Effect of Flow Direction on Two-Phase Flow Distribution of Refrigerants at a T-Junction

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The present study experimentally investigated the effect of flow direction and other flow parameters on two-phase flow distribution of refrigerants at a T-junction, and also suggested a prediction model for refrigerant in a T-junction by modifying previous model for air-water flow. R-22, R-134a, and R-410A were used as test refrigerants. As geometric parameters, the direction of the inlet or branch tube and the tube diameter ratio of branch to inlet tube were chosen. The measured data were compared with the values predicted by the models developed for air-water or steam-water mixture in the literature. We propose a modified model for application to the reduced T-junction and vertical tube orientation. Among the geometric parameters, the branch tube direction showed the biggest sensitivity to the mass flow rate ratio for the gas phase, while the inlet quality showed the biggest sensitivity to the mass flow rate ratio among the inlet flow parameters.

Key Words : Two-Phase Flow Distribution, Refrigerant, T-Junction

Nomenclature

A : Cross-sectional flow area [m^2]
a : Distance of dividing streamline [m]
D : Tube diameter [m]
F : Mass flow rate ratio, M_3/M_1
G : Mass flux [kg/m^2s]
j : Superficial velocity [m/s]
M : Mass flow rate [kg/s]
R : Radius of curvature [m]
u : Velocity [m/s]
X_{tt} : Lockart-Martinelli parameter
x : Quality

Greek letters

Θ : Angle of branch tube [degree]
ρ : Density [kg/m^3]
Ω : Angle of inlet tube [degree]

Subscripts

1 : Inlet tube
2 : Outlet tube
3 : Branch tube
G : Gas phase
L : Liquid phase

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1. Introduction

Dividing T-junction is a common component of piping systems, especially in the distribution header of a multi-pass evaporator, or the distribution kit of a system (multi) air-conditioner. When gas and liquid two-phase flow is moving in a pipe with a T-junction, it rarely splits with the same flow distribution and phase separation ratio. The dividing characteristics of the gas and liquid two-phase flow into the branch and outlet tubes are complex due to the many influencing variables.

The effect of the inlet mass flux and the inlet quality on the two-phase split in a T-junction had been studied by Saba and Lahey (1984), Seeger et al.(1986), Shoham et al.(1987), Ballyk et al.(1988), etc. Shoham et al.(1987), Ballyk et al.(1988), Azzopardi and Whalley (1982). Reimann and Seeger (1986) studied the effect of branch diameter and branch direction on two-phase split in a T-junction. Prediction methods for two-phase split in the T-junction were also suggested by Shoham et al.(1987), Azzopardi and Whalley (1982), Hart et al.(1991), and Hwang et al.(1988), etc.

Even though researchers have reported experimental or analytical results for two-phase split in the T-junction, most of the results cannot be applied for refrigerant flow. One reason is that all of the prediction methods were developed by using air-water or steam-water two-phase flow instead of refrigerant flow. The other reason is that there is little experimental data for two-phase flow of refrigerant in the T-junction that can verify the prediction method.

The first purpose of the present study is to measure two-phase flow distribution in the T-junction for R-22, R-134a, and R-410A by varying the flow direction of inlet and branch tubes. The second one is to suggest a modified model to be applied for vertical orientation of tubes and reduced T-junction.

2. Previous Works

Almost of the previous works focused on the experimental works on T-junction with a horizontal inlet tube using air-water or steam-water flow. They show that the flow distribution, phase separation and pressure changes at the junction are extremely complicated, and affected by inlet flow parameters, fluid properties and junction geometry, etc.

Azzopardi and Whalley (1982) studied the effect of branch diameter on phase separation in a 32 mm main inlet T-junction with branch diameters of 6.35, 12.7 and 19 mm, giving the diameter ratios of 0.2, 0.4 and 0.6, respectively.

Saba and Lahey (1984) presented air-water data of both phase redistribution and pressure changes in a horizontal T-junction with the same diameters of 38 mm. Three mass fluxes of 1353, 2041 and 2711 kg/m^{2}s were tested. The inlet quality was less than 0.01, which led to bubble flow and slug flow in the inlet tube. It was found that even for these low inlet qualities the degree of phase redistribution was quite pronounced with the gas phase preferentially separating into the branch. In their test conditions, they also found that the inlet mass flux had little effect on phase redistribution.

Shoham et al.(1987) performed air-water experiments in a 51 mm diameter T-junction. The data were collected at fixed inlet superficial gas velocities of 2.5, 6.1 and 26 m/s, while superficial liquid velocity varied from 0.0029 to 0.059 m/s for each gas velocity, thus giving rise to stratified and annular flow. In stratified flow they found that, in all conditions tested, at very low branch flow split, no liquid flowed into the branch. The liquid phase was extracted into the branch only after a higher portion of gas was diverted into the branch.

