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TWO-PHASE FLOW SPLIT AND PRESSURE DROP OF R-22 IN BRANCH TUBES

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ABSTRACT

The present study investigated two-phase flow distribution and phase separation of R-22 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). Predicted pressure profile agreed with the measured data within 25%. The flow distribution ratio decreased as the mass flux increased. The flow distribution ratio decreased as the inlet quality increased for cases B and C, but the opposite trend was observed for case A. The flow distribution ratio increased as the diameter ratio of branch tube to the inlet tube increased. The quality at the branch tube decreased as mass flux increased and inlet quality decreased. The diameter ratio of the branch tube to the inlet tube had little effect on the quality at the branch tube.

NOMENCLATURE

G : mass flux [kg/m^{2}s]
K : single-phase friction loss coefficient
L : tube length in the test section [mm]
$M+$: flow distribution ratio
P : pressure [MPa]
X : Lockhart-Martinelli parameter
x : quality

Greek letters

α : void fraction
ρ : density [kg/m^3]

Subscripts

1 : inlet tube
2 : run tube
3 : branch tube
J : junction

INTRODUCTION

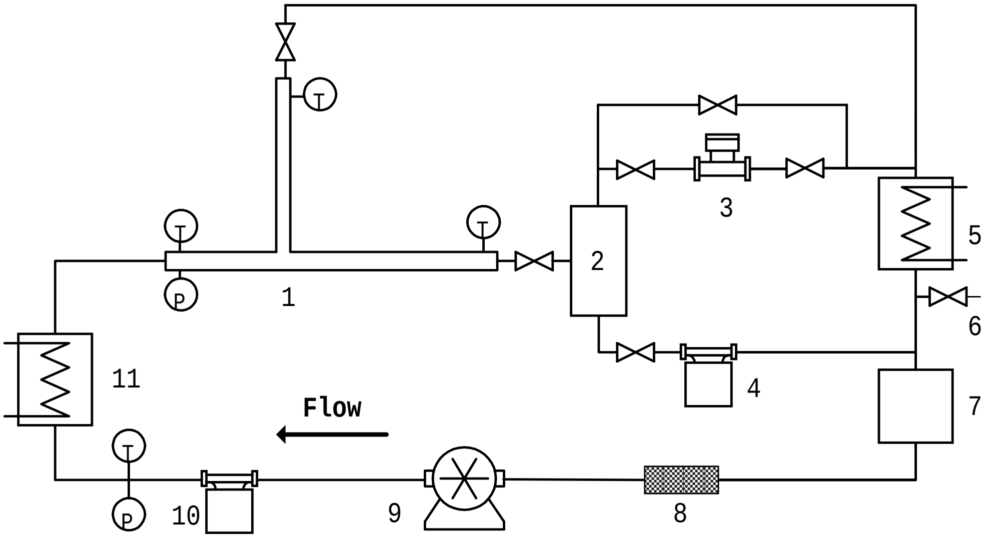
Two-phase branch flow has been widely applied for various industrial systems. Residential air-conditioner has employed multi-pass heat exchanger. Multi air-conditioner has multi indoor units for one outdoor unit, and it connects indoor units by using branch tube. Flow distribution through branch tube has to be investigated to design the system optimally. Two-phase flow distribution and phase separation through branch tube had been predicted partly for air-water or steam-water system with large tube diameter. Since they didn't consider refrigeration 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 [1], Shoham et al. [2], Hwang et al. [3], Azzopardi and Rea [4], Stacey et al. [5], and Van Gorp et al. [6] etc. And those for steam-water mixture were studied by Ballyk et al. [7], Seeger et al. [8], Reimann and Seeger [9] etc. Study on the phase separation and pressure drop for refrigerants through the T-type branch have rarely performed. Watanabe et al. [10] experimentally investigated the flow distribution and pressure drop for R-11 through four-pass junction. Park et al. [11] 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 the flow distribution and pressure difference of R-22 through T-type branch.

EXPERIMENTAL APPARATUS AND PROCEDURE

Fig. 1 shows the schematic diagram of experimental apparatus for the present study. The 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 variable refrigerant pump. The two-phase refrigerant discharged from the test section was separated in the gas-liquid separator and the flow rates were measured by gas and liquid mass flow meters.

