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A new flow pattern map for flow boiling of R1234ze(E) in a horizontal tube

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ABSTRACT

Considerable attention has recently been given to the new environment-friendly refrigerant of R1234ze(E) for applications such as heat pump and air-conditioning systems. In this study, an experiment was carried out to investigate two-phase flow patterns and flow transitions for R1234ze(E) in a smooth horizontal tube with an inner diameter of 6 mm. The experiments were performed at conditions covering saturation pressures from 0.215 to 0.415 MPa, mass fluxes from 130 to 258 kg/m^2 s and heat fluxes from 10.6 to 74.8 kW/m^2. The influences of saturation pressure, mass flux and heat flux on flow pattern transition were analyzed. Six well-known flow maps have been compared with the observed flow patterns of R1234ze(E). The results indicated that none of them can predict all the flow pattern transitions well. Thus, three dimensionless numbers K_1, K_2 and K_3 which represent the ratio of the evaporation momentum force to the inertia force, the evaporation momentum force to the surface tension force, and the shear force to the gravity force respectively were introduced. Based on dimensionless numbers K_1, K_2, K_3 and X_{tt}, a new flow pattern map for R1234ze(E) was proposed which could accurately predict the experimental data.

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1. Introduction

As refrigerants, hydrofluorocarbons (HFCs) are widely used in refrigeration and heat pump system. HFCs have zero ozone depletion potential (ODP) value, but they do have large global warming potential (GWP) value, which can lead to global warming. In 1997, the Kyoto Protocol issued rules to restrict the use of greenhouse gases including R134a and R32. Besides, United Nations (UN) F-gas regulation also established the limitations to the refrigerants with GWP value larger than 150 in new vehicle from 1 January 2011 and for all vehicles from 1 January 2017 (Union, 2006). Therefore, the use of environment-friendly refrigerant which has low-GWP and low-ODP value would be urgent demands in the refrigeration industry. In the recent years, halogenated olefins (HFOs) as one of the most promising alternatives have been investigated as possible solutions (Liu et al., 2016). In particular, R1234ze(E) (trans-CHF=$CHCF_3$) has low flammability, non-toxicity, zero ODP and quite low GWP (Mota-Babiloni et al., 2016; Stocker et al., 2013), is used as a promising substitute for the current refrigerant R134a. What's more, among its good environmental properties, R1234ze(E) has an atmospheric lifetime of only 11 days, while the R134a has 13 years.

Due to the good characteristics, R1234ze(E) is used as a near drop-in replacement to R134a in a lot of applications: from refrigeration to heat pump (Mota-Babiloni et al., 2014). Hence, many researches were investigated to analyze and evaluate the performance of R1234ze(E). Fukuda et al. (2014) evaluated the thermodynamic attribute of R1234ze(E) thermodynamically, experimentally and numerically. The results showed that R1234ze(E) has more potential for high-temperature heat pump systems rather than typical air conditioners or refrigeration systems. Janković et al. (2015) conducted an experiment to analyze R1234ze(E) as drop-in replacements for R134a in a small power refrigeration system. The drop-in analysis results showed that R1234ze(E) may perform better than R134a if an overridden compressor is used to match the refrigerating system cooling power. Motta et al. (2010) indicated that R1234ze(E) is a potential refrigerant for small commercial and residential refrigeration systems. They also evaluated the performance of R1234ze(E) in an actual vending system and result showed that the comparable performance to R134a can be achieved without significant hardware modification. Ansari et al. (2014) applied energy and exergy analysis method to compare R1234ze(E) with R134a theoretically. The result indicated that performance

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parameters of COP and exergetic efficiency for R1234ze(E) are almost same with R134a which only having a difference of 5.6%. Hence, R1234ze(E) is supposed as a good replacement to R134a if a certain modification is done in the design.

As the performance of R1234ze(E) is evaluated and R1234ze(E) is verified suitable as a drop-in replacement for R134a in several applications, thus, the investigations of flow characteristics of R1234ze(E) is becoming more and more important. Ribatski and Thome (2007) pointed out that it is essential to develop an accurately predictive methods to estimate heat transfer coefficient, pressure drop, void fraction and flow patterns in order to design more efficient and compact heat exchangers. They also indicated that system thermal efficiency of heat exchangers always depends on the heat transfer coefficient and the pressure drop directly, while the flow characteristics such as pressure drop rely on the void fraction. However, these parameters in turns depend on the local flow pattern, because the different flow pattern leads to the different phase distributions which result in the distinct for heat transfer coefficients, pressure drops and void fractions. Rollmann and Spindler (2015) also indicated that flow patterns have a significant influence on the heat transfer coefficient and the pressure drop during flow boiling process. The flow characteristics of working fluid play important parts in designing the heat exchangers. Therefore, the investigation on two-phase flow pattern are essential. Over the past decades, due to the important role of two-phase flow pattern in the industrial equipment, the studies related to two-phase flow patterns are still attractive. Many researches have been done to investigate the two-phase flow patterns of different refrigerants and develop new flow pattern transitions.