Ballyk et al.(1988) studied steam-water annular flow phase redistribution and pressure changes in a 25 mm diameter horizontal T-junction. These experiments were particularly interesting since the measurements included the void fraction profiles in the three legs of the junction, and the data were collected at a higher range of inlet mass flux of 450-1200 kg/m^{2}s, not previously tested. The inlet quality covered the range of 0.02-0.15. They reported that the branch quality was higher than the inlet quality over most of the flow split range, and only at low flow split was the branch quality less than that of the inlet. The maximum value of x_3/x_1 occurred at branch flow split ratio around 0.2. It is interesting to note that this result differs from that of Shoham et al.(1987) in which liquid tended to be extracted preferentially into the branch for most of the test conditions. These different trends are probably caused by the large difference of inlet mass flux used by the authors (2.9-59 kg/m^{2}s by Shoham et al.(1987) and 450-1200 kg/m^{2}s by Ballyk et al.(1988)). High inlet liquid velocity make the axial momentum flux of the liquid phase increase, and furthermore, generates higher entrainment of liquid droplets which have large momentum flux and the large resistance to being diverted to the branch. The data by Ballyk et al.(1988) also showed that an increase in inlet quality resulted in reducing the peak and the degree of the phase separation, x_3/x_1, and increasing the flow distribution ratio at which complete vapor extraction took place. The inlet mass flux, however, was found to have little effect on phase separation under their test conditions.

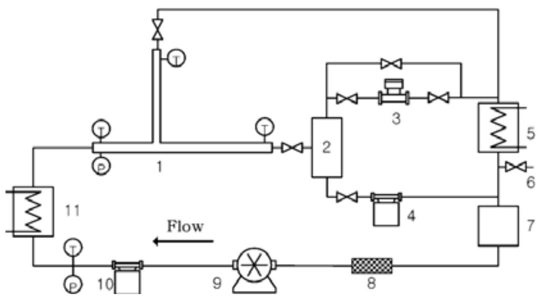
Rubel et al.(1988) performed steam-water experiments in a 37.6 mm equal diameter T-junction. The inlet mass flux and quality covered the ranges of 16.1-50.3 kg/m^{2}s and 0.21-0.87 respectively, which resulted mostly in stratified, stratified-wavy and semi-annular flow regime. Their data showed that the inlet mass flux did not have significant effect on the phase redistribution. However, when the inlet quality increased, the degree of phase separation x_3/x_1 decreased in the semi-annular flow and increased in stratified flow.

There was other a number of researches for two-phase flow distribution at a T-junction. They presented their experimental data for air-water or steam-water flow, and some of them suggested empirical prediction models. But, even though a number of researchers reported experimental or analytical results about the two-phase flow at T-junction, most of the methods to predict the flow characteristics of two-phase flow at a T-junction cannot be applied to the refrigerant cases. One of the reasons is that there are little experimental data for two-phase refrigerant at a T-junction to confirm the prediction methods.

3. Experiments

The experimental apparatus is schematically shown in Fig. 1. The system consists of a test section with a T-junction, a gas-liquid separator, gas and liquid flow meters, a pre-heater, a plate heat exchanger and a variable-speed refrigerant pump (0-0.333 kg/s). The sub-cooled refrigerant flow rate was controlled by the variable-speed refrigerant pump. The inlet mass flow rate of the refrigerant was measured by the Coriolis-type mass flow meter (0-0.333 kg/s range, 0.01% resolution). The inlet quality was controlled by the pre-heater. The two-phase refrigerant was discharged from the test section, and then separated in the gas liquid separator. The flow rates of each phase were measured by the gas mass flow meter (0-0.013 kg/s range, 0.5% resolution) and liquid mass flow meter (0-0.083 kg/s range, 0.01% resolution). The refrigerant in the branch tube and the refrigerant vapor separated by the gas liquid separator were merged, and then sub-cooled in the plate heat exchanger.

Figure 2 shows the details of the test section. The lengths of the inlet, outlet, and branch tubes



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

Fig. 1 Schematic diagram of the present experimental apparatus

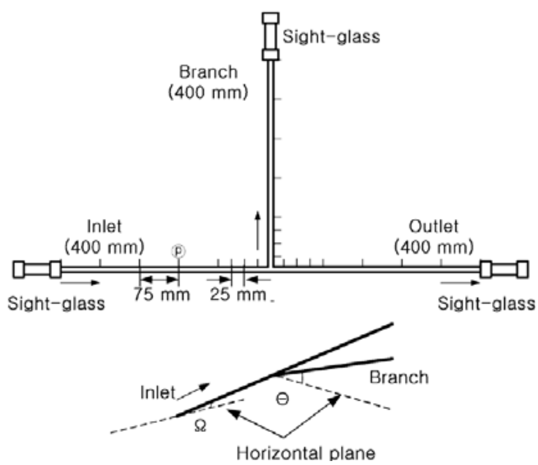


Fig. 2 Details of the test section

Table 1 Experimental parameters and ranges

Parameter	Unit	Range	Baseline case
Refrigerant	—	R-22, R-134a, R-410A	R-22
Inlet Mass Flux (G_1)	kg/m^2s	100, 300, 500, 700	300
Inlet Quality (x_1)	—	0.1, 0.3, 0.5, 0.7, 0.9	0.3
Inlet Diameter	mm	4.95, 8.12, 11.3	8.12
Diameter Ratio (D_3/D_1)	—	1, 0.72, 0.44	1
Branch Direction (Θ)	°	0°, +90°, −90°	0°
Inlet Direction (Ω)	°	0°, +90°, −90°	0°

were 400 mm, and the pressure measuring positions were marked.