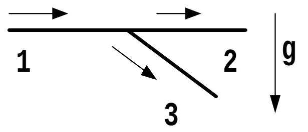
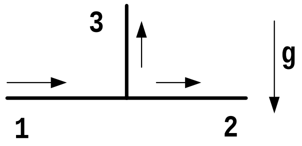
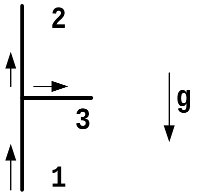
Table 1 shows the specifications of the test sections. The orientation of the inlet tube was either horizontal or vertical upward while the orientation of the branch tube was either horizontal or vertical upward. The inner diameter of inlet tube was fixed as 8.12 mm, while that of branch tube was varied from 4.95 to 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 flow distribution ratio (M+) was controlled as 0.3, 0.5, and 0.7 by using valves located at the downstream of the branch and outlet tubes. The flow distribution ratio (M+) was defined as the ratio of mass flow rate at the branch tube to that at the inlet tube. The absolute pressure at the inlet of test section was set at 0.65 MPa and monitored by a 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.



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

Figure 1: Schematic diagram of experimental system

Table 1: Specifications of the test section

Case	Orientation of inlet tube	Orientation of branch tube	Arrangement	Branch tube Inner Diameter (mm)	Ratio of diameter of branch e to inlet tube
A-I	Horizontal	Horizontal		8.12	1
A-II	Horizontal	Horizontal		4.95	0.61
B-I	Horizontal	Vertical upward		8.12	1
B-II	Horizontal	Vertical upward		4.95	0.61
C-I	Vertical upward	Horizontal		8.12	1
C-II	Vertical upward	Horizontal		4.95	0.61

PREDICTION OF PRESSURE DIFFERENCE IN THE BRANCH JUNCTION

The pressure loss at the junction between inlet and branch tubes was 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 at the junction between the inlet and run tubes was due to the Bernoulli effect. The momentum equation applied to the pressure change at the junction between the inlet and run tubes can be described as follows:

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

The void fraction, α , was calculated from Zivi's correlation. The pressure change at the junction between inlet and branch tubes was calculated as follows:

$$(\Delta P_{1-3})_J = (\Delta P_{1-3})_{momentum} + (\Delta P_{1-3})_{irreversible} \tag{2}$$

$$(\Delta P_{1-3})_{momentum} = \frac{1}{2}\left\{ G_1^{\,2}\left(\frac{x_1^{\,2}}{\alpha_1 \rho_G} + \frac{(1-x_1)^2}{(1-\alpha_1)\rho_L} \right) - G_3^{\,2}\left(\frac{x_3^{\,2}}{\alpha_3 \rho_G} + \frac{(1-x_3)^2}{(1-\alpha_3)\rho_L} \right) \right\} \tag{3}$$

$$(\Delta P_{1-3})_{irreversible} = \frac{K_{1-3}}{2}\frac{G_3{}^2(1-x_3)^2}{\rho_L}\left(1+\frac{C_{1-3}}{X}+\frac{1}{X^2}\right) \tag{4}$$

$$K_{1-3} = 0.95[1-(M+)]^2 + 0.8(M+)[1-(M+)] + 1.3(M+)^2 \tag{5}$$

The single-phase friction loss coefficient, K_{1-3}, was calculated by Gardel [12]'s correlation for single-phase flow in T-type branches. The C_{1-3}, as following equation, was suggested by Chisholm and Sutherland [13] for the two-phase T-type branch flow.

$$C_{1-3} = \left[\lambda + (C-\lambda)\left(\frac{\rho_L-\rho_G}{\rho_L}\right)^{0.5}\right]\left[\left(\frac{\rho_L}{\rho_G}\right)^{0.5} + \left(\frac{\rho_G}{\rho_L}\right)^{0.5}\right] \tag{6}$$

Chisholm and Sutherland [13] proposed λ =1 and C=1.75 for T-type branch flow.

RESULTS AND DISCUSSIONS

Pressure profile in the test section

Figure 2 shows the comparison of the correlations for pressure drop in the straight tube by Jung and Radermacher [14], Souza and Pimenta [15], Chisholm [16], Lockhart and Martinelli [17] and Friedel [18]. The measured data were predicted the best by the Friedel's correlation among the correlations. 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. As the flow distribution ratio increases, both the pressure changes between inlet and run and between inlet and branch tubes increase. Predicted values were differed from the measured data by 25% in the branch. The difference may be mainly due to inaccurate values of K_{1-3} and C_{1-3}, and effect of junction on the branch and run tubes within a certain length.

