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Geometric Effects on Phase Separation of Refrigerant at Horizontal Branching T-junction

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ABSTRACT

Separation technology has been widely developed to improve the performance of thermodynamic cycles, such as refrigeration, heat pump and power cycle. As a promising separator, T-junction has attracted widespread attention, due to the characteristics of simple geometry, low cost and compact size. Previous researches on the phase separation of air-water and steam-water have indicated that the separation performance depends heavily on the T-junction geometry. Therefore, in this work, geometric effects on phase separation of refrigerant were experimentally studied with different configurations of branching T-junction. In this study, all of the T-junctions had horizontal inlet and outlet tubes. The internal diameter of inlet tube was fixed at 8.0 mm, and the diameter ratio of the branch to the inlet was set to be 0.75 and 1.0. Furthermore, three branch angles (45°, 90° and 135°) were considered. More than 156 experimental runs were conducted using refrigerant R-600a with inlet mass flux and vapor quality being varied from 200 to 300 kg·m^{-2}·s^{-1} and from 0.1 to 0.9, respectively. Meanwhile, the mass flux of the branch was regulated by keeping the mass flow ratios in three levels: 0.3, 0.5 and 0.7. Flow regimes prior to the T-junction were identified and characterized. Based on these generated data, phase separation performance was analyzed in terms of mass flow ratio under given inlet vapor quality and mass flux. Effects of diameter ratio and branch angle were also investigated. From the test results, it can be concluded that the outlet quality of branch is always higher than the inlet quality. The fraction of vapor extracted into the branch decreases with the increase of inlet vapor quality. Under the same experimental conditions, the higher the mass flow ratio is, the larger the vapor fraction, while the inlet mass flux has little influence on the phase separation of refrigerant. As for the geometric effects, more vapors usually prefer to flow into the branch with the smaller diameter, when the mass flow ratio is relatively large. For the effect of branch angle, at low vapor quality, vapor fraction for the angle 45° is lower than those for angle 90° and 135° under the mass flow ratio of 0.5 and 0.7.

Keyword: Refrigerant, Separation, T-junction

1. INTRODUCTION

Vapor-liquid separators have been widely used to control and distribute the refrigerant flow in the thermodynamic systems, such as heat pump, refrigeration and power cycles. Compared with the traditional separators, such as gravity sedimentation separator, centrifugal separator, mist eliminator and liquid-gas coalescer, T-junction is much simpler, compacter, more integrated and cheaper. When the vapor-liquid two-phase flows into the T-junction, phase maldistribution occurs inevitably. Although the initial motivation for 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. In 1999, T-junction was first employed to separate the vapor and the liquid before the evaporator in trans-critical carbon dioxide refrigeration by Beaver et al. (1999). Thereafter, T-junction was applied in the mobile air conditioning system with R134a (Milosevic, 2011). The experimental results demonstrate that the coefficient of performance is greatly improved, compared with the systems without T-junction. and more uniform distribution of refrigerant is achieved in evaporator. Thus, T-junction has become a promising separation device in thermodynamic systems.

Geometric structures of T-junction have significant effects on the phase separation of two-phase fluids. In general, according to the relative orientation of inlet and outlet flows, T-junction can be classified as impacting type and branching type. For the impacting T-junction, the two coaxial outlet branches are perpendicular to the inlet. In order to enhance the vapor-liquid separation of impacting T-junction in thermodynamic systems, Tuo and Hrnjak (2014) experimentally studied the effects of T-junction geometry such as the inclination angle of inlet tube, diameter ratio on the phase split of refrigerant. As for the branching T-junction, one of outlet keeps the same direction with the inlet. However, although many literatures have been published to reveal the geometric effects of branching T-junction on the phase separation of multiphase flow (Azzopardi, 1999; Wren, 2001; Saieed et al., 2016), few papers are available for refrigerant. Therefore, this study focuses on the phase split of refrigerant at different branching T-junction configurations.
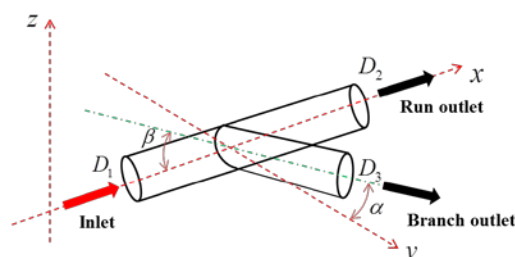

