Experimental Study on the Flow Patterns and Two-phase Pressure Drops in a Horizontal Impacting T-Junction

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Experimental study on the flow patterns and the two-phase pressure drops in a horizontal impacting T-Junction

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Abstract. The present paper analyzes the experimental results concerning the flow patterns and pressure drops in two-phase flow through a horizontal impacting T-junction, whose outlet pipes are aligned and perpendicular to the inlet pipe. The test section consists of plexiglass pipes with inner diameter of 10 mm. A mixture of water and air at ambient temperature and pressures up to 2.4 bar flows through the T-junction, with different splitting of flow rates in the two outlet branches; superficial velocities of air and water in the inlet pipe have been varied up to a maximum of 35 m/s and 3.5 m/s respectively. The flow patterns occurring in the inlet and branch pipes are compared with the predictions of the Baker and Taitel – Dukler maps. The pressure drops along the branches have been measured relatively to different splitting of the flow rate through the two branches and the pressure loss coefficients in the junction have been evaluated. Friction pressure drops have allowed us to evaluate two-phase friction multipliers, which have then been compared to the predictions of Lockhart-Martinelli, and Friedel correlations. Local pressure drops have been extrapolated at the junction centre and analyzed; the two-phase multiplier has been evaluated and compared with the predictions of Chisholm correlation; the value of the empirical coefficient that minimizes the discrepancy has also been evaluated.

1. Introduction

In both conventional and nuclear power plants there are several T-junctions where two-phase flow may occur in normal and accidental conditions. Both configurations of dividing tees, i.e. the impacting tee and the branching tee, have been studied in literature since the 80's [1-6]. An outlet pipe is aligned with the inlet pipe in the case of a branching tee, while both outlet pipes are perpendicular to the inlet pipe in the impacting tee.

The mass qualities in the two outlet branches can be different, as the T-junction can induce an uneven phase separation. At different mass fluxes and different qualities and void fractions, the local pressure drops in the junction as well as the friction pressure drops in the branches are measured, and different flow regimes are observed; moreover the orientation and the inclination of the T-junction strongly affect two-phase flow phenomena.

Even though several experiments have already been carried out, the prediction of the phase separation in T-junctions is still difficult and further experimental work is needed.

In the present study experiments on the horizontal T-junction that has been described in [7] have been performed. A plexiglass test section with 10 mm inner diameter has been chosen, since few experimental data for small diameters are available in the literature. Superficial velocities of air and water in the inlet pipe are varied up to a maximum of 35 m/s and 3.5 m/s respectively, with different partitioning of the flow rate through the outlet pipes.

Flow patterns in the inlet and branch pipes, that have been previously [7] compared with the Mandhane map, have been further analysed by means of the Baker and Taitel–Dukler maps. Moreover, the measured pressures have allowed the evaluation of the friction pressure drops along the branches, of the singular pressure drops in the junction as well as of the two-phase multipliers.

The test data of the friction pressure drop have been compared with the Lockhart-Martinelli and Friedel multipliers; as regards singular pressure drops the Chisholm correlation has been used and an empirical coefficient that minimises the discrepancy from the experimental values has been determined.

2. Experimental facility

The experimental facility is schematically shown in figure 1. It mainly consists of the feeding lines for air and water, the mixer, the T-junction, the outlet pipes and an air-water separator having a volume of approximately 0.4 m^3. The two-phase mixture develops in a T-mixer that is located at the inlet of the test section.

The test section is shown in figure 2. It consists of three plexiglass pipes (10 mm in diameter, about 1 m long) named inlet, right and left. Four pressure taps are placed on each of them; these measurements allow us to determine the pressure behaviour along the pipes and to extrapolate the pressure losses between the inlet and the branches. The flow patterns have been visualised by a Panasonic video camera Model AG-DVC30E, with a shutter opening time of 1/8000 s. Instrumentation and its accuracy is described in [7]. Table 1 summarizes the test conditions.