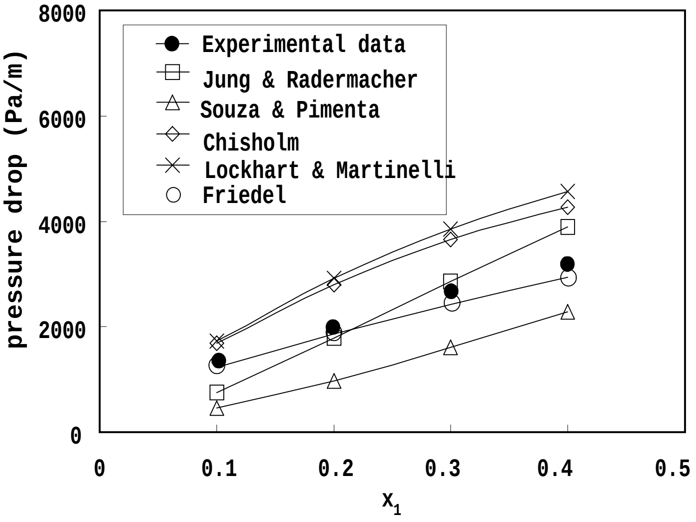


Figure 2: Comparison of correlations for Δ P in the straight tube

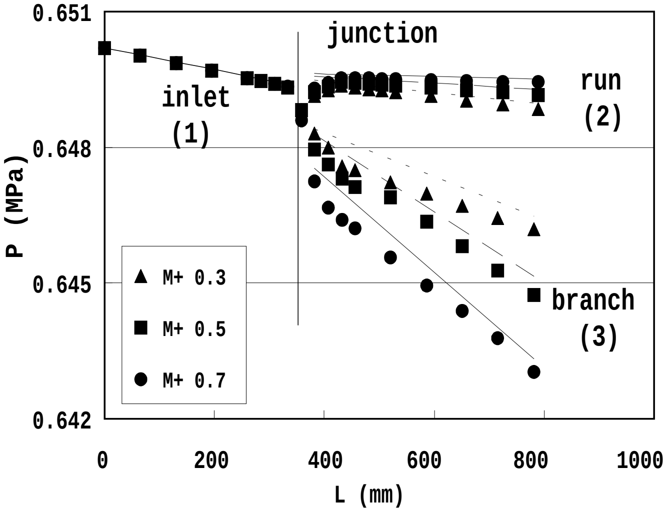


Figure 3: Pressure profile in the test section (G_1= 300 kg/m^{2}s, x_1= 0.3)

Flow distribution and phase separation in the test section

Figure 4 shows the effect of mass flux and quality at the inlet tube on the flow distribution for horizontal inlet and branch tubes. The flow distribution ratios were smaller than 0.5. The reason is that the flow resistance in the direction of branch is larger than that in the direction of run due to the change of flow direction into the branch and orifice effect occurred at the junction between inlet and branch tubes. This flow resistance due to the orifice effect was increased as the diameter of branch tube was decreased. Thus, the flow distribution ratios for case A-II were lower by average 12.4% than those for case A-I. As the mass flux at the inlet tube increased, the flow distribution ratios were continuously decreased. It is because the increase of mass flux at the inlet tube makes the momentum flux of refrigerant increase, and then makes it difficult for the two-phase refrigerant to flow into the branch. As the quality at the inlet tube was increased, the flow distribution ratio was increased. The reason is that refrigerant vapor, which has lower density compared with refrigerant liquid, is easier to flow into the branch than to flow into the run tube.