Figure 1: Branching T-junction with horizontal inlet

Figure 1 illustrates the branching T-junction with horizontal inlet. For the branch orientation, it can be vertical upward (α=90°), vertical downward (α=-90°) or horizontal inclination (β=45°, 90° and 135°). Furthermore, the diameter ratio (DR=D_3/D_1) can also be varied to achieve the desired phase separation. For T-junctions where all three branches are the same diameter, the term "regular T-junction" is often applied. Those with a smaller branch diameter are referred to as "reduced T-junction". During the past forty years, many researches have been conducted to explore the phase separation of air-water or steam-water for various branching T-junctions. Phase separation between the regular T-junctions and reduced T-junctions has been comprehensively compared by Azzopardi et al. (1988), Ballyk (1992) and Peng (1994). The effect of vertical branch orientation on the phase redistribution was revealed by Reimann et al. (1988), Marti and Shoham (1997), Wren (2001) and Tae and Cho (2006). However, for the horizontal branch angle, only Hwang et al. (1988) employed the mixture air-water to flow into the T-junctions with three different angles, namely β=45°, 90° and 135°. Other related studies on the branch angle were performed for branching T-junction with vertical inlet by (Lahey, 1986; Honan and Lahey, 1981). Furthermore, it should be noted that there is only one published paper to investigate the phase separation of refrigerants under the annular flow (Tae and Cho, 2006). Thus, so far, the study on the phase separation of refrigerant at branch T-junction is very limited, considering the complexity of vapor-liquid two-phase flow at different geometric configurations. Further experiments should be conducted to explore the geometric effects on phase separation of refrigerant at branching T-junction.

Based on the above literature review, it can be concluded that the existing researches on the phase separation of various branching T-junctions are mainly for air-water and steam-water. However, due to different thermophysical properties, very few results could be directly applied to refrigerant flow. Hence, this paper presents phase separation data of refrigerant R600a at horizontal branching T-junction and systematically studies the effects of diameter ratio and branch angle on the phase redistribution of refrigerant.

2. EXPERIMENTAL INVESTIGATION

2.1 Experimental facility
A closed-circuit system was designed and constructed to investigate the separation performance of different branching T-junctions using R600a, as illustrated in Figure 2. The system primarily consists of a test section with a T-junction, two Coriolis-type mass flow meters (MFM$_1$ and MFM$_3$), three condensers (CON$_1$, CON$_2$ and CON$_3$), two needle valves (VAL$_2$ and VAL$_3$), a liquid storage tank, a variable-speed gear pump (0.1-7 L/min) and a preheater. The sub-cooled refrigerant was supplied from the tank to the preheating section by using the gear pump and the mass flow rate was controlled by a frequency converter connected to the pump. The inlet mass flow rate of the refrigerant was measured by the MFM$_1$ in the pump discharge line. The vapor quality prior to the T-junction was

