HEFAT2007
5th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
Sun City, South Africa
Paper number: BC1

TWO-PHASE FLOW IN A HORIZONTAL T – JUNCTION: PRESSURE DROP AND PHASE SEPARATION

Bertani C., Malandrone M. and Panella B.*
*Author for correspondence
Dipartimento di Energetica –Politecnico di Torino
Corso Duca degli Abruzzi, 24,
10129 Torino,
Italy,
E-mail: bruno.panella@polito.it

ABSTRACT

An experimental investigation of dividing flow rates and pressure drops in a plexiglas tee junction with horizontal inlet, run, and branch sides using air-water mixtures has been performed. The branch stream is orthogonal to the inlet and run streams. The pipes forming the tee junction are about 1 m long, their inner diameter is 10 mm.

The flow loop was supplied with compressed air and water through a mixing tee, at 1.5 bar and approximately ambient temperature. Air flow rate ranges from 0.3 to 9 Nl/s, water flow rate from 14.5 to 58 g/s, air superficial velocity from 1.5 to 47 m/s, water superficial velocity from 0.2 to 0.7 m/s and flow quality from 0.6% to 43%. The extraction ratio (branch flow rate / inlet flow rate) ranges from 0 to 1. Intermittent (bubble and slug flow) and annular flow patterns, as well as transition flow patterns have been obtained.

Experimental values of flow rate, phases superficial velocity, extraction ratio and pressure drops across the tee junction pipes are here reported. Pressure drop test results across the inlet and branch pipes have also been compared with predicted ones. A new pressure drop correlation have been derived from test data.

INTRODUCTION

PROBLEM STATEMENT

In power and process industries, such as conventional steam plants, water nuclear reactor, and chemical applications, the two-phase flow encounters dividing tee junctions as it passes through the system. Considerable research efforts are still being carried out on this topic; it has been shown that in general the phases do not split evenly at the junction and the distribution of the phases is a complicated function of the inlet flow rates, inlet flow pattern, junction geometry and orientation, total mass split at the junction, and fluid properties; the existing prediction models for phase distribution and pressure drop at dividing junctions are not yet adequate for all the conditions.

The experimental studies on this subject have succeeded in identifying important flow phenomena: the flow quality in the branch and in the run pipes (see figures 1 and 2) are usually different from each other and also different from the inlet quality; the flow rate of the two phases splitting through the run and branch streams affects strongly the pressure drop across the channels downstream of the mixing tee. But further experimental studies are needed to improve the understanding of this problem. In fact the analysis of the literature has shown that more efforts have been devoted to the study of the splitting phases, while fewer works are related to pressure drops. Flow patterns have not been equally studied and experimental data on pressure drops are available only for some pipe diameters.

NOMENCLATURE

F_{BG}	[-]	W_{G3}/W_{G1}
F_{BL}	[-]	W_{L3}/W_{L1}
G	[kg/(s m^2)]	Mass velocity
J	[m/s]	superficial velocity
p	[mbar]	pressure
W	[kg/s]	mass flow rate

Special characters

ϕ	[-]	two phase multiplier
Δp_{12}	[mbar]	Pressure drop across the run line $(p_1 - p_2)$
Δp_{13}	[mbar]	Pressure drop across the branch line $(p_1 - p_3)$
ρ	[kg/m^3]	density

Subscripts

1	inlet
2	run
3	branch
G	gas
H	homogeneous model
L	liquid

Intuitively, the uneven phase split through the T-junction seems due to the different momentum flux of the two phases:

the fluid with higher momentum flux tends to flow preferably in the same inlet pipe direction: in a 90° T-junction, the preferred direction is therefore the one of the run pipe. On the other hand, the fluid with lower momentum flux should preferably enter the branch pipe. The phenomena are also strongly influenced by gravity effects, which depends on both layout (horizontal or vertical) and geometry of the T-junction, and the flow regime affects the pressure drops between the inlet and the outlet pipes. So the phenomena of phase separation in T-junction are very complex and dependent on several test parameters.

