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Research Paper

Experimental flow boiling characteristics of R134a/R245fa mixture inside smooth horizontal tube

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HIGHLIGHTS

- Flow boiling characteristics of R245fa mixture were investigated experimentally.
- Influences of mass flux, heat flux and evaporation pressure were obtained.
- R134a/R245fa has less pressure drop and higher heat transfer coefficient than that of pure fluid.
- Correlation for predicting the heat transfer coefficient were developed for the mixture.

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ABSTRACT

The flow boiling characteristics were experimentally studied in smooth horizontal tube for pure R245fa and one of its mixtures, R134a/R245fa with 0.82/0.18 in mass fraction, which was regarded as a promising working fluid for Organic Rankine Cycle (ORC). The flow boiling heat transfer coefficient and pressure drop for the two fluids were measured under different vapor quality, mass flux, tube wall heat flux and evaporating pressure. Correlation for predicting the flow boiling heat transfer coefficient was developed for the selected mixture based on the experimental data. The results indicated that the flow boiling heat transfer coefficients of the two working fluids went up with mass flux, heat flux and evaporating pressure under the experimental conditions. The mixture of R134a/R245fa with 0.82/0.18 in mass fraction had less pressure drop, but higher heat transfer coefficient than that of the pure R245fa. The absolute errors of 89% experimental data are within 10% of prediction of the present developed correlation for the mixture. The results may benefit the potential utilization of R134a/R245fa in ORC.

1. Introduction

Organic Rankine Cycle (ORC) has a broad prospect in the utilization of low-grade heat source, which attracts lots of research interests recently [1,2]. It is well known that the working fluids have great effects on the performance of ORC [3,4]. And also, the mixture has more advantages than pure working fluids under specific heat source and heat sink conditions [5,6], of which the heat transfer characteristics are the bases for the design of heat exchangers and optimization of ORC.

Numerous investigations have been conducted regarding the flow boiling characteristics of mixtures [7–13]. Van Wijk et al. [7] analyzed the influence of boiling point of refrigerant mixtures on the flow boiling performance, and explained that the inhomogeneity in the fluid consistency affects the heat transfer characteristics. Li et al. [8] investigated flow boiling heat transfer of the refrigerant mixture, HFO1234yf/R32, and found out that the nucleate boiling heat transfer is noticeably suppressed at low vapor quality for small boiling numbers, whereas the forced convective heat transfer is significantly suppressed at high vapor quality for large boiling numbers. Scriven et al. [9] considered the influence of mass transfer on the growth of a bubble in a binary mixture.

However, most studies on heat transfer of organic working fluids only considered the refrigerating cycle. Based on the previous studies, a mixture of R134a/R245fa with 0.82/0.18 in mass was selected as working fluid for ORC utilization in this paper. One of its components, R134a, is commonly used in refrigeration, while its flow boiling characteristic has been studied extensively [14–20]. R245fa has not been widely used as a refrigerant and the research of which is few. Ong et al. [19] compared the heat transfer coefficients of R134a, R236fa and R245fa in a 1.03 mm i.d. horizontal tube. The results showed that R134a has the best heat transfer

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Nomenclature

Bo	boiling number
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
D	diameter of tube, m
G	mass flux, kg m^{-2} s^{-1}
h	heat transfer coefficient, W m^{-2} K^{-1}
i_{lg}	latent heat of evaporation, J kg^{-1}
I	current, A
L	length of test section, m
M	molecular weight, g mol^{-1}
p	pressure, MPa
Pr	Prandtl number
q	heat flux, W m^{-2}
Re	Reynolds number
T	temperature, °C
V	voltage, v
w	power, W
x	vapor quality
Xtt	Lockharte Martinelli number
z	axial position, m

Greek symbols

Δ	difference
η	efficiency
λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, Pa s
ρ	density, kg m^{-3}

Subscripts

exp	experiment
f	working fluid
g	gas
i	inside
l	liquid
o	outside
sat	saturated
the	thermal
TP	two-phase
v	vapor
w	wall

performance under the experimental conditions, followed by R245fa. Tibiriçá et al. [20] measured flow boiling heat transfer coefficients of R134a and R245fa. The results showed that correlations of Saitoh et al. [14], Liu and Winterton [15] and Zhang et al. [16] fitted best. Bortolin et al. [21] conducted a flow boiling experiment of R245fa in a 0.96 mm i.d. tube and compared the results with the existing correlations. Agostini et al. [22,23] investigated the heat transfer features of R245fa and R236fa in microchannel, and found out that the heat transfer coefficient of R245fa is larger than that of R236fa.