controlled by the preheater, which consists of four independent heating sections with a total maximum heating power of 4.8 kW. Vapor and liquid of refrigerant were separated in the horizontal branch T-junction. Thereafter, the two outlet refrigerants were condensed into sub-cooled state, and the branching mass flow rate was measured by MFM_3. Two needle valves were installed to throttle the liquid refrigerant and adjust the outflow rate. Then the two flows mixed, totally condensed in CON_1, and flowed back to the receiver to complete the cycle.
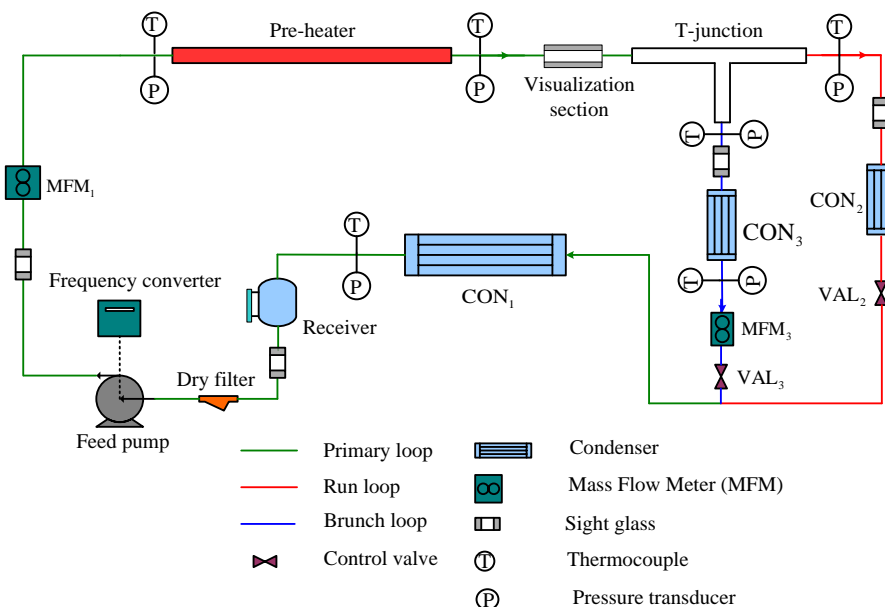

Figure 2: Schematic diagram of the experimental system

For the test section, the lengths of the inlet, outlet, and branch tubes were 400 mm. The inner diameter of inlet tube was always 8.0 mm, while the diameter ratio (DR) between the branch to inlet was varied between 0.75 and 1. As for the branch angle β, 45°, 90° and 135° were considered respectively. Furthermore, an 1100 mm long development section was set to guarantee that the two-phase flow of refrigerant was fully developed before entering the T-junction. A transparent section, which was made of quartz glass (L=180mm, D_i=8.0 mm and D_o=15.0 mm), was connected to the copper tube of T-junction via flange plates for visualizing the flow patterns at the T-junction inlet. The flow patterns under various inlet conditions were recorded by a high-speed camera (Photron FASTCAM SA-Z, Model 1000K-M32).

2.2 Experimental conditions and data reduction

For each geometry of T-junction, the inlet mass flux of R600a was varied between 200 and 300 kg·m^{-2}·s^{-1}, and the inlet quality was changed from 0.1 to 0.9, as listed in Table 1. Furthermore, in order to eliminate the influence of piping layout on the phase splitting, the outlet mass flow rates were controlled by adjusting the needle values. In this work, the mass flow ratio (mr) between the branch and inlet was set to be 0.3, 0.5 and 0.7.

Table 1: Experimental parameters and ranges

DR	β	x_1	G_1 (kg·m^{-2}·s^{-1})	G_3/G_1
1	90°	0.1~0.9	200, 300	0.3, 0.5, 0.7
0.75	90°	0.1~0.9	200, 300	0.3, 0.5, 0.7
1	45°	0.1~0.9	200, 300	0.3, 0.5, 0.7
1	135°	0.1~0.9	200, 300	0.3, 0.5, 0.7

Based on the energy balances within the loop, inlet and outlet vapor qualities are calculated from the measured data under various test conditions. For the vapor quality at the T-junction inlet, it's determined by Equations (1)-(3).