On the other hand few studies have been done on pressure drops. So it seems that an experimental study, particularly in the range of small diameter pipes, can shed light either on the phase separation or on the pressure drops.

For this reason a test facility with a T junction with 10 mm inner diameter pipes, able to cover different flow regimes (annular flow included), has been built at Dipartimento di Energetica of Politecnico di Torino and some experimental results are shown in the present report.

PHASE SEPARATION

As far as the phase separation is concerned, Azzopardi el al. [1] and Oranje [2] carried out the first studies on the uneven distribution of the phases at the junction exit. Azzopardi et al. [1] developed a map of flow patterns in the inlet pipe of a 90° T-junction. Azzopardi's map, whose parameters are F_{BL} and F_{BG} (see the Nomenclature), shows that the extraction behaviour depends on inlet flow patterns in case of bubbly and churn flow; on the other hand, flow parameters such as the superficial velocity of the phases strongly affect the phases split in annular flow.

The map of Buell et al.[3] shows that, at constant gas superficial velocity, the liquid preferably flows into the branch if its superficial velocity is low, while at high liquid superficial velocities the gas phase preferably runs into the branch pipe.

Jones et al. [4] represented the phase separation as function of superficial velocities and confirmed that, in annular flow, the test conditions have a strong influence on the prevailing phase through the branch.

PRESSURE DROPS

As far as pressure drops are concerned, Buell et al. [3] studied a 90° T–junction with pipes of equal diameter, while Walters et al. [5] also investigated junctions with a smaller diameter branch pipe.

The pressure near the junction is strongly affected by local effects; therefore the inlet to run and inlet to branch pipes pressure drops Δp_{12} and Δp_{13} have been determined by extrapolation of the pressure profile in zones far enough from the centre, so that the influence of the singularity is negligible: the experimental pressure behaviour in these zones is extended to the geometric centre of the junction (Buell et al. [3]).

According to Buell et al. [3], the two-phase inlet to run pipe pressure drop Δp_{12} is evaluated by a momentum flux balance with the correction factor k_{12} given by a polynomial best fit as a function of W_3/W_1:

$$\Delta p_{12} = k_{12} \cdot \left(\frac{G_2^2}{\rho_2} - \frac{G_1^2}{\rho_1} \right) \tag{1}$$

Alternatively to eq.(1), Reimann and Seeger [6] suggested to split the pressure drop Δp_{12} into two components that respectively give the pressure variation between the inlet and the vena contracta in the run (downstream of the junction) and the pressure variation in the expansion downstream of the vena contracta. The slip ratio correlation used in [6] is the one adopted by Rouhani [7, 8].

The inlet to branch pipe pressure drop Δp_{13} is the sum of the reversible pressure change due to kinetic energy variation and an irreversible pressure drop, which depends on the local pressure loss coefficient k_{13} referred to the mass velocity at the inlet and given by a polynomial best fit:

$$\Delta p_{13} = \frac{\rho_{H3}}{2} \cdot \left(\frac{G_3^2}{\rho_3^2} - \frac{G_1^2}{\rho_1^2} \right) + k_{13} \cdot \frac{G_1^2}{2 \cdot \rho_L} \cdot \phi \tag{2}$$

$$k_{13} = 1 - 0.982\left(\frac{W_3}{W_1}\right) + 1.843\left(\frac{W_3}{W_1}\right)^2 - 0.717\left(\frac{W_3}{W_1}\right)^3 \tag{3}$$

If run and branch pipes have the same diameter, $G_3 \le G_1$ and $G_2 \le G_1$; a pressure increase occurs along the path from inlet to run pipe and, as far as the reversible pressure change is concerned, also along the path from inlet to branch pipe.