In this paper, new experimental data of flow boiling heat transfer inside a 3 mm i.d. horizontal stainless steel tube for R245fa, as well as mixture of R134a/R245fa are obtained. The results may benefit the potential utilization of R134a/R245fa mixture as a promising working fluid used in ORC.

2. Physical properties of the selected mixture

Zeotropic mixtures are characterized by non-isothermal phase transitions at constant pressure, which have sloped phase-change profiles that may match well with heat source and heat sink in the cycle. This feature enables zeotropic mixtures to be excellent candidates for ORC system, reducing the exergy loss and improving the system performance [5,24,25]. However, the optimal mixtures for different heat source and heat sink profiles are different. When heat source inlet temperature is 100 °C and heat source temperature glide in evaporator is larger than 30 °C, it can be found from Fig. 1 that the mixture of R134a/R245fa with 0.82/0.18 in mass fraction shows the best performance [26]. For this reason, the mixture of R134a/R245fa with 0.82/0.18 in mass is selected as working fluid of ORC for low grade heat recovery, of which the flow boiling characteristic is investigated in this paper.

There are no essential differences in flow boiling characteristics caused by evaporating pressure under the subcritical conditions of the mixture, as shown in Table 1. In addition, the inlet temperature of the expander of ORC can be lower than 80 °C, even as low as 40 °C [27]. In order to simplify the test facilities to obtain accuracy experimental results, the evaporating temperature in this paper ranged from 33 to 46 °C for R245fa and 28 to 43 °C for the mixture selected.

The properties of working fluids at the saturation temperature of 20 °C are summarized in Table 1. In the case of a mixture, the saturation temperature is the bulk temperature at a vapor quality of 0.5. The REFPROP data base used for the properties of the present fluids come from the empirical equations of state for mixtures based on experimental data. These data are used to determine the structures, coefficients, and parameters of the correlation equations and to evaluate the behavior of the equation of state in different fluid regions. The models of Kunz et al. [28] and Lemmon and Jacobsen [29] are employed for calculating the thermodynamic data in REFPROP.

3. Experimental setup and data acquisition

3.1. Test facilities

The experimental setup which is used to investigate the evaporation heat transfer characteristics of working fluids is shown in Fig. 2. This setup mainly includes a test section, a pre-heater to

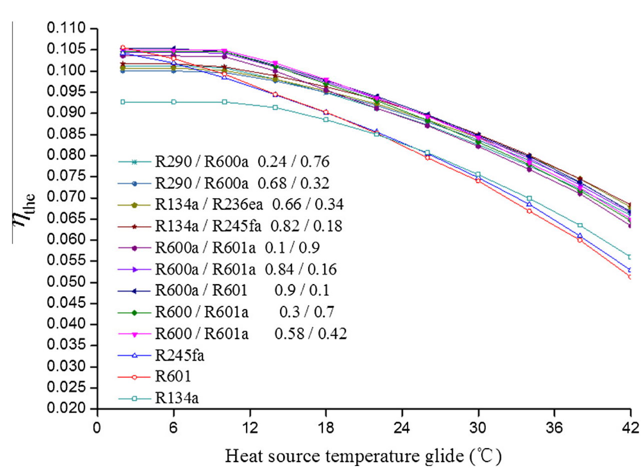

Fig. 1. Variations in cycle thermal efficiency with the heat source temperature gradient for different working fluids without recuperator for the heat source at 100 °C and the heat sink at 20–26 °C [26].