$$h_1 = h_{pre,in} + \frac{W_{sup} - W_{loss}}{m_1} \tag{1}$$

$$W_{loss} = \frac{2\pi(T_{surf} - T_{amb})L}{\ln(\frac{d_{o,ins}}{d_{i,ins}})\frac{1}{\lambda} + \frac{2}{d_{o,ins}\alpha}} \tag{2}$$

$$x_1 = \frac{h_1 - h_{sl,1}}{h_{sv,1} - h_{sl,1}} \tag{3}$$

where W_{sup} is the total heating power supply, kW, W_{loss} denotes the heat loss to ambient, kW. T_{surf} denotes the internal surface temperature of the thermal insulation material, °C, T_{amb} is the ambient temperature, °C, the heat conductivity coefficient (λ) is 0.044 W·m^{-1}·K^{-1}, the convective heat transfer coefficient (α) is 11.63 W·m^{-2}·K^{-1}, the outside and inside diameters of the thermal insulation material are $d_{o,ins}$=90 mm and $d_{i,ins}$= 50 mm. Furthermore, m_1 is the refrigerant mass flow rate in the primary loop, kg·s^{-1}. $h_{sv,1}$, $h_{sl,1}$ correspond the saturation enthalpy of vapor and liquid at the T-junction inlet pressure respectively, kJ·kg^{-1}. Based on the temperature and pressure at the inlet of preheater, the corresponding enthalpy $h_{pre,in}$ is calculated.

For the refrigerant quality at the branch outlet, it can be determined from the energy balance of the sub-loop condenser in Equations (4) and (5).

$$h_3 = h_{con,out} + \frac{Q_{con,3}}{m_3} \tag{4}$$

$$x_3 = \frac{h_3 - h_{sl,3}}{h_{sv,3} - h_{sl,3}} \tag{5}$$

where $Q_{con,3}$ is the heat transfer rate of branch condenser, kW. It's calculated from the mass flow rate and temperature rise of cooling water.

The obtained data for the two-phase flow separation are presented in terms of the mass flow rate ratio of vapor, namely the fraction of vapor taken off through the branch, as defined by Equation (6).

$$F_G = \frac{m_3 x_3}{m_1 x_1} \tag{6}$$

where G refers to the vapor phase.

The major errors in the present experiment originate from the measuring error and calculating error. The measurement error could be determined by the instrument accuracy as listed in Table 2, while the calculating error is analyzed by the method of Moffat (1988). For the inlet and branch outlet qualities, the uncertainties fall in the range of 1.2-6.6% and 3.8-13.6%. As for the vapor fraction, the uncertainty range is 2.9-8.7%.

Table 2: Instruments accuracy

Parameter	Instrument	Range	Accuracy
Pressure	Pressure transducer	0~1.6 MPa	±0.25% F.S.
Temperature	T-type thermocouple	-200~350℃	±0.1
Refrigerant mass flow rate	Coriolis-type mass flow meter	0~170 kg·h^{-1}	±0.11% F.S.
Cooling water flow rate	Electromagnetic flow meter	0~8 m^3·h^{-1}	±0.3% F.S.
Electrical heating power	Digital power meter	0~5 A	±0.5% F.S.

3. RESULTS AND DISCUSSION

In order to investigate the effects of diameter ratio and branch angle on the phase separation of refrigerant, more than 156 experimental runs were conducted under given parameters in Table 1. Experimental data on phase

separation of R600a are obtained for different diameter ratios and branch angles. Based on these generated data, the inlet flow patterns of the T-junction are identified, and the separation performances of different T-junction configurations are analyzed to reveal the influences of diameter ratio and branch angle.