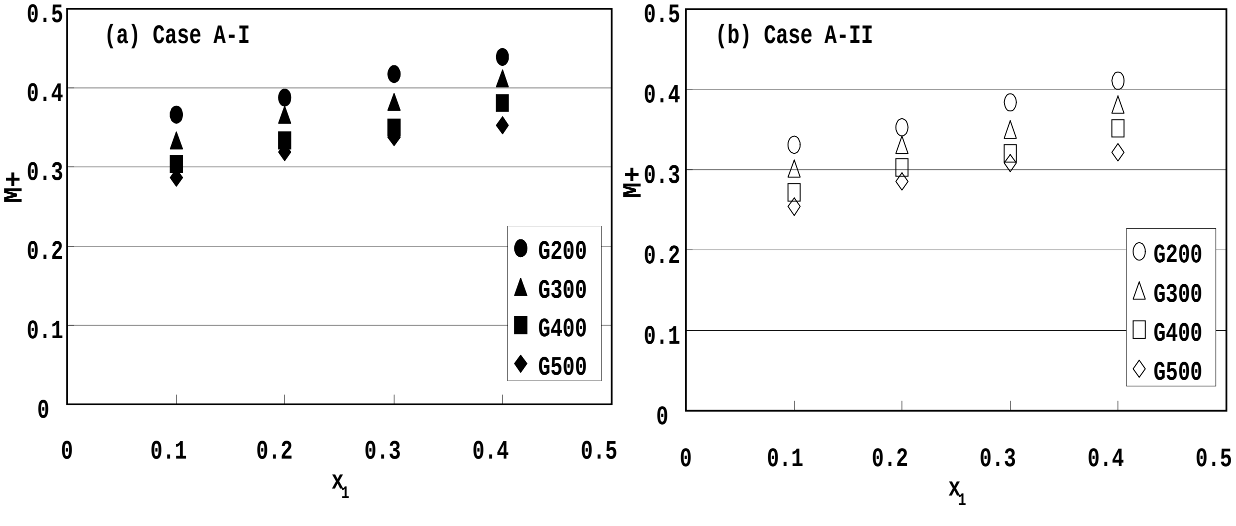


Figure 4: Flow distribution ratio for horizontal inlet and branch tubes

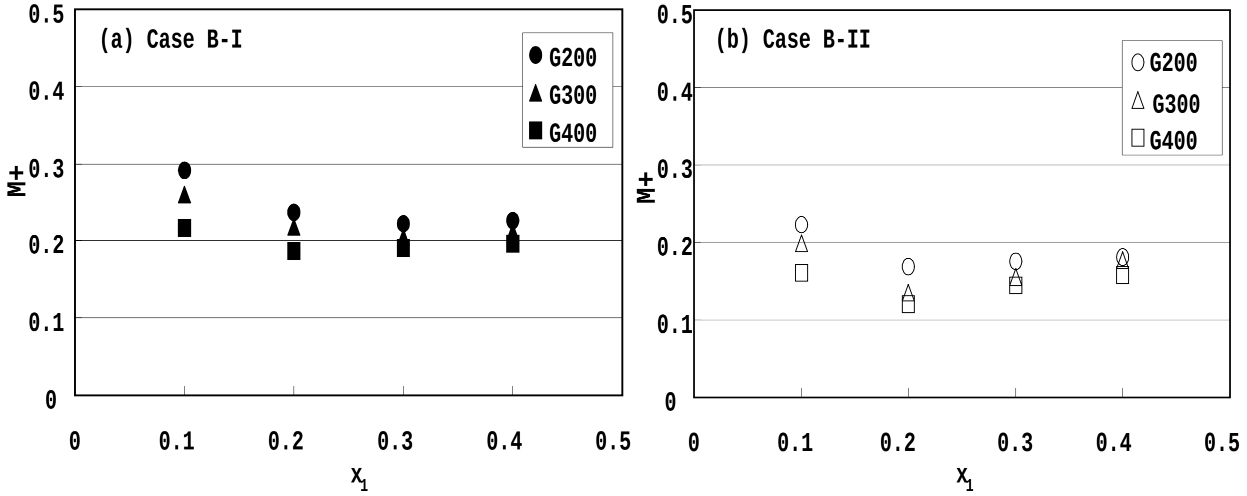


Figure 5: Flow distribution ratio for the horizontal inlet and vertical branch tubes

Figure 5 shows the flow distribution ratio for the horizontal inlet and vertical branch tubes. The flow distribution ratios for case B-II were lower by average 24.9% than those for case B-I, because of the orifice effect. The flow distribution ratios for the case B-I and B-II were smaller by 38.4% and 47.3% respectively than those for the case A-I and A-II. The reason is that the effect of gravity acting on the refrigerant at the junction made it difficult for the refrigerant to flow upward into the branch tube for the case B-I and B-II.

