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Experimental study on the constituent separation performance of binary zeotropic mixtures in horizontal branch T-junctions

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ABSTRACT

In this paper, the constituent separation performance of binary zeotropic mixtures, R134a/R600a, in horizontal branch T-junctions was experimentally investigated. The effects of flow conditions, mixture compositions and T-junction geometries on the constituent separation performance were studied. During the experiments, the inlet mass flux and quality were varied from 200 to 300 $kg{\cdot}m^{-2}{\cdot}s^{-1}$ and from 0.1 to 0.9, respectively. Meanwhile, the mass flux of the branch was regulated by keeping the branch-inlet mass flow ratios of 0.3 and 0.5. Furthermore, constituent distributions were compared for three different inlet R134a mass fractions, namely 0.3030, 0.5202 and 0.7053. The required mass fractions of R134a at the inlet and outlet of T-junctions were calculated based on the measured liquid density. As for the T-junction geometry, the diameter ratio of the branch tube to the inlet tube was set to be 0.75 and 1.0, and three branch angles, namely 45°, 90°, 135°, were considered. In order to represent the degree of actual separation to the complete separation, constituent separation efficiency is defined as the difference of the fractions of constituents taken off in the branch. Based on the generated experimental data, it's found that there generally exists an inflection point of separation around the vapor quality 0.2. Before the inflection point, the efficiency generally increases with the increase of inlet vapor quality. After that, the separation efficiency gradually decreases from the positive to the negative. It means that more R600a is extracted into the branch, due to the lower vapor density and vapor dynamic viscosity. Furthermore, for the three mixture compositions, R134a/R600a with an R134a fraction of 0.3030 has the best constituent separation performance. The largest variation range of outlet fraction is from 0.2559 to 0.3443 under the mass flow ratio of 0.3 and mass flux of 200 $kg{\cdot}m^{-2}{\cdot}s^{-1}$. However, the highest separation efficiency 9.49% is obtained under the mass flow ratio of 0.5. As for the effect of T-junction geometry, when the inlet quality is less than 0.4, increasing the diameter ratio can enhance the constituent separation. Compared with the angles 45° and 135°, the largest separation capacity is obtained by the angle 90°.

1. Introduction

With the increasing concerns on the environmental problems and energy crisis, the conversion of renewable energy sources such as solar energy, geothermal energy and waste heat into the power, heat and cooling has been widely studied. The main energy conversion technologies are represented by the Organic Rankine cycle (ORC) and vapor compression cycle (VCC). For the high utilization of these sources, how to improve the cycle efficiency is a key challenge. In general, considering the temperature glide during phase change, zeotropic mixture is recommended as the working fluid to improve the temperature match and reduce the irreversible loss in heat transfer process of thermodynamic cycle [1]. Furthermore, mixture composition can be regulated to achieve the best performance of thermodynamic cycles under the off-design conditions [2]. For the improvement of cycle performance, another way is to construct more efficient cycle configurations. So far, in the published literatures, there exist many different cycle configurations, such as the combined power and ejector refrigeration cycle [3], the auto-cascade solar ORC [4] and multi-stage VCC with two-phase refrigerant injection [5]. In these proposed systems, vapor-liquid phase separator is generally introduced to control and distribute the working fluid flow in the systems. Meanwhile, due to the composition difference between the vapor and liquid phases, the phase separator can also be used to regulate the refrigerant mixture composition in cycle.

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Nomenclature

Symbols

C	R134a mass fraction
CON	condenser
D	diameter (mm)
DR	diameter ratio of branch to inlet tubes
F	fraction of constituent taken off through the branch
G	mass flux (kg·m^{-2}·s^{-1})
h	enthalpy (kJ·kg^{-1})
m	mass flow rate (kg·s^{-1})
M	mixture
MFM	mass flow meter
mr	mass flow ratio
ORC	Organic Rankine Cycle
T	temperature (K)
VAL	Needle Valve
VCC	vapor compression cycle
x	vapor quality

Greeks

α	vertical branch orientation (Fig. 1)
β	horizontal branch angle (Fig. 1)
ρ	density (kg·m^{-3})
μ	viscosity (pa·s)
η	separation efficiency

Subscripts

1, 2, 3	inlet, run outlet, branch outlet (Fig. 1)
b	boiling point
in	inlet
out	outlet
V	vapor phase
L	liquid phase
sl	saturated liquid
sv	saturated vapor