The experimental geometric and inlet flow parameters and their ranges are presented in Table 1. The baseline condition ($\Theta=0°$, $\Omega=0°$) is for horizontal inlet and branch flow. Based on the baseline condition, the inlet or the branch flow direction was changed from horizontal to vertical upward or vertical downward.

The tube diameter ratio (D_3/D_1) was varied to 1, 0.72, and 0.44 based on the largest inlet tube diameter of 11.3 mm.

For each geometric condition, the inlet mass flux was changed to 100, 300, 500, 700 kg/m^2s, and the inlet quality was changed from 0.1 to 0.9. The test refrigerants were R-22, R-134a and R- 410A. The saturation temperature was fixed at 8.0℃.

The measured data for the two-phase flow distribution and phase separation were presented in terms of the mass flow rate ratios of gas and liquid phases. They were defined as follows:

$$F_G=\frac{M_{G3}}{M_{G1}} \quad (1)$$

$$F_L=\frac{M_{L3}}{M_{L1}} \quad (2)$$

The uncertainty of the experimental data was analyzed by the method suggested by Moffat (1985). The uncertainty ranged from 2.3-5.1% and 1.5-4.8% for mass flow rate ratios of gas (F_G) and liquid phases (F_L), respectively.

4. Prediction Model for Horizontal T-Junction

Prediction models for two-phase flow in a T-junction in the literature were developed for a certain flow regime such as annular flow, stratified flow etc. Thus, the flow pattern in the test section with a T-junction was examined. The predicted flow patterns of the two-phase refrigerant (R-22) are shown in Figs. 3 and 4 for horizontal and vertical flows, respectively. As shown in Fig. 3, most of flow patterns obtained by Taitel and Dukler (1976)'s map for horizontal flow and Hewitt and Roberts (1969)'s map for vertical flow were annular flow. Annular flow was also observed through the sight glass installed at the inlet of the test section.

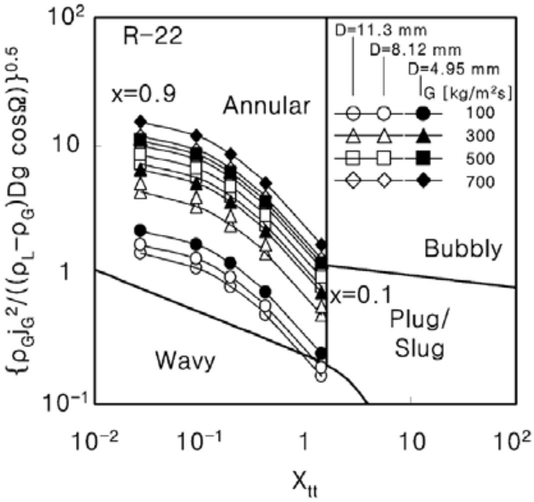


Fig. 3 Flow pattern for horizontal flow of R-22 based on Taitel and Dukler (1976) map

Two-phase flow distribution and phase separation of refrigerant may be affected by pressure gradient in the junction, gravity force, and diameter of the branch tube as well as the flow conditions of each phase entering the junction.

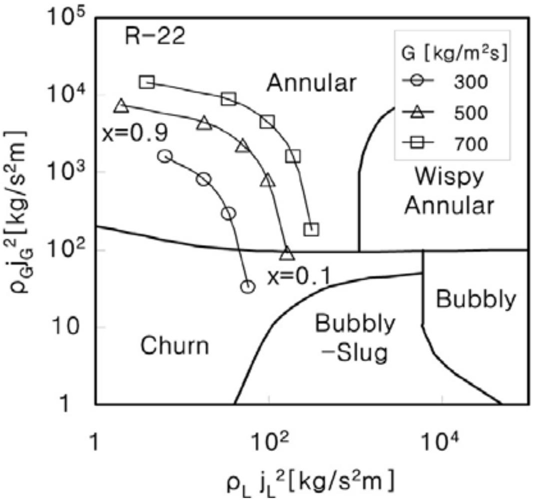


Fig. 4 Flow pattern for vertical flow of R-22 based on Hewitt and Roberts (1969) map

The mass flow rate ratio of gas, F_G, may be usually different from that of liquid, F_L. It may be assumed that there are two dividing streamlines for gas and liquid phases, which distinguish the flow entering the branch tube from the flow exiting to the outlet tube.

The streamline concept was used by Shoham et al. (1987), Hwang et al. (1988), etc. Figure 5 shows the distance of the dividing streamline for gas and liquid two-phase flows from the tube wall of the branch tube in the inlet tube by parameters a_G and a_L. The key assumption of the dividing streamline concept is that the gas or the liquid flow in the area located on the right side of the dividing streamlines (A_{G3} and A_{L3}) is diverted into the branch tube.

