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Two-Phase Flow Distribution and Phase Separation Through Both Horizontal and Vertical Branches

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The present study investigated two-phase flow distribution and phase separation of R-22 refrigerant through various types of branch tubes. The key experimental parameters were the orientation of inlet and branch tubes (horizontal and vertical), diameter ratio of branch tube to inlet tube (1 and 0.61), mass flux (200−500 kg/m^{2}s), and inlet quality (0.1−0.4). The predicted local pressure profile in the tube with junction was compared and generally agreed with the measured data. The local pressure profile within the pressure recovery region after the junction has to be carefully investigated for modeling the pressure drop through the branch. The equal flow distribution case can be found by adjusting the orientation of the inlet and branch tubes and the diameter ratio of the branch tube to the inlet tube. The T-junction with horizontal inlet and branch tubes showed the nearly equal phase distribution ratio. The quality at the branch tube varied from 0 to 1 as the orientation of the branch tube changed, while it varied within ±50% as the orientation of the inlet tube changed.

Key Words : Two-phase Flow, Flow Distribution, Phase Separation, R-22, Branch Tubes

Nomenclature

G : Mass flux [kg/m^{2}s]
K : Single-phase friction loss coefficient
L : Tube length in the test section [mm]
M : Mass flow rate [kg/s]
M^+ : Flow distribution ratio ($=M_3/M_1$)
P : Pressure [MPa]
x : Quality
X : Lockhart-Martinelli parameter

Greek letters

α : Void fraction
ρ : Density [kg/m^3]

Subscripts

1 : Inlet tube
2 : Run tube
3 : Branch tube
G : Gas
J : Junction
L : Liquid

1. Introduction

Two-phase branch flow has been widely applied for various industrial systems. Residential air-conditioner has employed multi-pass heat exchanger. Multi air-conditioner has multi indoor units for one outdoor unit, and it connects indoor units by using branch tube. Flow distribution through branch tube has to be investigated to design the system optimally. Two-phase flow distribution and phase separation through branch tube had been investigated mostly for air-water

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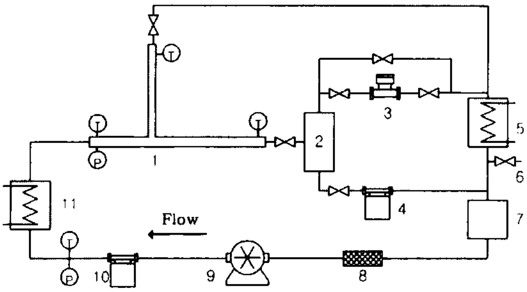
or steam-water system with large tube diameter. Since the air-water or steam-water system is different from the refrigerant system, they can't be directly applied for the refrigeration system.

The two-phase flow distribution and pressure drop for air-water mixture through a T-type branch were investigated by Saba and Lahey (1984), Shoham et al. (1987), Hwang et al. (1988), Azzopardi and Rea (1999), Stacey et al. (2000), and Van Gorp et al. (2001). And those for steam-water mixture were studied by Ballyk et al. (1988), Seeger et al. (1986), Reimann and Seeger (1986). Study on the phase separation and pressure drop for refrigerants through the T-type branch have rarely performed. Watanabe et al. (1995) experimentally investigated the flow distribution and pressure drop for R-11 through four-pass junction. Park et al. (1999) also experimentally investigated the flow separation and pressure drop in a T-type branch with different diameter branch tube for R-22. To author's knowledge, no study on the analytical prediction for the phase separation and the pressure drop for refrigerants through the T-type branch has been done so far. The present study investigated experimentally the flow distribution and pressure difference of R-22 through T-type horizontal and vertical branches.

