R134a mixture at 4 bar.

2.3. Test section

The test section for this experiment consists of two parts. First, there was a stainless-steel tube with an outer diameter of 6 mm