3.1 Phase separation analysis of T-junction

Previous researches on the phase redistribution of air-water and steam-water have shown that the inlet flow pattern has a significant influence on the separation performance of branching T-junction. Thus, before the analysis of experimental data, the flow patterns at the T-junction inlet are identified under the given parameters, as shown in Figure 3. Intermittent and annular flows were recorded by the high-speed camera under the inlet mass flux 300 $kg \cdot m^{-2} \cdot s^{-1}$. At the low vapor quality, the flow is characterized by the intermittent flow. It can be seen that there is a turbulent vapor-liquid interface, with a liquid layer presenting on the bottom of the tube and vapor bubbles and liquid drops flowing above this layer. However, with the increase of inlet vapor quality, the flow pattern starts to transfer from the intermittent flow to the annular flow. This regime is distinguished by vapor flowing in the center of the tube with a surrounded liquid film around the tube perimeter
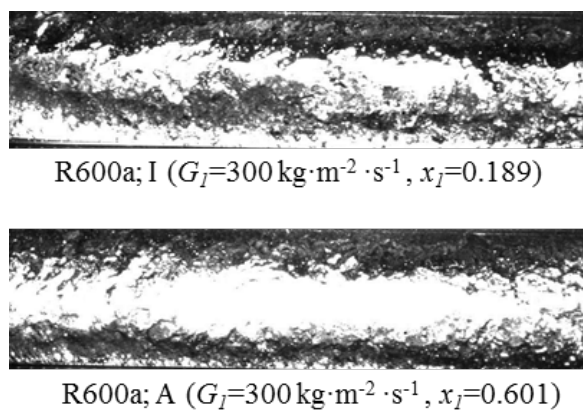

R600a; I (G_l=300 kg·m^{-2}·s^{-1}, x_l=0.189)

R600a; A (G_l=300 kg·m^{-2}·s^{-1}, x_l=0.601)

Figure 3: Typical flow patterns at T-junction inlet

In order to compensate for the lack of flow pattern measurement, flow patterns at the T-junction inlet are predicted using the flow pattern map of Wojtan et al. (2005) for diabatic two-phase flow in horizontal tube, as shown in Figure 4. The used saturation temperature is determined by averaging the inlet temperatures of T-junction. From the figure, it can be seen that the mass flux has little influence on the transition curve from slug/stratified wavy (S/SW) flow to intermittent/annular flow (I/A) within the experimental conditions, while the selected heat flux mainly affects the transition from annular flow to dry-out flow (D), and from dry-out flow to mist flow (M). Furthermore, Figure 4 also indicates that most of flow patterns are intermittent and annular flows under the experimental parameters. Only when the inlet vapor approaches to 1.0, the inlet flow pattern can be dry-out or mist flow.
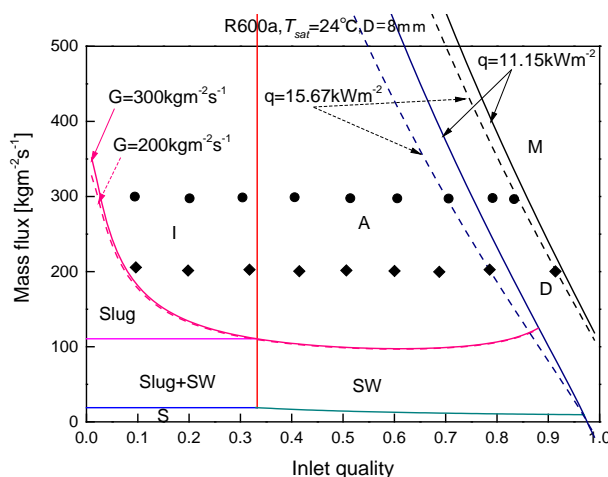

Figure 4: Flow pattern of refrigerants at T-junction inlet based on Wojtan et al. (2005)