Different correlations for the two-phase multiplier ϕ and density have been adopted in two-phase models; Buell [3] quotes the Homogeneous Flow Model (HFM), the Separated Flow Model (SFM) by Fouda and Rhodes, the Hwang and Lahey's Model (HLM), the Ballyk et al. Model (BM), the Reimann and Seeger's Model (RSM). Momentum densities and energy-weighted densities have to be used respectively in the evaluation of Δp_{12} and of Δp_{13}. Reimann and Seeger [6] suggested that also the pressure drop Δp_{13} can be split into the pressure difference between the inlet and the vena contracta in the branch and the pressure drop downstream of the vena contracta. According to Reimann, the best agreement with air-water data and a horizontal branch was reached by means of the HFM formulation, modified by the factor ρ_{H3} / ρ_{H1}.

Buell et al. showed that the best results for Δp_{12} are obtained by the SFM model: 71% of data show a maximum error of 30% and all the data in wavy, stratified-wavy, semiannular and annular regimes are predicted with a maximum error of 50%. Models are generally less accurate in the prediction of Δp_{13} and in this case SFM and RSM model are the most reliable. The irreversibile pressure drop between inlet and branch can also be calculated by the Chisholm correlation, that is reported in reference [6], where the two-phase multiplier $1 + C_{13}^* / \chi_{tt} + 1 / \chi_{tt}^2$ is used.

EXPERIMENTAL FACILITY

The experimental facility is schematically represented in fig. 1. It essentially consists of a water feed line provided with a centrifugal pump and flow intake from a bypass line, an air feed line connected to the compressed air system and the test section, that includes a plexiglas horizontal T-junction with three pipes about 1 m long and a group of valves that connect the outlet pipes to the separation tank. The two-phases are mixed by means of the air water mixer, that is located at the inlet on the test section.

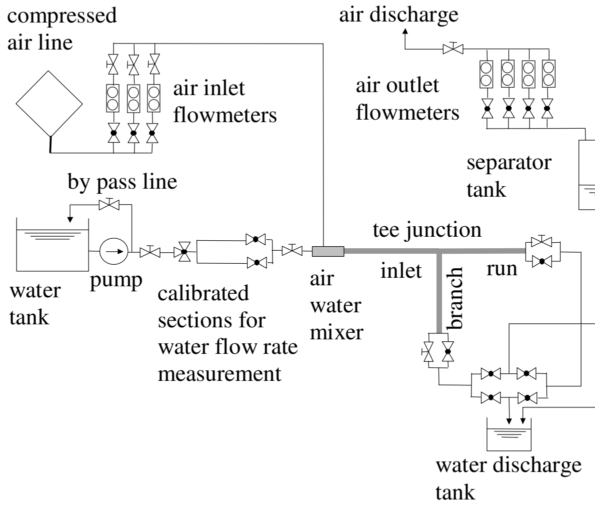

Figure 1 Schematic diagram of two-phase flow facility

The water flow rate is evaluated by measuring the pressure drop across calibrated pipes. The air flow rate at the test section inlet is measured by flowmeters. At the test section inlet the two-phase mixture temperature and pressure are measured.

The instrumentation uncertainty is: 0.5 % for the pressure drops, 3% for the air flow rate, 2 % for the water flow rate.

Figure 2 shows the test section, which consists of three transparent plexiglas pipes having an inner diameter of 10 mm and a length of 1.095 m. The three pipes, which work as inlet pipe, run pipe (i.e. the outlet pipe aligned with the inlet) and branch pipe (i.e. the outlet pipe perpendicular to the inlet), are connected by a proper plexiglas junction to form a T; each pipe has four pressure taps.

