Adiabatic Two-Phase Flow Patterns for Zeotropic Mixtures of Tetrafluoromethane/Ethane in a Horizontal Smooth Tube

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Abstract. Mixed-refrigerant Joule-Thomson refrigeration (MJTR) systems have distinct advantages in the temperature range from 80 to 230 K. Tetrafluoromethane (R14) and ethane (R170) are essential components of mixed-refrigerants. Heat transfer and pressure drop for two-phase flow are closely related to corresponding flow patterns. In this paper, an experimental investigation on adiabatic two-phase flow patterns for R14/R170 mixtures in a horizontal smooth tube with inner diameter of 4 mm was presented. Experiments were carried out at mass fluxes from 100 to 350 kg m⁻² s⁻¹ and saturation pressures from 1.5 to 2.5 MPa over the entire range of vapor quality. The effects of concentration, mass flux, saturation pressure and vapor quality were analyzed and discussed. Furthermore, the observed flow patterns were compared with six existing flow pattern maps. Our previous model developed for pure R14 shows the best predictive ability with 80.16% of the data points can be accurately predicted.

Keywords: Flow pattern, Tetrafluoromethane/ethane, Adiabatic, Horizontal tube

1. Introduction

With the rapid development of life science and the increasing demand of clean energy, refrigeration technology in the temperature range from 80 to 230 K is widely required. Gong et al. [1] pointed out that mixed-refrigerant Joule-Thomson refrigeration (MJTR) has distinct advantages in this temperature range: i.e., convenient cooling power adjustability, simple structure, and high reliability due to non-moving parts at low temperature stages. The working fluids of MJTR are typically zeotropic mixtures, which are generally mixed by several pure components. With atmospheric boiling point of 145.1 K and 184.6 K, tetrafluoromethane (R14) and ethane (R170) are essential component of mixed-refrigerants. Regarding to the real performance of MJTR systems, the exergy loss in heat exchanger is a crucial part for MJTR (always greater than 20%). Most fluids in heat exchangers are in two-phase state. Thus, the
investigation and prediction of two-phase flow patterns are crucial for designing and optimizing a MJTR system.

Several well-defined adiabatic two-phase flow patterns have been identified. The common flow patterns in horizontal tubes are the following, bubble flow, stratified flow, wavy-stratified flow, slug flow, plug flow, annular flow and mist flow. Furthermore, Kim et al. [2] subdivided the annular flow into wavy-annular flow and smooth-annular flow, and the flow pattern of the transition from the slug flow to the annular flow was defined as transition flow.

Flow pattern maps are employed to predict the local flow patterns in a tube. In the past few decades, several researches, both analytical and experimental, were directly towards the study of two-phase flow pattern maps. Based on the flow pattern data of R12, R113, R11 in horizontal tubes with diameter ranging from 4.8 to 22 mm, Breber et al. [3] developed a two-phase flow pattern map with modified dimensionless vapor velocity as ordinate and Martinelli parameter as abscissa. Tandon et al. [4] selected dimensionless vapor velocity and void fraction function, \((1-\epsilon)/\epsilon\), as the coordinate axes of their new flow pattern map, and they classed annular flow and semi-annular flow into one region. Barbieri et al. [5] performed experiments to observe two-phase flow characteristics of R134a in horizontal tube. They noted the transition qualities diminish with mass flux and increase with tube diameter. Froude number was contained in their model to account for the effects of mass flux and tube diameter. By applying the force balance analysis of the two-phase flow, Weber number, Bond number, Froude number and Martinelli parameter were employed in the flow pattern model of Nema et al. [6]. By analyzing the flow pattern characteristics of R170, Zhuang et al. [7] put forward the transition criteria by concerning inertia force, viscous force and surface tension force, but gravity force was absent. Recently, our group examined the flow patterns of R14 in a horizontal smooth tube [8]. Plug flow, slug flow, transition flow, wavy-annular flow, smooth-annular and wavy-stratified flow were observed, and relative transition curves were also proposed.

In the present work, an experimental study on adiabatic flow patterns of R14/R170 mixtures over a wide range of operating conditions was implemented. The effects of concentration, mass flux and saturation pressure on two-phase flow pattern transitions were studied and analyzed. Finally, the observed results were compared with six well-known flow pattern maps.