For the regular T-junction with branch angle 90°, Figure 5 shows the trends of vapor fraction with the inlet quality under various experimental conditions. It can be seen that the higher the mass flow ratio is, the larger the fraction of vapor extracted into the branch is. When the mass flow ratio is fixed, the vapor fraction is always higher than the mass flow ratio. This means that the outlet quality of branch is higher than the inlet quality. Since the vapor has far less axial inertia than the liquid phase, the vapor can be expected to turn the corner into the branch easier than the liquid. Especially at low vapor quality, all the vapors turn the corner and exit through the branch to assure the mass flow ratio, and the vapor fraction is 1.0. As the vapor quality increases, the vapor fraction decreases sharply under the fixed mass flux and mass flow ratio. It's not only because of the increase of vapor amount, but also due to the transition of inlet flow pattern. For the inlet annular flow, besides the liquid film and vapor, there are liquid droplets entrained in the vapor core. At the T-junction, liquid droplets will flow straightly into the run outlet, due to the high momentum. Furthermore, the momentum ratio of vapor to liquid increases with the increase of vapor quality under the inlet annular flow. Thus, the vapor fraction (F_G) continues to decrease moderately but with a gentle rate. Thereafter, as the vapor quality approaches to 1, the flow pattern becomes dry-out or mist flow. The liquid only exists in the form of droplets and has much higher momentum flux than the vapor. Therefore, all the droplets are expected to flow into the run straightly, and the branch outlet quality can reach up to 1.0. As for the effect of mass flux on the phase separation, no significant change of vapor fraction is observed for different inlet mass fluxes. This is because that the variation of mass flux doesn't cause the change of inlet flow regime.
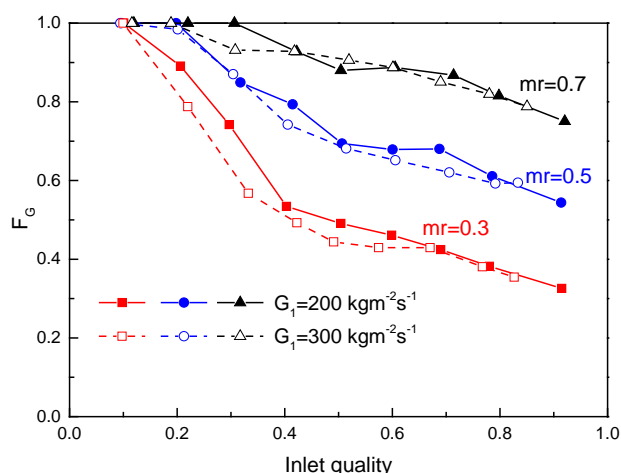

Figure 5: Vapor fraction of the branch for T-junction with DR=1 and β=90°

3.2 Effect of diameter ratio on phase separation

The effect of diameter ratio on the phase separation is presented in Figure 6 under the inlet mass flux 200 kg·m⁻²·s⁻¹. Compared with the regular T-junction, the reduced T-junction generally has a higher fraction of vapor at the same vapor quality and mass flow ratio. This can be related to the shorter passage time and reduced area of the smaller side arm available for vapor and liquid take off into the branch. Accordingly, the vapor requires a larger pull to overcome the inertial force of the liquid, thus increasing the vapor fraction intake into the branch to guarantee the mass flow ratio. The extent of the branch vapor intake increase depends primarily on the mass flow ratio. For the mass flow ratio 0.7, the reduced branch diameter has no effect on the phase separation at low vapor quality. As the vapor quality increases, obvious effect of the diameter ratio is observed. When the flow pattern is dry-out or mist flow, only liquid droplets exist. Thus, the difference of vapor fraction between the regular and the reduced T-junctions is diminished. Furthermore, special attention should be given to the phase separation at the low mass flow ratio and vapor quality. For the flow ratio 0.3, when the vapor quality is less than 0.4, the vapor fraction of reduced T-junction is less than that of regular T-junction. This can be explained by the higher vapor velocities encountered in the reduced branch tube. The acceleration of the vapor can overcome the axial momentum of the liquid phase and draw more liquid into the branch arm for the same fraction of vapor drawn off. However, when the vapor quality is larger than 0.4, the effect of diameter ratio is little for mass flow ratio 0.3, as observed in Figure 6.
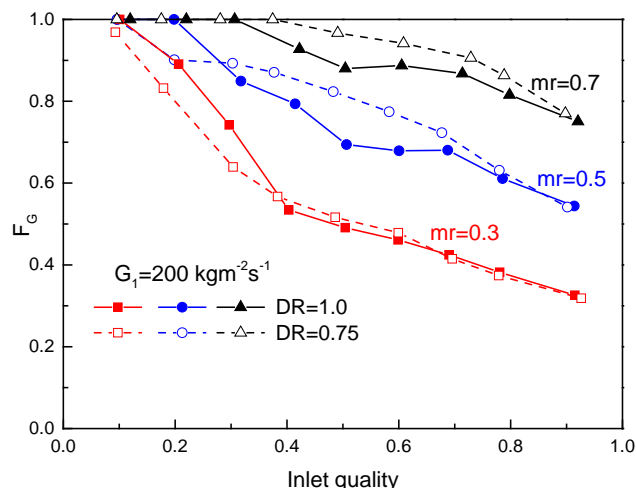
Figure 6: Effect of diameter ratio on the vapor fraction under the inlet mass flux 200 kg·m^{-2}·s^{-1}