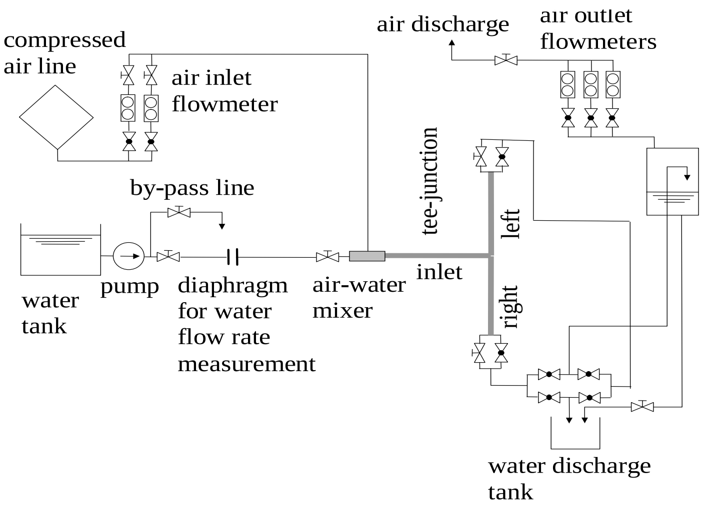
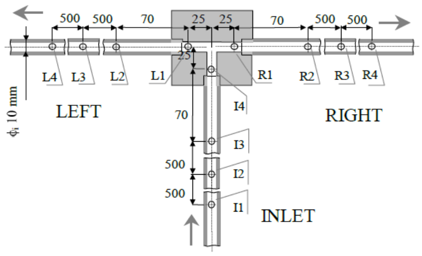


Figure 1. Experimental facility



Pressure taps:
Inlet I1÷I4
Right R1÷R4
Left L1÷L4.

Figure 2. Test section

Table 1. Tests conditions.

Water inlet flow rate: six values from 80 g/s to 280 g/s
Air inlet flow rate: three values for each water flow rate (inlet pressure from 1.5 bar to 2.4 bar)
Extraction ratios: four values from 0 to 1 for each pair of water and air flow rates
Flow pattern in the inlet pipe: annular, intermittent and bubbly

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3. Experimental results

Measurements of the two-phase flow have been carried out for six different values of water flow rate. At each water flow rate, the feed pressure has been varied in order to obtain three values of the air flow rate; several groups of three measurements have been carried out by varying the splitting of the phases and therefore the extraction ratio.

The mass velocity G in the inlet branch and the flow quality x in each pipe are reported in table 2, where for each run the minimum (min) and the maximum (max) measured values are reported. Table 2 also shows the values of the absolute pressure measured at pressure tap I1 at the test section inlet. The extraction ratios ER_R and ER_L of the right and left branch range from 0 to 0.5 and from 0.5 and 1 respectively.

4. Flow patterns

The flow patterns observed in all experimental tests of groups 1, 2, 3 and 4 are intermittent flow (plug – slug, I) and annular flow (A), as defined in [8].

More than one flow pattern has been observed in most cases: annular flow and intermittent flow are found alternatively, but the annular regime is prevailing (A-I); in other tests the intermittent regime prevails (I-A). Many flow patterns are therefore close to the transition conditions.

The flow patterns in the groups 5 and 6 have not been systematically analysed, as the rather high mass flux makes difficult the observation; anyway, in such tests bubble flow is prevailing in the inlet pipe. Table 3 reports the percentage of occurrence of the different flow patterns.

Table 2. Two-phase flow data

Group	p_{I1} [MPa]	G_1 [kg/(sm^2)]	x_I [%]	x_L [%]	x_R [%]
1	0.157-0.241	1019-1117	1.45-5.19	1.33-6.05	1.46-5.36
2	0.159-0.240	1289-1394	0.78-4.85	0.19-5.23	0.77-4.59
3	0.160-0.236	1614-1760	0.36-3.01	0.13-3.10	0.34-2.97
4	0.156-0.232	2133-2345	0.13-1.52	0.00-1.59	0.13-1.57
5	0.154-0.227	2717-2984	0.08-0.77	0.0-0.77	0.11-0.84
6	0.174-0.223	3266-3528	0.06-0.43	0.00-0.41	0.07-0.46

Table 3. Percentage of occurrence of the flow pattern

Observed flow pattern	% of the total
annular	1.5
annular - intermittent	18.9
intermittent - annular	22.0
intermittent	57.6

As part of the experimental points are in disagreement with the Mandhane map [7], the comparison has been extended to the Baker [9] and Taitel - Dukler [9] maps. The Baker maps are represented in figures 3a, 3b, 3c and 3d. They show that the experimental points of the test groups 1 and 2 predominantly lie in the annular flow region of the map; on the other hand the experimental points of group 3 partly lie also in the slug flow region and those of group 4 predominantly lie in the slug flow region.