2. Experimental Apparatus and Procedure

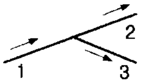
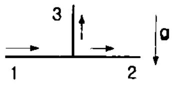
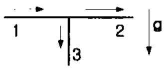
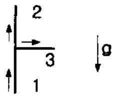
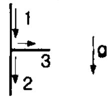
Figure 1 shows the schematic diagram of experimental apparatus for the present study. The



1. Test section	2. Separator
3. Gas mass flow meter	4. Liquid mass flow meter
5. Plate heat exchanger	6. Inlet port
7. Receiver	8. Filter
9. Refrigerant pump	10. Liquid mass flow meter
11. Pre-heater	

Fig. 1 Schematic diagram of the experimental apparatus

Table 1 Specification of the test section

Case Number	Orientation of the inlet tube	Orientation of the branch tube	Arrangement	Ratio of diameter of branch to inlet tube
HH(I)	Horizontal	Horizontal		1
HH(II)				0.61
HVU(I)	Horizontal	Vertical Upward		1
HVU(II)				0.61
HVD(I)	Horizontal	Vertical Downward		1
HVD(II)				0.61
VUH(I)	Vertical Upward	Horizontal		1
VUH(II)				0.61
VDH(I)	Vertical Downward	Horizontal		1
VDH(II)				0.61

experimental system consists of a test section with T-branch, a gas-liquid separator, gas and liquid flow meters, a pre-heater, a plate heat exchanger and a speed-controlled refrigerant pump. The two-phase refrigerant discharged from the test section was separated in the gas-liquid separator and the flow rates of each phase were separately measured by gas and liquid mass flow meters.

Table 1 shows the specification of the test section. The orientations of the inlet tube were horizontal, vertical upward, and vertical downward while the orientations of the branch tube were horizontal, vertical upward and vertical downward. The inner diameter of the inlet tube was fixed as 8.12 mm, while the inner diameters of branch tube were 4.95 and 8.12 mm. The mass fluxes of refrigerant at the inlet tube were ranged from 200 to 500 kg/m^{2}s, and the qualities at the inlet tube were varied from 0.1 to 0.4. The absolute pressure at the inlet of test section was set at 0.65 MPa and monitored by an absolute pressure transducer (15 bar range, ±0.1% resolution). The pressure difference in the test section was measured by a differential pressure gauge (350 mbar range, ±0.1% resolution) between the inlet and various positions in the test section.

The error analysis was carried out using the method suggested by Moffat (1985). The uncertainty of the flow distribution ratio was 1.0–5.3%, and that of the quality at the branch tube was 4.8–14.0%.

3. Prediction of Pressure Difference in the Branch Junction

The pressure drop through the junction between inlet and branch tubes is caused by the momentum change due to the change of flow direction and the frictional pressure drop due to the orifice effect. The pressure gain through the junction between the inlet and run tubes is due to the Bernoulli effect. The momentum equation applied for the pressure change through the junction between the inlet and run tubes can be described as follows (1984):

$$(\Delta P_{1-2})_J=(\Delta P_{1-2})_{momentum}$$
$$=\frac{1}{2}\left\{G_1^2\left(\frac{x_1^2}{\alpha_1\rho_G}+\frac{(1-x_1)^2}{(1-\alpha_1)\rho_L}\right)-G_2^2\left(\frac{x_2^2}{\alpha_2\rho_G}+\frac{(1-x_2)^2}{(1-\alpha_2)\rho_L}\right)\right\} \quad (1)$$

The void fraction, α, was calculated by following correlation by Zivi (1964).

$$\alpha=\left[1+\left(\frac{1-x}{x}\right)^1\left(\frac{\rho_G}{\rho_L}\right)^{0.67}\right]^{-1} \quad (2)$$

The pressure change through the junction between inlet and branch tubes was calculated as follows:

$$(\Delta P_{1-3})_J=(\Delta P_{1-3})_{momentum}+(\Delta P_{1-3})_{irreversible} \quad (3)$$

$$(\Delta P_{1-3})_{momentum}$$
$$=\frac{1}{2}\left\{G_1^2\left(\frac{x_1^2}{\alpha_1\rho_G}+\frac{(1-x_1)^2}{(1-\alpha_1)\rho_L}\right)-G_2^2\left(\frac{x_3^2}{\alpha_3\rho_G}+\frac{(1-x_3)^2}{(1-\alpha_3)\rho_L}\right)\right\} \quad (4)$$

$$(\Delta P_{1-3})_{irreversible}$$
$$=\frac{K_{1-3}}{2}\frac{G_3^2(1-x_3)^2}{\rho_L}\left(1+\frac{C_{1-3}}{X}+\frac{1}{X^2}\right) \quad (5)$$

$$K_{1-3}=0.95[1-M^+]^2 +0.8M^+[1-M^+]+1.3M^{+2} \quad (6)$$

The single-phase friction loss coefficient, K_{1-3}, was calculated by using Gardel (1957)'s correlation for single-phase flow through T-type branches. The C_{1-3}, as following equation, was suggested by Chisholm and Sutherland (1969) for the two-phase T-type branch flow.