3.3 Effect of branch angle on phase separation

Figure 7 illustrates the effect of branch angle on the vapor fraction under the inlet mass flux 200 kg·m^{-2}·s^{-1}. It can be seen that a large deviation of vapor fraction exists for various branch angles at low vapor quality. When the mass flow ratio is 0.5 or 0.7, the vapor fraction for the branch angle 45° is lower than those for the angle 90° and 135° at low vapor quality. When the branch tube is not perpendicular to the inlet tube, the axial distance covered by the entrance to the branch increases. Hence, for the branch angel 45°, the liquid phase has more time to be influenced to change direction and so be drawn off down the branch. Furthermore, since the liquid phase normally has a higher axial inertia than the vapor phase, the larger the branch angle is, the more difficult the extraction of liquid is at the same mass flow ratio. For the angle 90° and 135°, due to the fact that the axial velocity of each phase must be decreased to zero before entering the branch, there is no great difference of vapor fraction between the angle 90° and 135°. However, when the mass flow ratio is fixed at 0.3, the vapor fraction for the branch angle 135° is lower than those for the angle 45° and 90° at low vapor quality. Maybe it can be explained by the fact that the pressure drop between the inlet and the branch for angel 135° is larger, thus drawing more liquid into the branch. In addition, as the inlet quality increases, little effect of branch angle on the phase separation is observed.
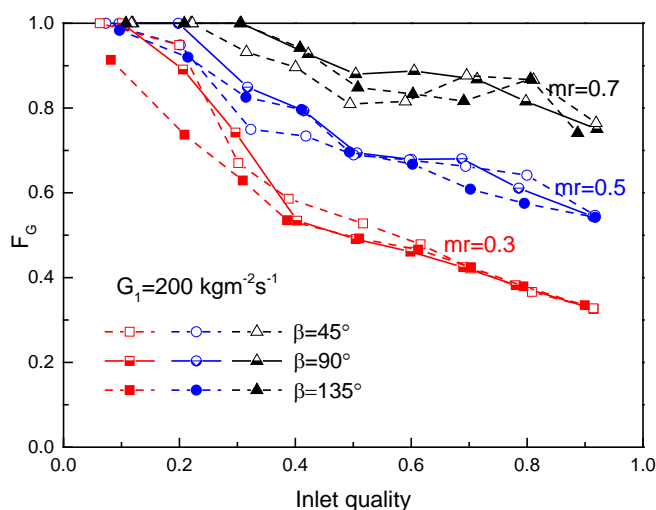

Figure 7: Effect of branch angle on the vapor fraction of regular T-junction under the inlet mass flux 200 kg·m^{-2}·s^{-1}

Figure 8 presents the branch outlet quality for different T-junction structures under the inlet mass flux 200 kg·m^{-2}·s^{-1} and mass flow ratio 0.5. It can be seen that the branch outlet quality is always higher than the inlet quality. At the low inlet quality 0.1and 0.2, the outlet quality almost keeps the same with each other. This is because that all the inlet vapors are extracted into the branch to guarantee the given mass flow ratio, as shown in Figures 5 through 7. As