As it can be seen in table 2, mass velocities in the experiments of test group 1 are slightly higher than 1000 kg/(s m^2), while the mass velocities of the tests of the other groups are higher than 2000 kg/(s m^2) in test group 4.

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The comparison shows a poor agreement at low mass velocities, as annular flow is foreseen while intermittent flows are observed; a better agreement is evident at higher flow rates, as the experimental points lie mainly in the slug flow region of the map and the observed flow regime is actually predominantly intermittent.

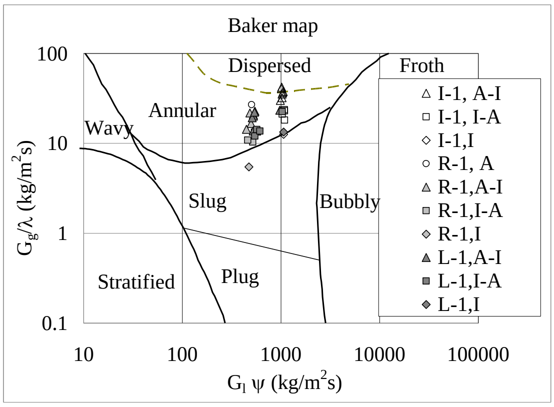

Figure 3a. Comparison of the group 1 results with the Baker Map; I (Inlet), R (Right), L (Left), 1 (Group 1)

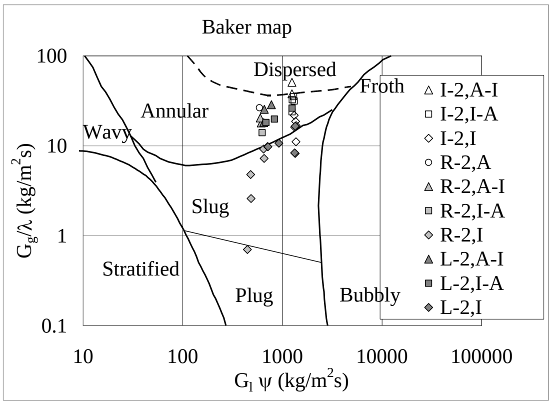

Figure 3b. Comparison of the group 2 results with the Baker Map; 2 (Group 2)

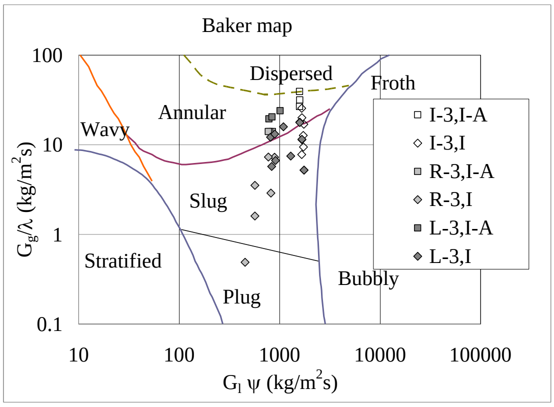

Figure 3c. Comparison of the group 3 results with the Baker Map; 3 (Group 3)

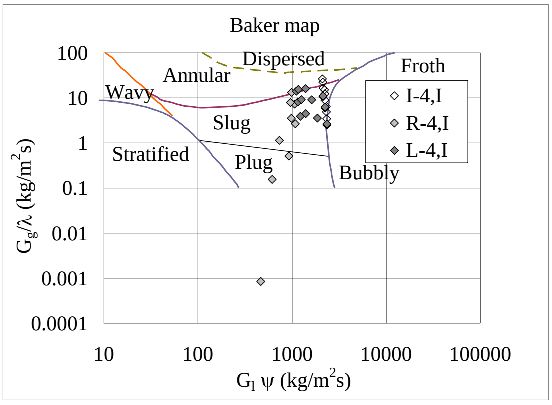

Figure 3d. Comparison of the group 4 results with the Baker Map; 4 (Group 4)

The comparison with Taitel–Dukler maps is shown in figures 4a- 4h, which reports the Froude number Fr and the non-dimensional parameter T versus the Martinelli parameter χ.
In most of the experimental tests of test groups 1, 2 and 3, the annular flow has been observed, but it alternated with intermittent flow. The Taitel-Duckler maps show that experimental points of test groups 1, 2 and 3 lie in the transition zone. Some points of test group 1 are in the intermittent flow region.
All experiments of test group 4 revealed an intermittent flow and their relative points lie in the intermittent zone of Taitel-Duckler map. Therefore we can state that the Taitel-Duckler maps give a good prediction of the flow pattern of all tests.