To find out the relations between F_G and F_L, the measured data were compared with the values predicted by the previous models in the literature. Most of the previous models were developed by using air-water or steam-water data instead of refrigerant. Figure 6 shows the comparison between the measured data for R-22 and the values predicted by several previous models. As shown in Fig. 6, the model by Hwang et al. (1988) showed the best agreement with the present data. The models by Azzopardi and Whaley (1982) and Roberts et al. (1997) under-predicted the F_G at the fixed F_L because both models are based on the

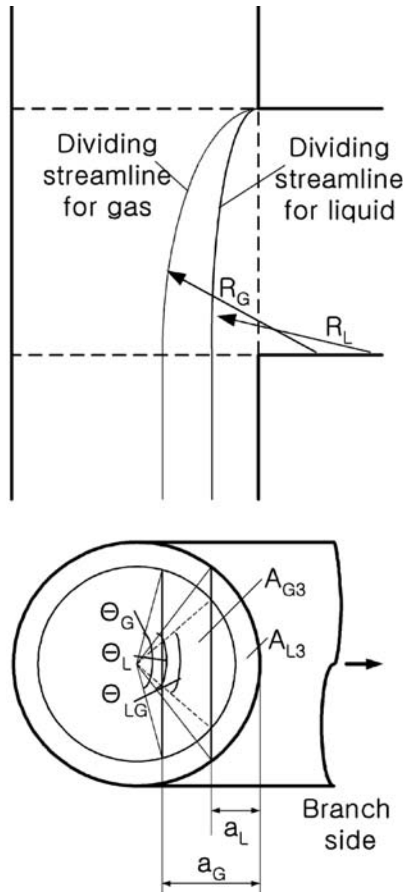


Fig. 5 Dividing streamlines for gas and liquid two-phase flows

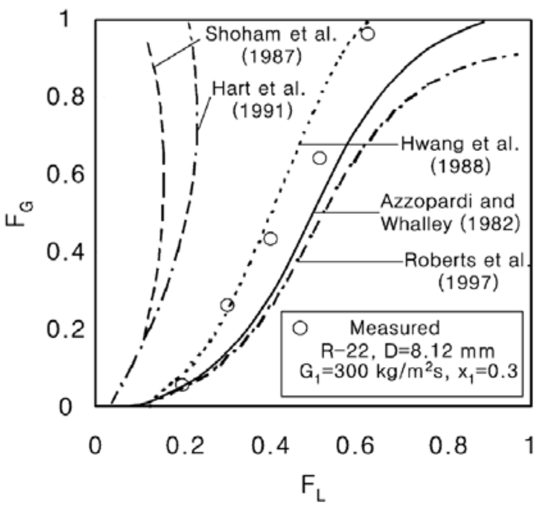


Fig. 6 Comparison of experimental data with predicted values

assumption of the same dividing streamline for both gas and liquid phases even though the dividing streamline of the gas phase is actually located far from the branch side wall than that of the liquid phase. The models by Shoham et al. (1987) and Hart et al. (1991) over-predicted the experimental data. The reason is as follows; the density ratio of gas and liquid phases of a refrigerant flow is bigger than that of air-water flow. For example, the density ratio (ρ_G/ρ_L) for air-water at 0.1 MPa, 25.0℃ is 0.001, while that for R-22 at the saturated pressure of 0.65 MPa is 0.022. As the density ratio was increased, F_G was decreased for the fixed F_L.

Hwang et al. (1988) developed a phenomenological model for the horizontal T-junction with the same diameters based on different dividing streamlines for gas and liquid phases. For the separated two-phase flow such as stratified and annular flows, it was found that the influence of the interfacial drag force is relatively small and may be neglected. Then, the model is simplified to the balance between centrifugal forces of the two phases as follows:

$$\frac{\rho_G u_G^2}{R_G} = \frac{\rho_L u_L^2}{R_L} \tag{3}$$

where the radii of the curvature of gas and liquid phases dividing streamlines are assumed to satisfy the following relation:

$$\frac{R_G}{R_G} = \frac{\left(\frac{a_L}{D_1}\right)^{n_L}}{\left(\frac{a_G}{D_1}\right)^{n_G}} \tag{4}$$

The exponent n_k in equation (4) was empirically determined by Hwang et al. (1988) as:

$$n_k = 5 + 20 \exp\left[-53\left(\frac{a_k}{D_1}\right)\right] \tag{5}$$

Thus, the relation between the dividing streamlines of gas and liquid phases is:

$$\frac{\left(\frac{a_L}{D_1}\right)^{n_L}}{\left(\frac{a_G}{D_1}\right)^{n_G}} = \frac{\rho_G u_G^2}{\rho_L u_L^2} \tag{6}$$

The relation between the dividing streamlines

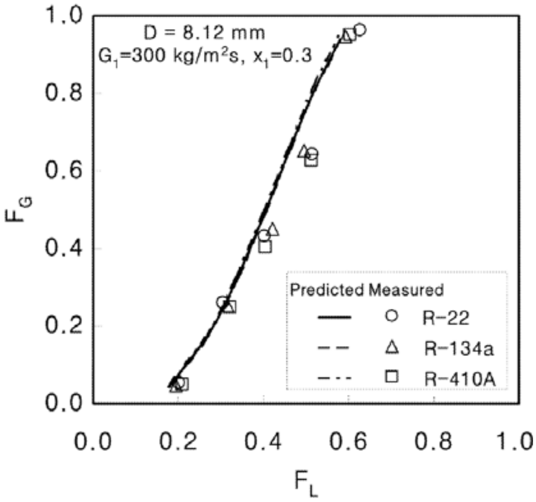


Fig. 7 Mass flow rate ratio (F) for various refrigerants

(a_L, a_G) and the mass flow rate ratios (F_L, F_G) was presented in Appendix A.