Figure 6 shows phase separation for horizontal inlet tube. The quality at the branch tube for both cases A-I and A-II almost linearly increases as the quality at the inlet tube increases. But, the quality at the branch tube for the cases B-I and B-II logarithmically increased as the quality at the inlet tube increases, and then reaches 1. Almost none of refrigerant liquid flows into the branch tube above the inlet quality of 0.4 for cases B-I and B-II. Figure 7 shows the flow distribution for horizontal branch tube. The flow distribution ratios were decreased as the mass flux at the inlet was increased due to the increase of momentum flux of two-phase refrigerant. For the cases C-I and C-II, the flow distribution ratio decreases as the quality at the inlet tubes increases. The flow distribution ratios for cases B and C showed the opposite of the case A. The flow distribution ratio increased as the orientation of inlet tube switched from horizontal to vertical upward. As shown in Fig. 7, the flow distribution ratios for the cases C-I and C-II were larger by 21-68% and 15-64% than those for the cases A-I and A-II.

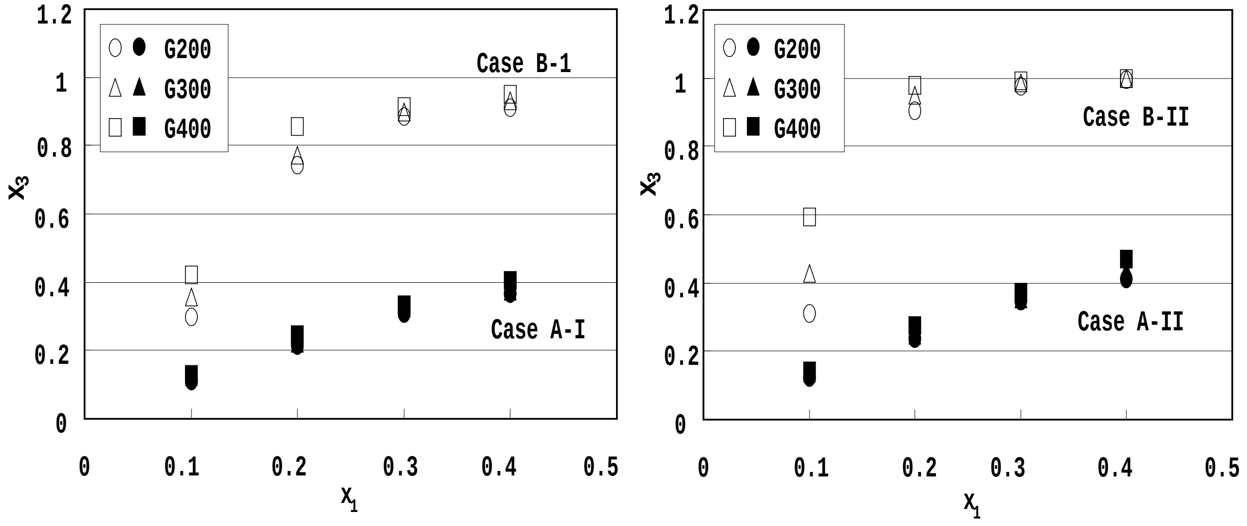


Figure 6: Phase separation for horizontal inlet tube.