5. Friction pressure drops

Friction pressure gradients along the branches have been evaluated by using the differential pressure measured between pressure taps I1, I2, I3, L1, L2, L3, R1, R2, R3 and by neglecting the acceleration pressure drop, as it is lower than 1% of the total pressure difference. The experimental results have then been used in order to determine the two-phase friction multipliers.

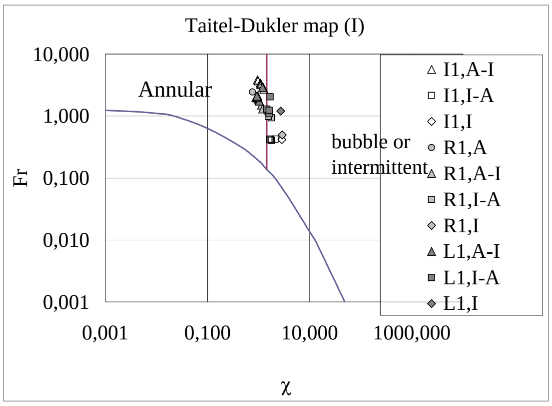

Figure 4a. Comparison of the group 1 results with the Taitel- Duckler maps; I (Inlet), R (Right), L (Left), 1 (Group 1)

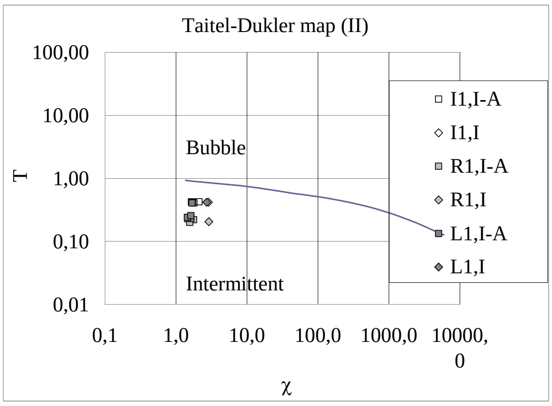

Figure 4b. Comparison of the group 1 results with the Taitel- Duckler maps

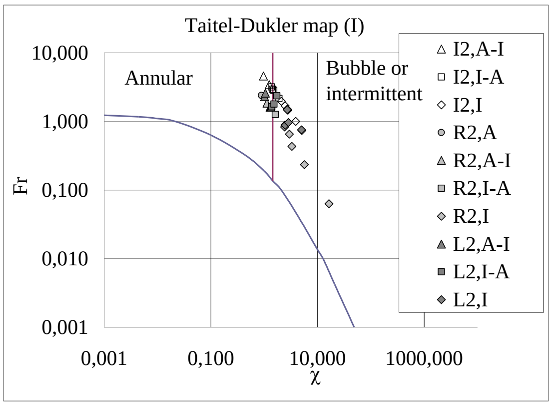

Figure 4c. Comparison of the group 2 results with the Taitel- Duckler maps

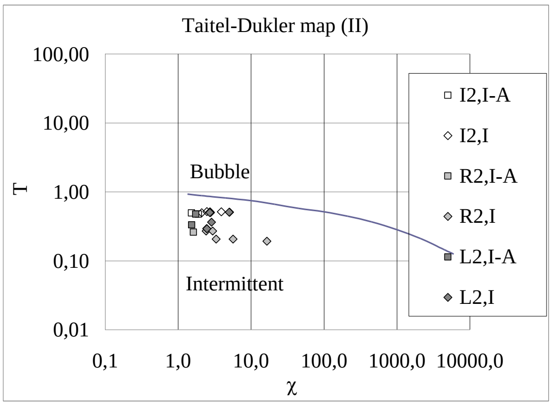

Figure 4d. Comparison of the group 2 results with the Taitel- Duckler maps

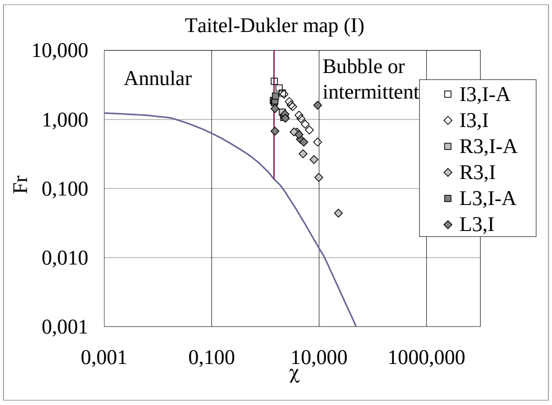

Figure 4e. Comparison of the group 3 results with the Taitel- Duckler maps

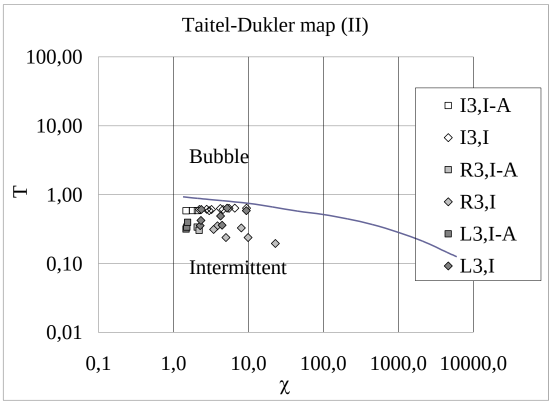

Figure 4f. Comparison of the group 3 results with the Taitel- Duckler maps