$$C_{1-3}=\left[\lambda+(C-\lambda)\left(\frac{\rho_L-\rho_G}{\rho_L}\right)^{0.5}\right]\left[\left(\frac{\rho_L}{\rho_G}\right)^{0.5}+\left(\frac{\rho_G}{\rho_L}\right)^{0.5}\right] \quad (7)$$

Chisholm and Sutherland (1969) proposed $\lambda=1$ and $C=1.75$ for T-type branch flow.

4. Results and Discussions

4.1 Pressure profile in the test section

Figure 2 shows the comparison of the measured pressure drop in the straight tube and the predicted one by using the correlations of Jung and Radermacher (1989), Souza and Pimenta (1995), Chisholm (1973), Lockhart and Martinelli (1949) and Friedel (1979) when the inlet mass flux was 300 kg/m^{2}s. Among the correlations, Friedel's correlation showed the best agreement. Hence, the Friedel's correlation was applied for the prediction of pressure drop in the straight tube sections.

Figure 3 shows the pressure profile in the test section for the case HH(I) when the inlet mass flux was 300 kg/m^{2}s, and the inlet quality was 0.3. The local pressures in the test section were predicted by using Friedel's (1979) correlation in the straight tube and equations from (1) to (7) through the T-junction. Predicted values were different from the measured data by the maximum 25% in the whole experimental ranges. The difference may be mainly due to inaccurate values of K_{1-3} and C_{1-3}, and the effect of junction on the branch and run tubes within pressure recovery zone. The equation (6) and (7), used in this prediction, were developed based on water or steam-water data for large tube diameter case. To author's knowledge, there is no published experimental data for refrigerant.

4.2 Two-phase flow distribution

Figure 4 shows the effect of the orientation of branch tube on the flow distribution ratio (M^+) for horizontal inlet tubes. The flow distribution ratio (M^+) was defined as the ratio of mass flow rate at the branch tube (M_3) to that at the inlet tube (M_1). The flow distribution ratios for tube diameter ratio of 0.61 were smaller than those for tube diameter ratio of 1. The flow distribution ratios for case HH(II), HVD(II) and HVU(II) were lower by 12.4% than those for case HH(I), HVD(I) and HVU(I). The reason is that the flow resistance due to the orifice effect occurred at the junction between inlet and branch tubes increased as the tube diameter ratio decreased. As the mass flux at the inlet tube increased, the flow distribution ratios continuously decreased. It is because the increase of mass flux at the inlet tube makes the momentum flux of refrigerant increase, and then it makes the two-phase refrigerant flow into the branch be difficult. As the quality at the inlet tube increased, the flow distribution ratio in-

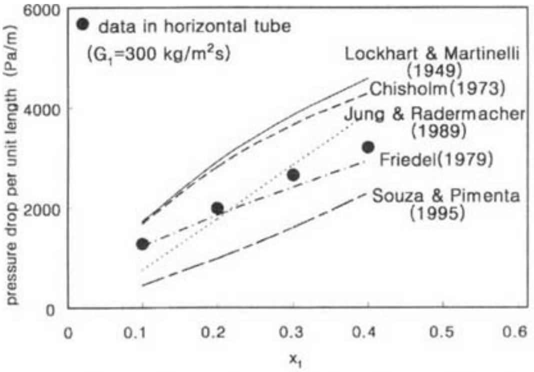


Fig. 2 Comparison of correlations for ΔP in the horizontal straight tube

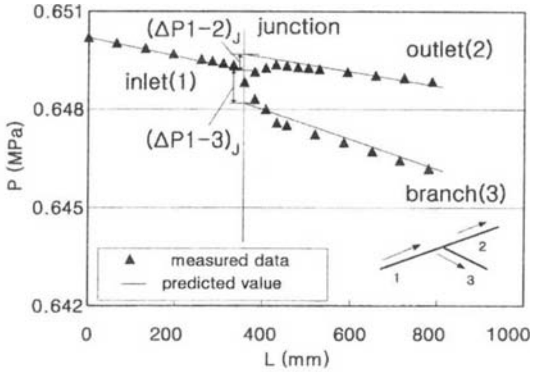


Fig. 3 Pressure profile in the test section for the case HH(I) (G_1=300 kg/m^{2}s, x_1=0.3)