Figure 7 shows the mass flow rate ratio of gas and liquid phases through the T-junction with horizontal inlet and branch tubes for various refrigerants. As shown in Fig. 7, the differences of F's for different refrigerants were negligible. The momentum flux ratios ($\rho_G u_G^2/\rho_L u_L^2$) under the conditions used in Fig. 7 were 0.193, 0.196 and 0.182 for R-22, R-134a and R-410A, respectively. Since the momentum flux were not changed significantly, the a's were not changed much. Therefore, the F's did not show significant difference. Figure 8 shows the effect of the inlet mass flux on F's for R-22 when the inlet quality was 0.3 for the horizontal inlet and branch tubes with the diameter of 8.12 mm. As the inlet mass flux was increased, the F_G at the fixed F_G was increased. The momentum flux ratio ($\rho_G u_G^2/\rho_L u_L^2$) at G_1 of 100 kg/m^{2}s was 0.373, but decreased to 0.149 at G_1 of 700 kg/m^{2}s because the gas velocity was increased more rapidly than the liquid velocity as the inlet mass flux was increased. As the momentum flux ratio was decreased, gas was flowed more easily into the branch tube, and the mass flow rate ratio, F_G, was increased at the fixed F_L.

Figure 9 shows the effect of the inlet quality on F's for R-22 when the inlet mass flux was 300 kg/m^{2}s in the horizontal inlet and branch tubes with

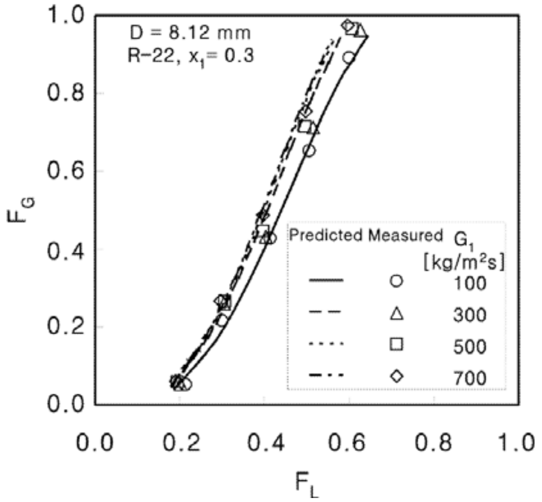


Fig. 8 Effect of the inlet mass flux on F's

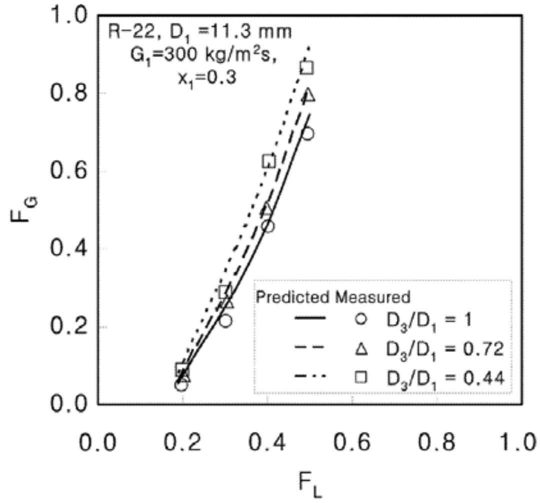


Fig. 10 Effect of the tube diameter ratio on F's

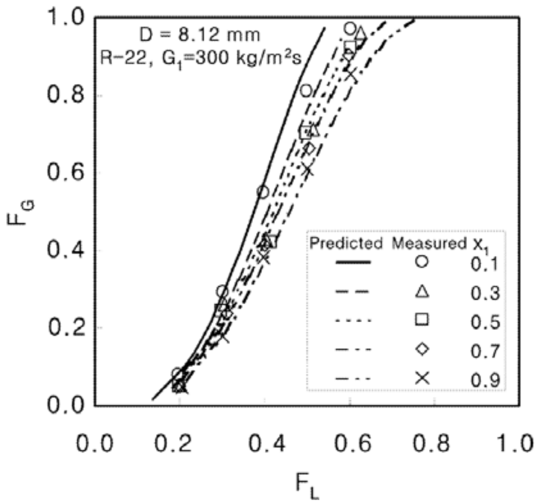


Fig. 9 Effect of the inlet quality on F's

the diameter of 8.12 mm. The mass flow rate ratio of gas, F_G, was decreased at the fixed F_L, as the inlet quality was increased. Also, it may be explained by the momentum flux ratio of gas and liquid phases. As the inlet quality was increased from 0.1 to 0.9, the momentum flux ratio ($\rho_G u_G^2/\rho_L u_L^2$) was also increased from 0.115 to 0.502 at the fixed inlet mass flux of 300 kg/m^{2}s.