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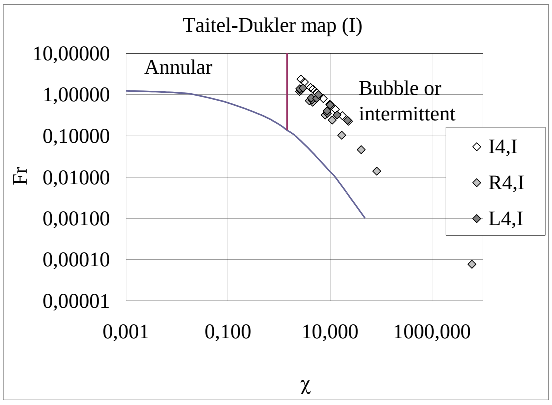

Figure 4g. Comparison of the group 4 results with the Taitel- Duckler maps

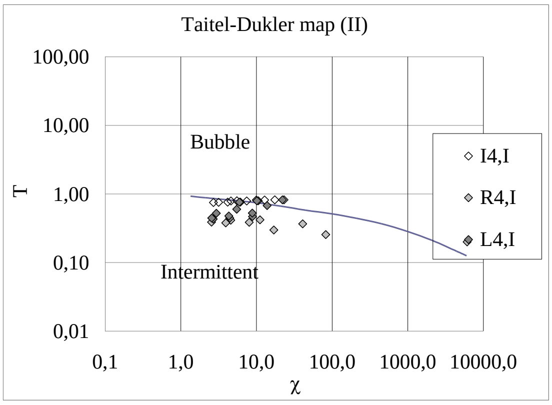

Figure 4h. Comparison of the group 4 results with the Taitel- Duckler maps

The two-phase friction pressure drop has been related to the single-phase pressure drop that is evaluated considering the friction factor deduced from the experiments that have been carried out with single-phase water. The two-phase multipliers ϕ_l^2 e ϕ_g^2 have been then evaluated: they are reported in figures 5a-5b for the test groups 1 and 2 and in figures 5c-5d for the test groups 3 and 4 versus Martinelli parameter χ. The figures also report the curves of the correlations that have been proposed by Chisholm [9] with C equal to 10 (turbulent flow of liquid, laminar flow of gas) and 20 (turbulent flow for both gas and liquid):

$$\phi_l^2 = 1 + \frac{C}{\chi} + \frac{1}{\chi^2} \qquad \phi_g^2 = 1 + C\,\chi + \chi^2 \tag{1}$$

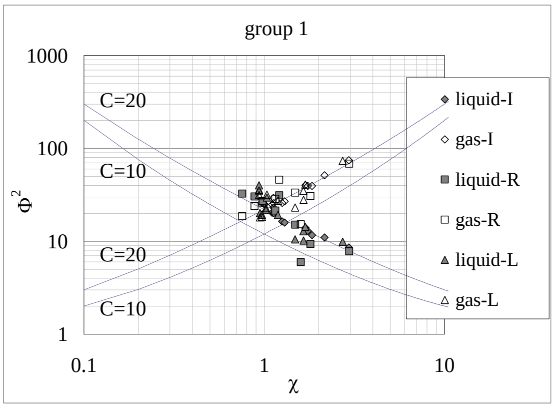

Figure 5a. Comparison of the two-phase multipliers of group 1 with the Lockhart-Martinelli correlation