the inlet quality increases, obvious difference of outlet quality is observed. For the considered T-junctions, reduced T-junction has the largest outlet quality at the same inlet quality. Compared with the effect of diameter ratio, the influence of branch angle on the outlet quality is less. Furthermore, when the inlet vapor quality is close to 1, the inlet flow regime becomes dry-out or mist flow, so that no liquid droplets turn the corner into the branch. Thus, the outlet quality reaches up to 1.0 for the considered T-junctions.
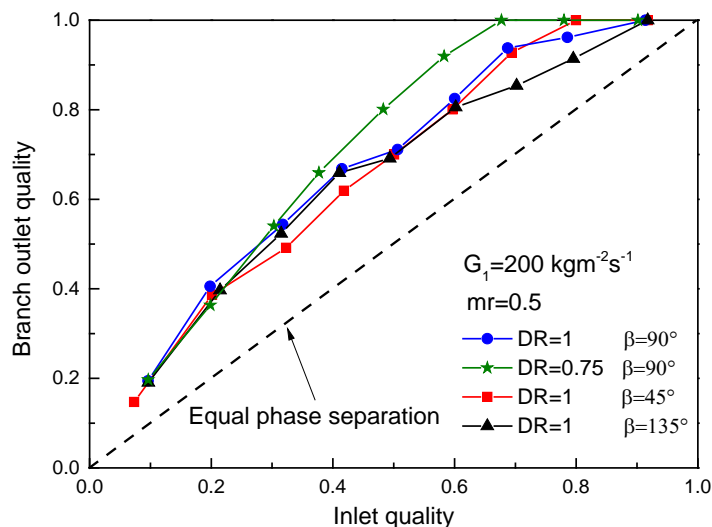

Figure 8: Branch outlet quality for different T-junction configurations under the inlet mass flux 200 kg·m^{-2}·s^{-1} and mass flow ratio 0.5

4. CONCLUSIONS

This paper experimentally studied the geometric effects on the phase separation of refrigerant at the horizontal T-junction. Two diameter ratios (0.75 and 1) and three branch angles (45°, 90° and 135°) were considered. Based on the experimental data, phase separation of R600a is analyzed in terms of the operating conditions and T-junction geometry. The conclusions are drawn as follows:

(1) For a given T-junction, the fraction of vapor extracted through the branch decreases with the increase of the inlet vapor quality. However, the effect of inlet mass flux can be neglected for the same flow pattern. Furthermore, the larger the mass flow ratio is, the higher the vapor fraction is.

(2) The branch diameter has a great effect on the phase separation of refrigerant. The reduced T-junction generally has higher vapor fraction and outlet quality than the regular T-junction for a large mass flow ratio. When the mass flow ratio is relatively small, the vapor fraction may be lower for the reduced T-junction at low vapor quality.

(3) For the effect of branch angle on the phase separation, when the vapor quality is relatively low, the fraction of vapor for branch angle 45° is lower than those for the angle 90° and 135° at a large mass flow ratio. However, at small mass flow ratio, the vapor fraction for angle 135° is the lowest. Furthermore, no obvious difference of phase separation for various branch angles is observed at high inlet vapor quality.

NOMENCLATURE

A	Annular flow	
CON	Condenser	
D	Diameter, dry-out flow	
DR	Diameter ratio of the branch to the inlet	(—)
F	Fraction of phase taken off through the branch	(—)
G	Mass flux	(kg·m^{-2}·s^{-1})
h	Enthalpy	(kJ·kg^{-1})
I	Intermittent flow	
m	Mass flow rate	(kg·s^{-1})

M	Mist flow	
MFM	Mass flow meter	
mr	Mass flow ratio	(—)
S	Stratified flow	
SW	Stratified-wave flow	
T	Temperature	(°C)
VAL	Needle Valve	
x	Vapor quality	(—)

Greek

α	Vertical branch orientation in Figure 1
β	Horizontal branch angle in Figure 1

Subscript

1, 2, 3	Inlet, run outlet, branch outlet in Figure 1
G	Vapor phase
sat	Saturation
sl	Saturated liquid
sv	Saturated vapor

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