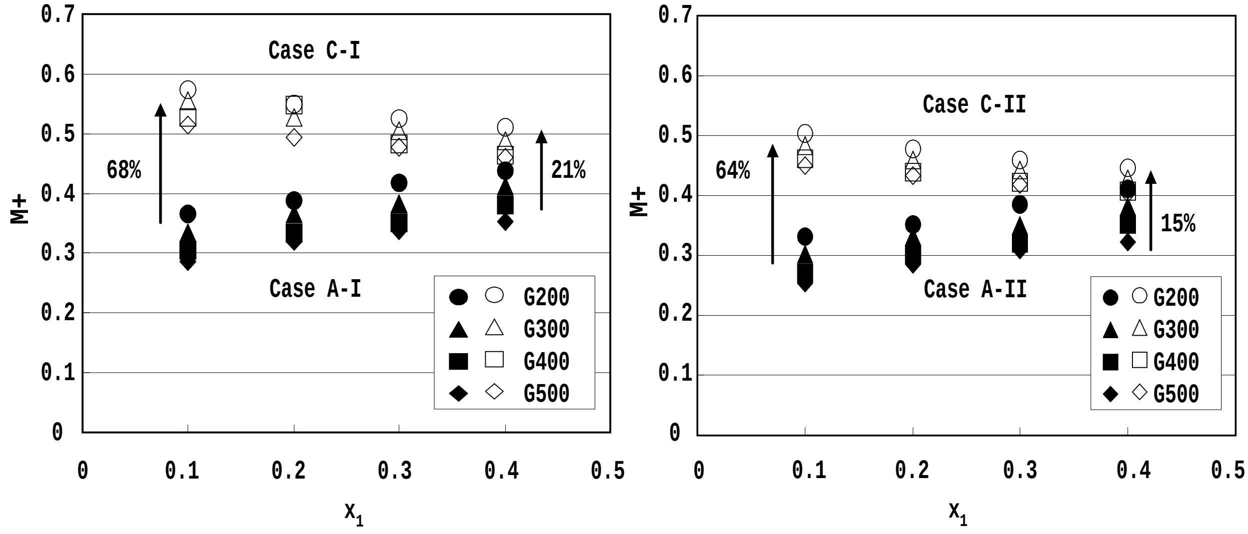


Figure 7: Flow distribution ratio for horizontal branch tube.

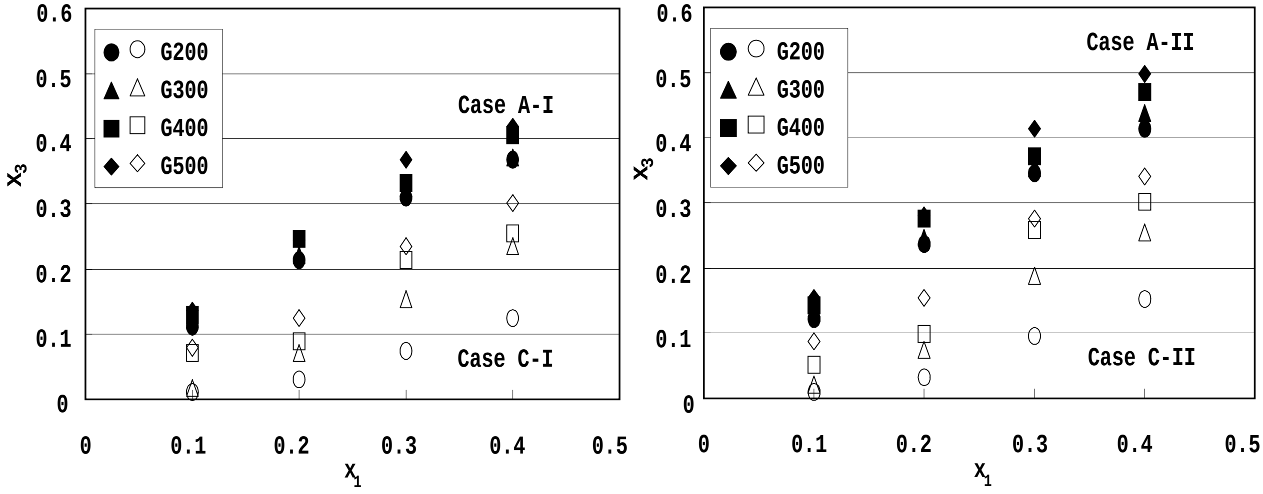


Figure 8: Phase separation for horizontal branch tube.

Figure 8 shows the phase separation for horizontal branch tube. The qualities at the branch for the case C-I and II were smaller than those for cases A-I and A-II. The smaller the quality at the branch was, the smaller the mass flux and the quality at the inlet tube were. As the case varied from A-I to C-I, the quality at the branch was decreased by 89% for the mass flux of 200 kg/m^{2}s and inlet quality of 0.1, and by 28% for the mass flux of 500 kg/m^{2}s and inlet quality of 0.4. The same trend was found when the case varied from A-II to C-II.

CONCLUSIONS

1. Pressure profile in the test section was predicted within 25% deviation from the measured data. Further studies on $K_{1\text{-}3}$, $C_{1\text{-}3}$, and two-phase disturbance effect after the junction are needed.

2. The flow distribution ratio decreased as the mass flux at the inlet tube increased, and the inlet quality increased except for the horizontal inlet and branch tubes. And, the flow distribution ratio increased as the diameter ratio of branch tube to the inlet tube increased.
3. The quality at the branch tube decreased as mass flux increased, and inlet quality decreased. And, the effect of the diameter ratio on the quality at the branch tube was fairly small.

ACKNOWLEDGEMENTS

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