In engineering applications, there are many separators used, such as gravity sedimentation separator, centrifugal separator, mist eliminator and liquid-gas coalesce [6]. However, the phase separators employed in thermodynamic cycles should have not only high separation capacity but also the small dimension to minimize the refrigerant inventory. As an unconventional phase separator, T-junction has advantages such as simple structure, compact size, easy maintenance and low cost. It has been successfully applied in thermodynamic systems [7,8]. When the vapor-liquid two-phase flows into the T-junction, phase maldistribution occurs inevitably at the outlets of T-junction. Although the initial driving force behind the research of T-junction was to understand how to minimize the phase redistribution problem, it soon became apparent that this phenomenon could be utilized in a positive way for phase separation. According to the orientation of inlet flow with respect to outlet flows, T-junctions can be classified into two types: branch type and impacting type T-junctions. For the impacting T-junction, the two coaxial outlet tubes are aligned perpendicular to the inlet, while one of outlets keeps the same direction with the inlet in the branch T-junction. Since Zheng et al. [9] already experimentally studied the distribution of constituents of zeotropic mixtures in vertical impacting T-junction, this work focuses on the constituent separation of binary zeotropic mixtures in branch T-junction.

Fig. 1 shows the branch T-junction with horizontal inlet. For the branch orientation, it can be vertical upward ($\alpha = 90°$), vertical downward ($\alpha = -90°$) or horizontal inclination ($\alpha = 0°$, $\beta = 45°$, $90°$, $135°$). Furthermore, the diameter ratio (DR) of branch to inlet tubes can also be varied to achieve the desired phase separation. When DR = 1, the term “regular T-junction” is employed. For DR < 1, it’s referred as “reduced T-junction”. In order to understand the separation mechanism of T-junction, much effort has been devoted to investigate the effects of flow conditions, geometrical parameters and fluid properties on the separation performance. For instance, Shoham et al. [10], Saba and Lahey [11] and Buel et al. [12] experimentally investigated the phase distribution of air-water in the regular T-junction under different inlet mass flow rates and vapor qualities. The separation performance of steam-water was investigated by Seeger et al. [13], Rubel et al. [14], Ballyk [15] and Peng [16]. For the phase separation of refrigerants in branch T-junction, Tae and Cho [17] experimentally obtained the separation performance of R22, R134a and R410A under the annular flow condition at inlet. Thereafter, Su et al. [18] experimentally investigated the phase redistribution of R134a, R600a and R245fa and clarified the effects of vapor quality, mass flux, mass flow ratio and refrigerant on the phase separation of T-junction. As for the effect of T-junction geometry, phase separations for different diameter ratios were comprehensively compared by Azzopardi et al. [19], Ballyk [15] and Peng [16]. The effect of vertical branch orientation on the phase redistribution was revealed by Reimann et al. [20], Marti and Shoham [21], Wren [22] and Tae and Cho [17]. For the effect of horizontal branch angle, Hwang et al. [23] employed the mixture air-water to flow through the T-junctions with three different angles, namely $\beta = 45°$, $90°$, and $135°$. However, it should be noted that most of the above literatures aim at the vapor-liquid separation of air-water or steam-water in the T-junction. To the best of authors’ knowledge, no researches have been conducted on the constituent separation of zeotropic mixtures in the branch T-junction.

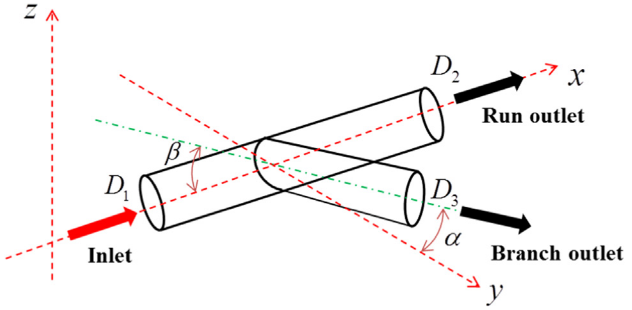

Fig. 1. Branch T-junction with horizontal inlet.

According to the above literature review, it can be concluded that although there are many studies conducted on the phase separation of branch T-junctions, most of them focused on the separation of air-water or steam-water, none of them investigated the separation of zeotropic mixtures in the branch T-junction. Due to the existence of composition difference between the vapor and the liquid phases of two-phase zeotropic mixture under isothermal condition, vapor-liquid separation contributes to the uneven distribution of mixture’s constituents at the outlets of T-junction. On this basis, T-junction can be employed to regulate the mixture composition in thermodynamic cycles and control the system capacity dynamically. Therefore, it’s of great significance to study