The case with the different tube diameters for the inlet and branch tubes ($D_1 > D_3$) can't be considered for the model suggested by Hwang et al. (1988). Results by Buell et al. (1994), Walters et al. (1998), Azzopardi (1999), and Wren et al. (1999) showed that the mass flow rate ratio of gas (F_G) at the fixed mass flow rate ratio of liquid (F_L) was increased for the reduced T-junction ($D_3/D_1 < 1$). Thus, the modified model for the reduced T-junction is suggested in equation (7) by modifying equation (6) and considering the diameter ratio effect.

$$\frac{\left(\frac{a_L}{D_1}\right)^{n_L}}{\left(\frac{a_G}{D_1}\right)^{n_G}} = \frac{\rho_G u_G^2}{\rho_L u_L^2}\left(\frac{D_3}{D_1}\right)^k \quad (7)$$

The k was determined as 1.25 by utilizing the present experimental data for refrigerants. The values predicted by modified model were compared with the measured data for the reduced T-junction in Fig. 10.

5. Prediction Model for Vertical T-Junction

Since the model developed by Hwang et al. (1988) can be applied for only horizontal tube, it cannot be applied for a vertical inlet and branch tubes with T-junction. Therefore, a modified model is needed for two-phase refrigerant flow with the vertical tube orientation.

The modified model for the vertical tube orientation as well as reduced T-junction, is suggested in equation (8) by considering both the angles of the branch tube (Θ) and inlet tube (Ω).

$$\frac{\left((1+0.52\sin\Theta-0.48\sin\Omega)\dfrac{a_L}{D_1}\right)^{n_L}}{\left((1-0.65\sin\Theta+0.28\sin\Omega)\dfrac{a_G}{D_1}\right)^{n_G}}=\frac{\rho_G u_G^2}{\rho_L u_L^2}\left(\frac{D_3}{D_1}\right)^{1.25} \quad (8)$$

Based on the measured data, the constants on the left hand side of equation (8) were the same for all test cases within the experimental uncertainty range.

Figure 11 shows the effect of the orientation of the inlet and branch tubes on F's. The mass flow rate ratios of gas at the fixed FL were large for the vertical upward branch case (Θ=+90°, Ω=0°), followed by the vertical downward inlet case (Θ=0°, Ω=−90°), horizontal T-junction case (Θ=0°, Ω=0°), the vertical upward inlet case (Θ=0°, Ω=+90°), and the vertical downward branch case (Θ=−90°, Ω=0°). For the vertical upward branch case (Θ=+90°, Ω=0°), the

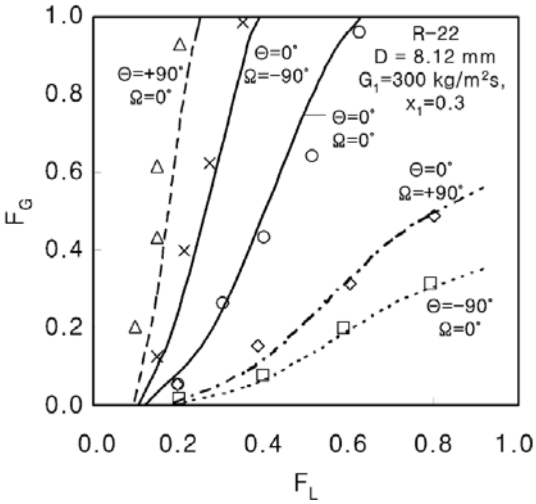


Fig. 11 Effect of the orientation of inlet and branch tubes on F's

Table 2 Mass flux and quality at the outlet and branch tubes

Θ	Ω	F_L	F_G	G_2	x_2	G_3	x_3
0	0	0.201	0.053	253	0.337	47	0.102
		0.305	0.261	212	0.313	88	0.268
		0.403	0.432	176	0.290	124	0.315
		0.515	0.642	134	0.240	166	0.348
+90℃	0	0.098	0.203	261	0.275	39	0.470
		0.151	0.432	229	0.223	71	0.551
		0.150	0.615	213	0.163	87	0.637
		0.205	0.932	173	0.035	127	0.661
−90°	0	0.203	0.015	256	0.346	44	0.031
		0.401	0.075	209	0.398	91	0.074
		0.589	0.198	158	0.455	142	0.126
		0.793	0.312	105	0.588	195	0.144
0	+90°	0.198	0.052	254	0.336	46	0.101
		0.387	0.151	205	0.372	95	0.143
		0.605	0.312	145	0.427	155	0.181
		0.802	0.487	88	0.526	212	0.207
0	−90°	0.150	0.125	257	0.306	43	0.263
		0.215	0.398	219	0.247	81	0.442
		0.275	0.623	186	0.182	114	0.493
		0.353	0.987	137	0.009	163	0.545

* R-22, D=8.12 mm, G_1=300 kg/m²s, x_1=0.3

gravity force was acted in the opposite direction to the branch flow at the junction area. Due to the difference of the densities between gas and liquid phases, the acting gravity force of liquid was also larger than that of gas. Thus, the mass flow rate ratio of liquid was rapidly decreased for the vertical upward case. For the vertical downward branch case, the direction of gravity force was parallel to the direction of branch flow, and thus large amount of liquid was extracted into the branch tubes. Table 2 shows the mass fluxes and qualities at the outlet and branch tubes when the two-phase distribution occurred as shown in Fig. 11.