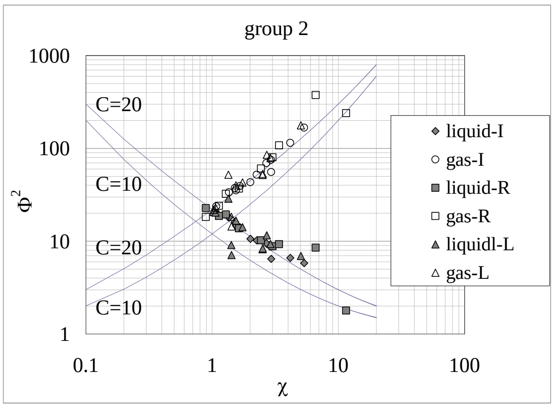

Figure 5b. Comparison of the two-phase multipliers of group 2 with the Lockhart-Martinelli correlation

The spread of the experimental points is higher for group 1 tests (lower mass velocities); anyway the experimental points are in reasonable agreement with the Lockhart–Martinelli correlation with C = 20; nevertheless the correlation tends to underestimate the majority of experimental results.

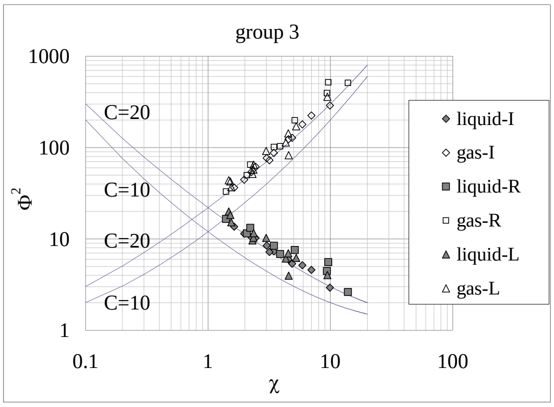

Figure 5c. Comparison of the two-phase multipliers of group 3 with the Lockhart-Martinelli correlation

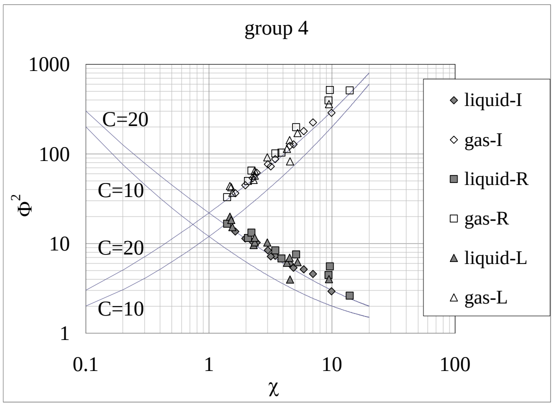

Figure 5d. Comparison of the two-phase multipliers of group 4 with the Lockhart-Martinelli correlation

The results have also been compared with the prediction of the Friedel correlation [10], that is valid also for horizontal pipes:

$$\phi_{lo}^2 = E + \frac{3.24\,F\,H}{Fr^{0.045} We^{0.035}} \qquad E = (1-x)^2 + x^2 \frac{\rho_l C_{f,go}}{\rho_g C_{f,lo}} \qquad F = x^{0.78}(1-x)^{0.224}$$

$$H = \left(\frac{\rho_l}{\rho_g}\right)^{0.91} \left(\frac{\mu_g}{\mu_l}\right)^{0.19} \left(1-\frac{\mu_g}{\mu_l}\right)^{0.7} \qquad Fr = \frac{G^2}{g\,d\,\rho_h^2} \qquad We = \frac{G^2 d}{\sigma\,\rho_h} \qquad \rho_h = \left(\frac{x}{\rho_g} + \frac{1-x}{\rho_l}\right)^{-1} \tag{2}$$