2. Experimental apparatus

2.1. Test facility

Fig. 1 shows a schematic view of the present experimental apparatus for this study. It consists of a test loop and two cooling loops. The subcooled test fluid (R14/R170) is circulated in the test loop with the aid of a magnetic-driven pump. The test fluid passes through a mass flow meter followed by a sheathed preheater. The fluid is partially evaporated to a desired vapor quality in the preheater. After the preheater, the fluid flows through an entrance effect eliminated section which is a horizontal smooth tube. Then, the two-phase flow enters a sight glass using the quartz glass with the inner diameter of 4 mm and length of 100 mm, as shown in Fig. 2.

A Motion Studio high speed camera was used for flow visualization. The high-speed camera has the highest shooting frequency of more than 10,000 FPS and the minimum exposure time of 1 μs. Adiabatic two-phase flow patterns were captured from the sight glass. In order to ensure the accuracy
of the experiments, the preheater and entrance effect eliminated section were insulated by an aluminum plating film and placed in a vacuum chamber as well as sight glass with a vacuum consistently less than 5 Pa. A more detailed description of the experimental apparatus has been shown in the previous work [8].

![Schematic diagram of the experimental apparatus.](image)

**Fig. 1.** Schematic diagram of the experimental apparatus.

![Photograph of the sight glass.](image)

**Fig. 2.** Photograph of the sight glass.

### 2.2. Data reduction and uncertainty analysis

The vapor quality of the sight glass is the vapor quality at the outlet of the preheater, which can be obtained by the $p$-$H$ flash model. The specific enthalpy of the sight glass can be calculated as follows:

$$h = h_{\text{preh}} \left( T_{\text{sub}} \cdot p_{\text{preh}} \cdot X_{\text{R14}} \right) + \frac{Q_{\text{preh}}}{m}$$

where $Q_{\text{preh}}$ is the electrical heat power applied to the preheater, W; $m$ is the mass flow rate, kg s$^{-1}$; $h_{\text{preh}}$ is the inlet specific enthalpy of preheater, J kg$^{-1}$; $T_{\text{sub}}$ is the temperature of the subcooled liquid test fluid entering the preheater, K; $X_{\text{R14}}$ is the initial concentration of R14 in mole fraction; $p_{\text{preh}}$ is the local pressure of preheater, Pa. All the thermophysical properties of mixtures used in this work were obtained with the aid of PR equation of state and Van der Waals mixing rule.

The uncertainties in the present experimental data are estimated with the method suggested by NIST [9]. The individual standard uncertainties of the measurements are summarized in Table 1.
Table 1. Measurement instruments and their uncertainties.

| Parameters       | Instruments                                | Range         | Uncertainties |
|------------------|--------------------------------------------|---------------|---------------|
| Temperature      | PT100 thermometer                          | 80-373 K      | 0.1 K         |
| Absolute pressure| Mensor 6000 pressure transducer             | 0-5 MPa       | 0.02%         |
| Mass flow        | EMERSON Micro Motion ELITE Coriolis mass flow meter | 0-108 kg h⁻¹ | 0.1%          |
| Voltage          | Keithley 2700 multimeter                   | 0-300 V       | 0.01%         |
| Direct current   | ZW1659T amperemeter                        | 0.03-15 A     | 0.2%          |

3. Results and discussion

3.1. Experimental flow patterns

The flow visualization experiments of R14/R170 were carried out over a range of mass fluxes from 100 to 350 kg m⁻² s⁻¹ and a range of saturation pressures from 1.5 to 2.5 MPa over the entire vapor quality range. Within the present experimental conditions, five flow patterns of intermittent flow (it was subdivided into slug flow and plug flow in our previous work [8]), churn flow (has similar definition with transition flow in our previous work [8]), wavy-annular flow and smooth-annular flow were observed. All these flow patterns have been described in detail in previous work [7]. And the representative photographs are illustrated in Fig. 3.

![Photographs of R14 adiabatic flow patterns](image_url)

**Fig. 3.** Photographs of R14 adiabatic flow patterns: (a) intermittent flow, (b) churn flow, (c) wavy-annular flow, (d) smooth-annular flow, and (e) wavy-stratified flow.

The flow pattern transition characteristics of R14/R170 mixtures change with mass flux, saturation pressure and concentration in some regularity. Fig. 4 to Fig. 6 present these effects in detail. Fig. 4 illustrates that the initial vapor qualities decrease with the increase in mass flux. The reason is that higher mass flux leads to higher two-phase velocities and greater inertial force, which results in vapor qualities corresponding to flow pattern transitions occur earlier. Besides, wavy-stratified flow occupies the region of lower mass flux, which also results from the poor inertia effect of lower mass fluxes.