For the vertical upward inlet case, the gravity force acts in the opposite direction to the inlet flow. Around the junction area, the gravity force pushes the liquid with the larger density into the branch tube, while the gas with the smaller density flows up to the outlet tube. Thus, the mass flow rate ratio of the liquid phase for the vertical case was increased more than that of the horizontal case. For the vertical downward case, the gravity force was acted in the inlet flow direction, and it makes more liquid flows to the outlet tube. Thus, the mass flow rate ratio of the liquid phase was decreased. Similar phenomena were observed for all refrigerants. The effects of the refrigerant property on the two-phase flow split through the T-junction were not significant. The predicted values agreed with the measured data.

Figures 12 and 13 show the effect of inlet mass flux and inlet quality in a vertical T-junction on the mass flow rate ratio, respectively. As, shown in Figs. 12 and 13, the predicted values predicted by the modified model were also agreed with the measured data for various inlet mass flux and quality in the vertical T-junction. The inlet mass flux was more sensitive for vertical downward branch case than for vertical upward branch case. The inlet quality was more sensitive for vertical upward branch case than for vertical downward branch case. The sensitivities of the geometric and inlet flow parameters were presented in Table 3. The sensitivity of parameter was defined as the maximum difference between reference value at the F_L of 0.5 for the baseline case listed in Table 1 and the value at the different conditions. As shown in Table 3, the branch tube direction was the most sensitive parameter among the test parameters. The inlet quality was the most sensitive parameter among the inlet flow parameters, while the branch tube direction was the most sensitive one among the geometric parameters. Table 3 also shows the maximum prediction error between the measured data and the values predicted by the modified model.

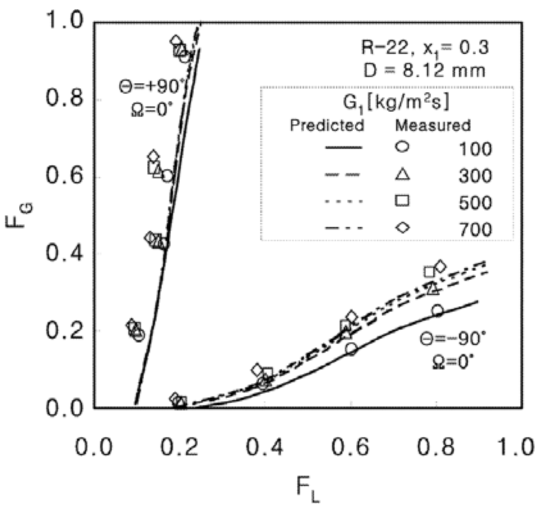


Fig. 12 Effect of inlet mass flux on F's in vertical branch

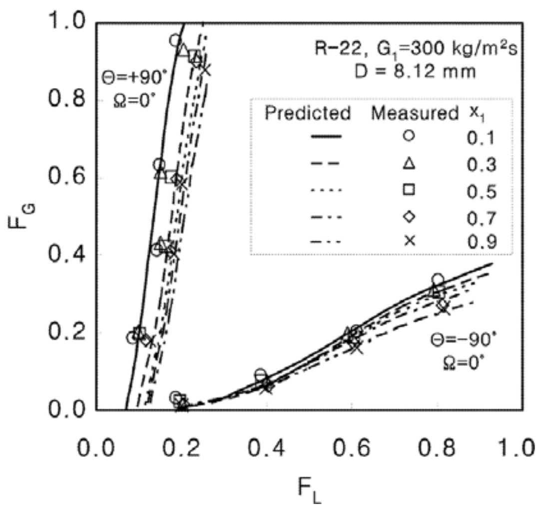


Fig. 13 Effect of inlet quality on F's in vertical branch

Table 3 Sensitivity of parameters

Parameter		Range	Sensitivity	Maximum prediction error
Inlet flow	Refrigerant	R-22, R-134a, R-410A	2.5%	17%
	Inlet mass flux (kg/m^2s)	100, 300, 500, 700	23.4%	17%
	Inlet quality	0.1−0.9	43.6%	17%
Geometric	Diameter ratio	1, 0.72, 0.44	26.5%	17%
	Branch direction	0°, +90°, −90°	198%	25%
	Inlet direction	0°, +90°, −90°	181%	25%

6. Conclusions

This present study experimentally investigated the two-phase flow split of refrigerants in both horizontal and vertical tubes with the T-junction. The modified model for refrigerant flow in the horizontal and vertical tube with the reduced T-junction was suggested.

(1) Among the models for the two-phase flow split at the T-junction in the literatures, the models developed by Hwang et al. (1988) gave the best agreement with the measured data at a horizontal T-junction for refrigerants.

(2) Hwang et al. (1988)'s model was modified for applying for the reduced T-junction and vertical orientation of the tubes.

(3) Two-phase flow distribution at the T-junction was the most sensitive to the branch tube direction among the test parameters and the inlet quality among the inlet flow parameters.

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References

Azzopardi, B. J. and Whalley, P. B., 1982, "The effect of Flow Patterns on Two-Phase Flow in a T-Junction," *Int. J. Multiphase Flow*, Vol. 8, pp. 491∼507.

Azzopardi, B. J., 1999, "The Effect of Side Arm Diameter on Phase Split at T-Junctions," *SPE Annual Technical Conference and Exhibition, Houston*, October, pp. 1∼8.