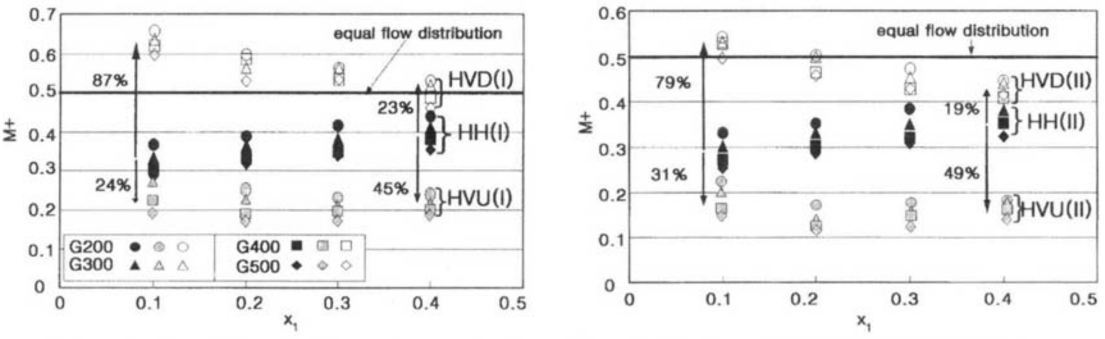


Fig. 4 Effect of the orientation of branch tube on flow distribution ratio for horizontal inlet tube

creased for case HH. For the horizontal inlet and branch tubes, the refrigerant gas, which has a smaller momentum than liquid due to the difference of density, is easier than the refrigerant liquid to change its flow direction and flow into the branch. So, as the inlet quality increased, the amount of refrigerant gas flowing into the branch tube increased. But for other cases, the gravity affected more than the momentum on the two-phase flow distribution. For both the cases HVU and HVD, the flow distribution ratio decreased as the quality at the inlet tube increased. For the vertical upward branch, refrigerant liquid divided into the branch decreased due to the gravity effect as the inlet quality increased. The direction of gravity force was opposite to the direction of branch tube. So, it is difficult for the refrigerant liquid, which had larger density than refrigerant gas, to flow upward into the branch tube. For the vertical downward branch, most of refrigerant liquid flowed into the branch tube at the low quality condition, because the direction of gravity force was the same with direction of branch tube. But the amount of the refrigerant liquid flowing into the branch tube decreased, as the inlet quality increased. Due to the gravity effect at the junction, the flow distribution ratios for vertical downward branch were larger than those for horizontal branch, whereas the flow distribution ratios for vertical upward branch were smaller than those for horizontal branch. As shown in Fig. 4, as the orientation of branch tube changed from horizontal to vertical upward, the flow distribution ratio (M^+) decreased by 24% and 31% at the inlet quality of 0.1 and by 45% and 49% at the inlet quality of 0.4 for tube diameter ratio of 1 and 0.61 respectively. As the orientation of branch tube changed from horizontal to vertical downward, the flow distribution ratio (M^+) increased by 87% and 79% at the inlet quality of 0.1 and by 23% and 19% at the inlet quality of 0.4 for tube diameter ratio of 1 and 0.61 respectively.