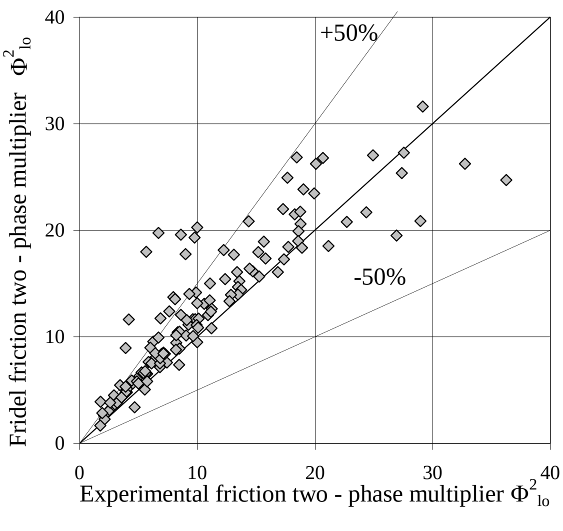

Figure 6. Comparison of the experimental two-phase multiplier with the Friedel multiplier

The experimental values and the Friedel correlation prediction are reported in figure 6, which shows a rather good agreement: it correlates the test data within 50% at a probability level of 86%, within 30% at a probability level of 73% and within 20% at a probability level of 46% . The discrepancies higher than 50% that can be observed in fig.6 (in a few tests they exceed 100%) occur

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predominantly when the pressure drops are low, as these tests are affected by a higher relative uncertainty. The error analysis gives an uncertainty of the two-phase multipliers of Lockhart-Martinelli and Friedel in the range 5-25%.

6. Local pressure drops

The local pressure drops have been evaluated using an extrapolated pressure at the junction determined by the methodology reported in [7]; in fact, the procedure that is generally followed in the literature is based on extrapolated pressures; these values will be different from the real ones measured at pressure taps I4, L1 and R1, but at least they are not affected by local effects occurring near the junction.

The two-phase local pressure drops were evaluated by the Separated Flow Model SFM proposed in [3] and [11] for the pressure drop between the inlet pipe and the perpendicular branch pipe of a branching T-junction. The application to the case on an impacting T gives:

$$\Delta p_{I,j} = \frac{\rho_{hj}}{2}\left(\frac{G_j^2}{\rho_j^2} - \frac{G_I^2}{\rho_I^2}\right) + K_{Ij}\frac{G_I^2}{2\rho_l}\phi_{lo}^2 \tag{3}$$

The subscript I refers to the inlet pipe and j to the right or left outlet branch; K_{Ii} is the local loss coefficient evaluated in single-phase flow; ρ_{hj} is the homogeneous density, while ρ_j and ρ_I are the energy-weighted densities in the branches and inlet pipe evaluated as follows [3]:

$$\rho = \left[\frac{(1-x)^3}{(1-\alpha)^2\rho^2} + \frac{x^3}{\alpha^2\,\rho_g^2}\right]^{-0.5} \tag{4}$$

The drift flux model for horizontal slug flow has been adopted to evaluate the void fraction.

$$\alpha = \frac{1}{1.2\left[1 + G_l\rho_g/(G_g\rho_l)\right]} \tag{5}$$

The two-phase multiplier has been evaluated by the Chisholm correlation that is valid for T-junctions [8] and, in general, for several types of local pressure drops [11], by using different values of the coefficient C_i (the Martinelli parameter is evaluated for turbulent flow in both liquid and gas):

$$\phi_{lo}^2 = (1-x_I)^2\left(1 + \frac{C_{Ij}}{\chi_{tt}} + \frac{1}{\chi_{tt}^2}\right) \qquad \chi_{tt} = \left[\left(\frac{x_I}{1-x_I}\right)\left(\frac{\rho_l}{\rho_g}\right)^{0.5}\right]^{-1}$$

$$C_{Ij} = \left[1 + (C_j - 1)\left(\frac{\rho_l - \rho_g}{\rho_l}\right)^{0.5}\right]\left[\left(\frac{\rho_l}{\rho_g}\right)^{0.5} + \left(\frac{\rho_g}{\rho_l}\right)^{0.5}\right] \tag{6}$$

The coefficient K_{Ij} has been expressed as a function of the extraction rate ER by the polynomial (7), which has been obtained by applying the minimum square root method to the single-phase tests with air only and water only:

$$K_{Ij} = -0.5723\ ER^2 + 0.9958\ ER + 0.5309 \tag{7}$$

In [8] a value of C_j = 1.75 is suggested for the pressure drop between inlet and branch pipes of a branching T-junction (no other values are suggested in [8] for the impacting T).

The extrapolated values of the differential pressure are used to evaluate the two-phase multiplier, that have then been compared with the prediction of Chisholm correlation. Using C_i = 1.75 the Chisholm two-phase multipliers are much higher than the experimental values (the discrepancy is lower than 50% only in 9% of the tests).