Taitel and Dukler (1976) put forward a theory model to predict the flow pattern transitions in an horizontal tube by taking the effect of properties of the fluids, pipe diameter, and angle of inclination into account. The theory model was developed without flow regime data and the mechanisms of flow pattern transition were based on physical concepts. After a comparison with the experimental data, this theory model showed a good predictive ability. Barnea et al. (1983) found that with decrease of pipe diameter, the deviation between the predictive models (Taitel and Dukler, 1976; Taitel et al., 1980) and experimental data was accentuated. So they modified the theoretical models by taking surface tension effects into account. Furthermore, they also drew a conclusion that surface tension play a major role in the stratified-intermittent transition in small pipes, while for large pipes the Kelvin-Helmholtz instability is the dominant factor. Kattan et al. (1998) performed tests with R134a, R123, R402A, R404A and R502 in a tube with a diameter of 12.0 mm and proposed a new flow pattern map included four improvements to the Steiner (1993) map. In the new flow pattern map, the new transition curve between stratified-wavy flow pattern and annular flow pattern was adjusted by taking account of the influence of the heat flux and onset of dryout at high vapor quality. Importantly, in order to identify the flow patterns for convenience, the map was also transformed into a mass velocity versus vapor quality format. Zürcher et al. (2002) found that void fraction is not a continuous function during the flow pattern transition. Thus, different void fraction was used for different flow pattern in the new flow transition models. Based on experimental data of flow patterns for R717, R134a, R407C covering a wide range of conditions and flow pattern model of Kattan et al. (1998), a modified flow pattern model was proposed which took the inception of dryout at the top of tube into account. Through a comparison with the experimental data, this proposed modifications showed a good agreement with flow pattern transitions for different fluids. Wojtan et al. (2005a) proposed new flow pattern transitions of annular to dryout and dryout to mist based on new heat transfer measurements and flow pattern observations. And these two new transition curves were added into Kattan et al. (1998) map. According to the dynamic void fraction measured by optical void fraction measurements technique, stratified-wavy region has subdivided into three subzones: slug, slug-stratified wavy and stratified wavy. Besides, vapor qualities corresponding to the flow transition of stratified to stratified wavy flow has also been modified. These modifications of flow transitions not only promote the prediction accuracy of flow pattern transition but also improve the identification of the dryout start. Revellin and Thome (2007a) conducted a flow boiling experiment for R134a and R245fa in tubes with diameter of 0.509 and 0.790 mm under the diabatic condition. Based on the observations, flow patterns were classified into three types and a new flow pattern transition correlation was proposed. This new flow pattern transition correlation was expressed by the dimensionless numbers of liquid Reynolds number, the liquid Weber number and Boiling number. Furthermore, they also pointed out the feasible operating range of microevaporators which made with circular microchannels can also be determined by using this flow pattern map. Barbieri et al. (2008) conducted an experiment of convective boiling for R134a in smooth brass tubes with inner diameters varying from 6.2 mm to 12.6 mm. Flow patterns was obtained through a sight glass and the data of flow patterns were mapped out. They found that mass velocity, vapor quality and inner tube diameter have effects on the intermittent to annular transition. By taking these effective parameters into account, two dimensionless numbers of liquid Froude number Fr_l and Martinelli parameter X_{tt} were introduced. Furthermore, data points related to the intermittent to annular transition in terms of the liquid Froude number Fr_l and Martinelli parameter X_{tt} under the logarithmic coordinates are found grouping around a linear curve. Based on this phenomenon, a new intermittent to annular transition correlation is developed. Ong and Thome (2011a) conducted an experiment to investigate the two-phase flow patterns of R134a, R236fa and R245fa in tubes with diameters of 1.03, 2.2 and 3.04 mm. A new macro-microscale flow pattern map was proposed by taking gravity, inertia and surface tension effects into accounts. What's more, they also found that gravity force is a dominant factor on the flow pattern transitions when confinement number less than 0.34, while it is suppressed when the confinement number larger than 1. Costa-Patry and Thome (2013) found a phenomenon that the initial vapor quality of coalescing bubble flow regime to annular flow transition is closed to inflection point where the minimum value of heat transfer coefficients occur. This phenomenon can be used to track the flow pattern transition. By using this criteria, a new coalescing bubble to annular flow transition equation was developed. Three database from Ong and Thome (2011b) and Costa-Patry et al. (2011, 2012) were introduced to compare with the new flow pattern transition, and the results indicated that within the experimental resolution the prediction accuracy can reach about 95%.

Although many researches on two-phase flow patterns and flow pattern transitions were conducted, most of them were developed for adiabatic conditions. Besides, an investigation on flow characteristics of R1234ze(E) is rarely reported and flow pattern transition of R1234ze(E) is still lacking. In this work, the experiment on flow characteristics was conducted under several operating conditions covering saturation pressures from 0.215 to 0.415 MPa, mass fluxes from 130 to 258 kg/m^2 s, heat fluxes from 10.6 to 74.8 kW/m^2 and the flow patterns were captured through high speed camera. The effect of mass flux, heat flux and saturation pressure on two-phase flow pattern transitions were studied and the transition mechanism was analyzed. Moreover, prediction models from the literature were used to compare with the experimental data. By taking inertia force, surface tension force, shear force, gravity force, evaporation momentum force into account, three dimensionless numbers were introduced. Based on the

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