Figure 5 shows the effect of the orientation of the inlet tube on the flow distribution ratio (M^+) for the horizontal branch tube. The flow distribution ratios for tube diameter ratio of 0.61 were smaller than those for the tube diameter ratio of 1 for all cases. The flow distribution ratios continuously decreased as the mass flux at the inlet tube increased. As the inlet direction changed from horizontal to vertical upward, the flow distribution ratio (M^+) increased. The reason is that the refrigerant liquid, which has larger density than refrigerant gas, tends to flow into the horizontal branch, that had normal direction to the gravity force, than into the vertical upward run tube, which had the direction opposite to the gravity force. As the inlet direction changed from horizontal to vertical downward, the flow distribution ratio (M^+) decreased. The reason is that the refrigerant liquid tends to flow into the vertical downward run tube, that had the same direction with the gravity force, than into the branch tube. As the quality at the inlet tube increased, the flow distribution ratio increased. As the orientation of inlet tube changed from horizontal to vertical upward, the flow distribution ratio (M^+)

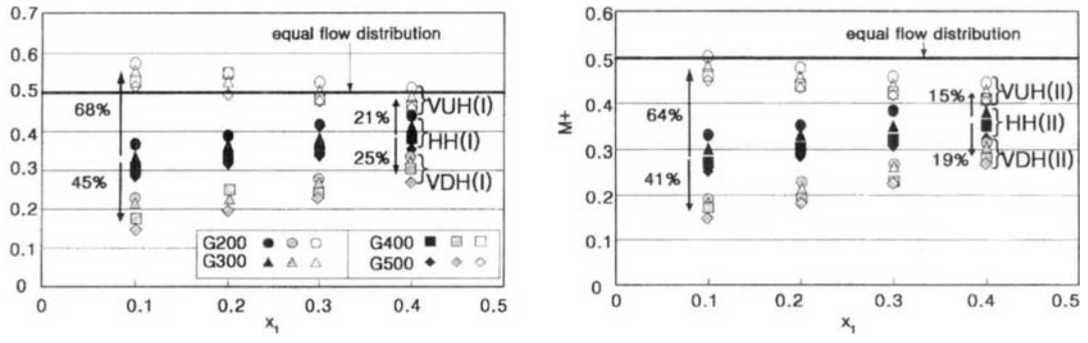


Fig. 5 Effect of the orientation of inlet tube on flow distribution ratio for horizontal branch tube

increased by 68% and 64% at the inlet quality of 0.1 and by 21% and 15% at the inlet quality of 0.4 for tube diameter ratio of 1 and 0.61 respectively. As the orientation of inlet tube changed from horizontal to vertical downward, the flow distribution ratio (M^+) decreased by 45% and 41% at the inlet quality of 0.1 and by 25% and 19% at the inlet quality of 0.4 for the tube diameter ratio of 1 and 0.61 respectively.

As shown in Figs. 4 and 5, the M^+ of 0.5 shows the equal flow distribution through T-junction. Among ten different cases, HVD cases showed the closest to the equal flow distribution. The two-phase flow distribution can be estimated by considering the orientations of inlet and branch tubes, tube diameter ratio, inlet mass flux and quality, and refrigerant.

4.3 Phase separation

Figure 6 shows the effect of the orientation of branch tube on the phase separation for horizontal inlet tube. Equal phase separation can be obtained when the inlet quality (x_1) is the same with the quality at branch tube (x_3). The case HH showed the closest to the equal phase separation among all cases. The quality at the branch tube for the case HVU logarithmically increased as the quality at the inlet tube increased. The gas phase tends to flow into the vertical upward branch tube than the horizontal run tube, whereas the liquid phase tends to flow into the horizontal run tube than the vertical upward branch tube. The reason is that the direction of the gravity force acting at the junction is opposite to the branch tube, and normal to the run tube for the case HVU. The qualities at the branch tube for the case HVD were smaller than those for the case HH. The reason is that the refrigerant liquid tends to flow into the vertical downward branch tube than the horizontal run tube. The quality at the branch