The minimum mean square error method has been used to determine the value of C_i (the value of 0.432 has been found); figure 7 compares the experimental two-phase multiplier with the Chisholm prediction, that correlates the test data within 50% at a probability level of 86%, within 30% at a probability level of 49%, and within 20% at a probability level of 32%. The error analysis gives an uncertainty of the two-phase multipliers for the local pressure drops in the range 6-20%.

The minimum mean square error method has also been used to evaluate C_{lj}, which has resulted to be 9.53; considering this value, the discrepancy between experiment and prediction is very similar to that one shown in figure 7.

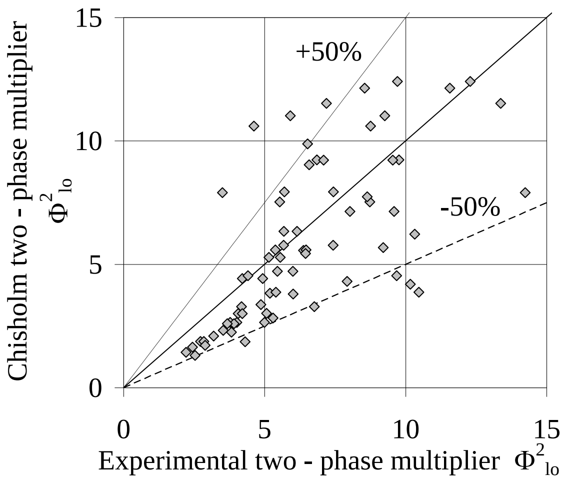

Figure 7. Comparison between the experimental two-phase multiplier and the Chisholm prediction with C_j = 0.432

7. Conclusions

The present paper further analyzes the results of tests with a two-phase mixture of air and water flowing through a horizontal impacting T- junction, that have been presented in [7].

The experimental flow patterns have been compared with the prediction of the Baker and Taitel–Dukler maps. The agreement to the Baker map is rather poor at low mass velocity, but it is satisfying at higher mass velocities. On the other hand, the Taitel – Dukler maps appropriately predicts flow regimes at every flow rate.

The friction pressure drops have also been investigated and the two-phase friction multipliers have been evaluated: on the average, they are higher than the values predicted by the Lockhart–Martinelli correlation. The Friedel correlation is in better agreement with the experimental results, even though it slightly overestimates the two-phase multiplier and can be applied along the branches up to the junction, with discrepancies that are typical of the two-phase flow correlations.

The pressure drops at the junction centre have been extrapolated to determine the two-phase multipliers of the irreversible local pressure drop in the junction; the experimental values have been compared with the predictions of Chisholm correlation. The optimum value of the coefficient C_i was determined with reference to the present experimental data.

Acknowledgment

The authors wish to thank M. Fogliacco for her valuable help.

Nomenclature

C_f	Fanning friction factor	T	$\left[\left\|(dp/dz)_l\right\|/g(\rho_l-\rho_g)\right]^{1/2}$	σ	surface tension (N/m)
d	inner diameter (m)	x	mass flow quality	$\phi^2_{l,g}$	$\left[(dp/dz)_{TP}/(dp/dz)_{l,g}\right]$
ER	extraction ratio (G_j/G_I)	z	axial coordinate (m)	ϕ^2_{lo}	$\left[(dp/dz)_{TP}/(dp/dz)_{lo}\right]$
Fr	$G_g/\left[\rho_g(\rho_l-\rho_g)d\,g\right]^{1/2}$	α	void fraction	χ	$\left[(dp/dz)_l/(dp/dz)g\right]^{0.5}$
g	gravity constant (m/s^2)	λ	$\left[(\rho_g/\rho_a)\cdot(\rho_l/\rho_w)\right]^{0.5}$	χ_{tt}	$1/[x_I-(1-x_I)(\rho_l/\rho_g)0.5]$
G	mass velocity (kg/m^2 s)	μ	dynamic viscosity (kg/m s)	ψ	$\sigma_w/\sigma\left[\mu_l/\mu_w(\rho_w/\rho_l)^2\right]^{1/3}$
p	pressure (Pa)	ρ	density (kg/m^3)		

Subscripts

A	air at ambient condition	l, lo	liquid, liquid only
g, go	gas, gas only	L	left
H	homogenous	R	right
j	right, left	TP	two - phase
I	inlet	w	water at ambient conditions

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