Fig. 5 presents the effect of saturation pressure on flow patterns of R14/R170 mixtures. With the increasing saturation pressure, vapor qualities corresponding to flow pattern transitions tend to decrease. Increasing saturation pressure leads to the decrease in liquid density, while results in the increase in vapor density. That lead to a decrease of vapor void fraction at a similar vapor quality. Thus, intermittent flow will expand to a wide range of vapor quality. In addition, decreasing liquid density and increasing vapor density induce higher liquid velocity and lower vapor velocity, which can weaken the shear force
between two-phase. Then, annular flow will be compressed to a narrow range of vapor quality.

Fig. 6 displays the influence of concentration on flow pattern transitions of R14/R170 mixtures. It can be clearly seen that the inception vapor qualities of flow pattern transitions increase with the increasing concentration of R14. The impact of concentration on flow patterns mainly result from the changing thermodynamic properties. Two-phase densities increase with the increasing concentration of R14, which will generate lower two-phase velocities at a constant mass flux and saturation pressure. Consequently, the feeble inertia force transfers initial vapor qualities to a higher value.

**Fig. 4.** Effect of mass flux on flow pattern transitions of R14/R170 mixtures.

![Graph](image)

**Fig. 5.** Effect of saturation pressure on flow pattern transitions of R14/R170 mixtures.

![Graph](image)

**Fig. 6.** Effect of concentration on flow pattern transitions of R14/R170 mixtures.

![Graph](image)
3.2. Comparison with existing flow pattern maps

In this part, two-phase flow patterns of R14/R170 mixtures are compared with several flow pattern maps from literature, as shown in Table 2. Our previous model shows the best agreement with 80.16% of the data points can be accurately predicted. Fig. 7 depicts the comparisons between R14/R170 flow patterns and existing flow pattern maps. Both flow pattern maps of Breber et al. [3] and Tandon et al. [4] can well predict the majority of annular flow patterns. While, almost all the wavy-stratified flow data fall outside the corresponding region. In the model of Barbieri et al. [5], only transition curve of intermittent to annular flow was proposed and this boundary can accurately predict the tendency of the transition from intermittent flow to annular flow. However, they didn’t put forward the transition lines for other flow patterns. The flow pattern map of Nema et al. [6] successfully predicts most of the wavy-stratified flow, intermittent flow and all churn flow. However, annular flow is predicted at relative higher vapor quality, which is inappropriate with the experimental observations. The flow pattern map of Zhuang et al. [7] shows a relatively poor predictive ability to the present data. This model takes into account the effects of vapor inertia force, liquid viscous force and surface tension, but gravity force is absence, which plays an important role in the present experiments. Furthermore, several wavy-stratified flow data take up the coincide position with other flow patterns in the flow pattern map of Breber et al. [3], Tandon et al. [4], Barbieri et al. [5] and Zhuang et al. [7]. Namely, these models can’t separate the wavy-stratified flow from the other flow patterns, which means these dimensionless number pairs are feeble in predicting all flow regimes. Our previous model [8] developed for pure R14 flow patterns can well capture the transitions between intermittent flow, churn flow, wavy-annular flow and smooth annular flow. And the dimensionless number pairs of $S$ and $X_{tt}$ can isolate all five flow patterns separately. While, the transition line between wavy-stratified and other flows is higher than experimental data, especially for the high values of Lockhart-Martinelli parameter.

Table 2. Statistical assessment of six existing flow pattern maps.

| Models          | $\eta$ (%) |
|-----------------|-------------|
| Breber et al. [3] | 57.26      |
| Tandon et al. [4] | 53.78      |
| Barbieri et al. [5] | 65.44      |
| Nema et al. [6] | 69.31      |
| Zhuang et al. [7] | 58.90      |
| Song et al. [8] | **80.16**  |

($\eta$: the percentage of flow regime data that can be accurately predicted.)
4. Conclusions

This paper presents the observations on flow patterns for R14/R170 mixture over a wide range of mass flux, saturation pressure and vapor quality. The transition vapor qualities between different flow patterns decrease with the increasing mass flux and the decreasing saturation pressure. The increasing concentration of R14 gives a rising transition vapor quality. In addition, all flow patterns were compared with six existing prediction models. The results indicated that our previous model has the best predictive ability with 80.16% of the data points can be accurately predicted.
5. References

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