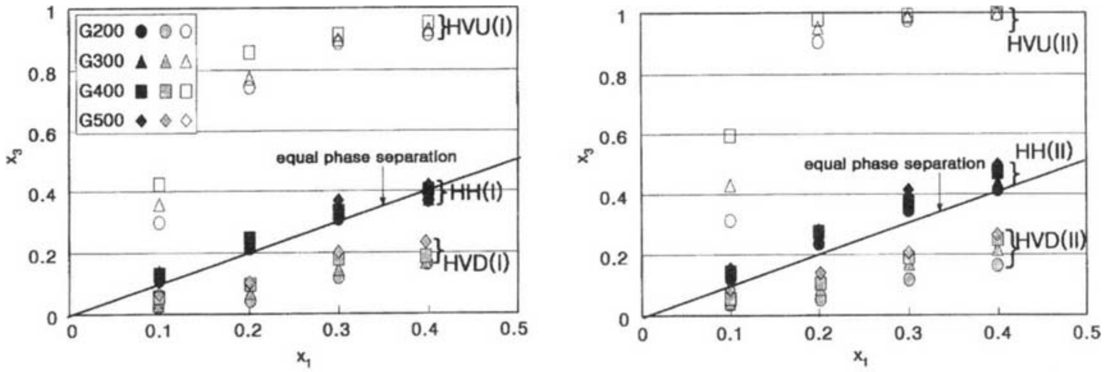


Fig. 6 Effect of the orientation of branch tube on phase separation for horizontal inlet tube

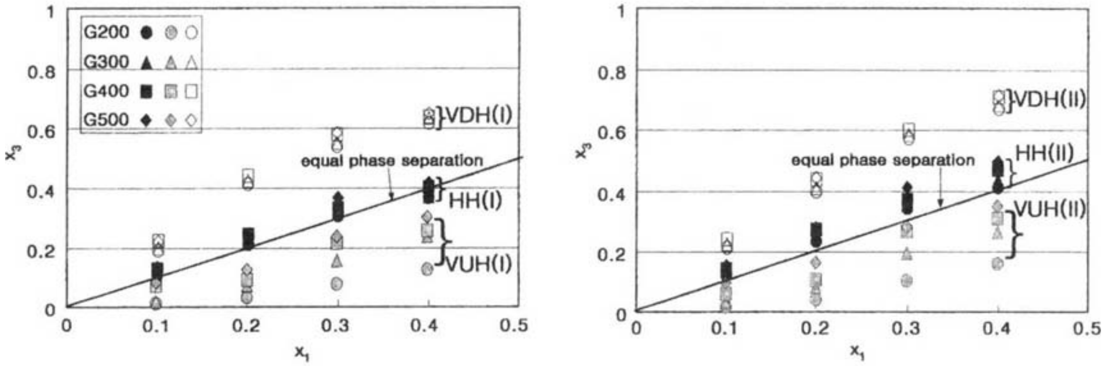


Fig. 7 Effect of the orientation of inlet tube on phase separation for horizontal branch tube

tube was decreased as the branch direction changed from horizontal to vertical downward. As the inlet quality increased, the quality at the branch tube was increased for all cases.

Figure 7 shows the effect of the orientation of the inlet tube on the phase separation for horizontal branch tube. As the inlet direction changed from horizontal to vertical upward, the quality at the branch tube decreased. The reason is that it is easier for gas phase to flow upward into the run tube than liquid phase due to the difference of density of each phase and gravity effect. As the mass flux decreased, the quality at the branch tube for case VUH decreased. The reason is that as the mass flux at the inlet tube decreases, the momentum of liquid phase in the direction of inlet flow decreases. As the inlet direction changed from horizontal to vertical downward, the quality at the branch tube increased. Because refrigerant liquid tends to flow downward into the run tube due to the gravity.

Among the different cases, HH cases showed the closest to the equal phase separation. Phase separation can be also estimated by considering the orientations of inlet and branch tubes, tube diameter ratio, inlet mass flux and quality, and refrigerant. The case with the equal two-phase flow and phase distribution was the HH case with the inlet quality of 0.5 to 0.6 and the tube diameter ratio of 1. The two-phase flow distribution and phase separation can be controlled by adjusting the orientation and size of T-junction, inlet quality and mass flux.

Conclusions

(1) The predicted local pressure profile in the tube with junction was compared and generally agreed with the measured data. The local pressure profile within the pressure recovery region after the junction has to be carefully investigated for modeling the pressure drop through the branch.

(2) The equal flow distribution case can be found by adjusting the orientation of the inlet and branch tubes and the diameter ratio of the branch tube to the inlet tube.

(3) The case of horizontal inlet and horizontal branch tubes showed the nearly equal phase separation ratio, whereas the quality at the branch tube varied from 0 to 1 as the orientation of the branch tube changed and varied within ±50% as the orientation of the inlet tube changed.

Acknowledgment

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