Ballyk, J. D., Shoukri, M. and Chan, A. M., 1988, "Steam-Water Annular Flow in a Horizontal Dividing T-Junction," *Int. J. Multiphase Flow*, Vol. 14, No. 3, pp. 265∼285.

Buell, J. R., Soliman, H. M., and Sims, G. E., 1994, "Two-Phase Pressure Drop and Phase Distribution at a Horizontal Tee Junction," *Int. J. Multiphase Flow*, Vol. 20, No. 5, pp. 819∼836.

Hart, J., Hamersma, P. J., and Fortuin, J. M. H., 1991, "Phase Distribution During Gas-Liquid Flow Through Horizontal Dividing Junctions," *Nuclear Engineering and Design*, Vol. 126, pp. 293∼312.

Hewitt, G. F. and Roberts, D. N., 1969, "Studies of Two-Phase Flow Patterns by Simultaneous X-ray and Flash Photography," AERE-M 2159, HMSO.

Hwang, S. T., Soliman, H. M., and Lahey, Jr., R. T., 1988, "Phase Separation in Dividing Two-Phase Flows," *Int. J. Multiphase Flow*, Vol. 14, No. 4, pp. 439∼458.

Moffat, R. J., 1985, "Using Uncertainty Analysis in the Planning of an Experiment," *Trans. ASME J. Fluid Eng.*, Vol. 107, pp. 173∼182.

Reimann, J. and Seeger, W., 1986, "Two-Phase Flow in a T-Junction with a Horizontal Inlet, Part II : Pressure Differences," *Int. J. Multiphase Flow*, Vol. 12, No. 4, pp. 587∼608.

Roberts, P. A., Azzopardi, B. J. and Hibberd, S., 1997, "The Split of Horizontal Annular Flow at a T-Junction," *Chemical Engineering Science*, Vol. 52, No. 20, pp. 3441～3453.

Rubel, M. T., Soliman, H. M. and Sims, G. E., 1988, "Phase Distribution During Steam-Water Flow in a Horizontal T-Junction," *Int. J. Multiphase Flow*, Vol. 14, No. 4, pp. 425～438.

Saba, N. and Lahey, Jr., R. T., 1984, "The Analysis of Phase Separation Phenomena in Branching Conduits," *Int. J. Multiphase Flow*, Vol. 10, No. 1, pp. 1～20.

Seeger, W., Reimann, J., and Muller, U., 1986, "Two-Phase Flow in a T-Junction with a Horizontal Inlet, Part I: Phase Separation," *Int. J. Multiphase Flow*, Vol. 12, No. 4, pp. 575～585.

Shoham, O., Brill, J. P., and Taitel, Y., 1987, "Two-Phase Flow Splitting in a Tee Junction Experiment and Modeling," *Chem. Eng. Science*, Vol. 42, No. 11, pp. 2667～2676.

Taitel, Y. and Dukler, A. E., 1976, "A Model for Predicting Flow Regime Transitions in Horizontal and Near Horizontal Gas-Liquid Flow," *AIChE J.*, Vol. 22, pp. 47～55.

Walters, L. C., Soliman, H. M. and Sims, G. E., 1998, Two-Phase Pressure Drop and Phase -istribution at Reduced Tee Junctions," *Int. J. Multiphase Flow*, Vol. 24, pp. 775～792.

Wren, E., Azzopardi, B. J. and Rea, S., 1999, "Geometric Effects on Phase Split in a Large Diameter T-Junction," *2nd Int. Symp. on Two-Phase Flow Modeling and Experimentation, Pisa*, pp. 23～26.

Appendix A

The following equations show the relation between dividing streamlines and mass flow rate ratios for each phase. The equations can be readily obtained from geometric considerations.

$$A_{G1}=\frac{\pi}{4}(D-2\delta)^2=A\alpha \tag{A.1}$$

$$A_{L1}=\pi\delta(D-\delta)=A(1-\alpha) \tag{A.2}$$

$$A_{G3}=\frac{\theta_G}{2}\left(\frac{D}{2}-\delta\right)^2-\left(\frac{D}{2}-\delta\right)\left(\frac{D}{2}-a_G\right)\sin\frac{\theta_G}{2} \tag{A.3}$$

$$A_{LG3}=\frac{\theta_{LG}}{2}\left(\frac{D}{2}-\delta\right)^2-\left(\frac{D}{2}-\delta\right)\left(\frac{D}{2}-a_L\right)\sin\frac{\theta_{LG}}{2} \tag{A.4}$$

$$A_{L3}=\frac{\theta_L}{8}D^2-\frac{D}{2}\left(\frac{D}{2}-a_L\right)\sin\frac{\theta_L}{2}-A_{LG3} \tag{A.5}$$

$$\theta_G=2\cos^{-1}\left(\frac{D-2a_G}{D-2\delta}\right) \tag{A.6}$$

$$\theta_L=2\cos^{-1}\left(\frac{D-2a_L}{D}\right) \tag{A.7}$$

$$\theta_{LG}=2\cos^{-1}\left(\frac{D-2a_L}{D-2\delta}\right) \tag{A.8}$$

$$F_G=\frac{A_{G3}}{A_{G1}} \tag{A.9}$$

$$F_L=\frac{A_{L3}}{A_{L1}} \tag{A.10}$$