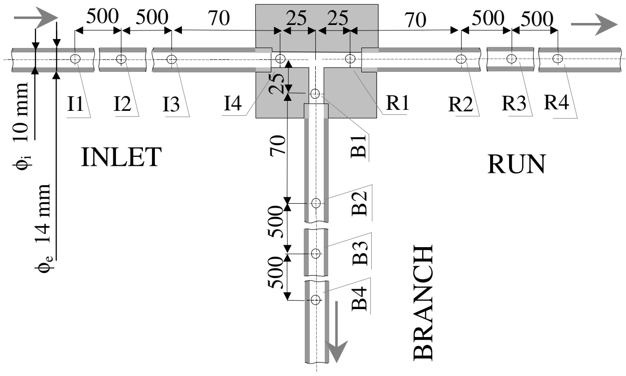

Figure 2 Test section, with the pressure taps I1÷I4, R1÷R4, B1÷B4

The water flow rates are evaluated by the weighting technique. The entrainment of water in the air was estimated negligible in the present test conditions shown in Tables 2 and 3.

Table 2 Operating conditions in single-phase tests
Inlet flow rate [g/s]: 105 ÷ 147.2 (water), 7.1 ÷ 15 (air)
Temperature [°C]: 13.1 (water), 20 (air)
Flow rate in the run pipe [g/s]: 0 ÷ 98 (water), 0 ÷ 8.5 (air)
Flow rate in the branch pipe [g/s]: 44.3 ÷ 137 (water), 3.1 ÷ 7.2 (air)

Table 3 Operating conditions in two-phase tests
Water flow rate at the inlet [g/s]: 14.5 ÷ 58.0
Water temperature [°C]: 14.2 ÷ 17.3
Inlet pressure [barg] : 1.42 ÷ 1.58
Average pressure at the junction inlet [barg]: 1.50
Air flow rate at the inlet [Nm^3/h]: 1.0 ÷ 33.0
Mixture quality at the inlet [%]: 0.6 ÷ 43.1 (average 13)
Branch flow rate / inlet flow rate: 0 ÷ 1 (average 0.48)
Superficial velocity of the liquid phase [m/s]: 0.18 ÷ 0.74
Superficial velocity of the gas phase (referred to 1.5 barg) [m/s]: 1.5 ÷ 47.2
Flow pattern at the junction inlet: intermittent slug and plug, annular- annular dispersed and transition regimes

EXPERIMENTAL RESULTS

The experimental campaign started with preliminary single-phase tests and went on with the two-phase tests. In single-phase tests (air or water), the pressure along the T-junction pipes has been measured when the run pipe valve was kept closed and with both branch and run pipes valves kept open. In the two-phase tests, different ratios of the run /branch pipes flow rate have been obtained and pressure change and phase split between the two junction outlets have been also measured.

A gage pressure of 1.5 barg has been maintained in all two-phase tests at the inlet of the test section (i.e. at the first pressure tap 1.095 m upstream the T-junction).

The observed flow patterns at the junction inlet are intermittent (slug and plug flow) and the annular-annular dispersed regimes; transitions between annular and intermittent regimes have been observed. The observed flow patterns are reported in figure 3 as a function of the air and water superficial velocity; the transition lines between the different flow patterns are calculated by means of the model of Taitel and Duckler [9].

Some typical experimental results concerning the phase separation and pressure drops are reported in the following (further experimental data can be found in Bertani et al.[10]).

Figures 4, 5 ,6 and 7 show the phase separation results with different air and water superficial velocity at the run inlet.

At low F_{BL} (figures 5, 6 and 7) the liquid fraction in the branch is higher than the gas fraction, while for F_{BL} greater than about 0.2 (figure 5) and 0.3 (figures 6 and 7), the gas fraction is higher in the branch. F_{BG} becomes unitary for F_{BL} greater than about 0.5 and such value slightly increases as the air superficial velocity increases. On the other hand the intermittent- annular flow pattern transition occurring at higher gas superficial velocity is consistent with higher F_{BL} at constant F_{BG} .

Figures 4, 5 and 6 show that increasing liquid superficial velocities slightly enhances the phases splitting ability of the junction.

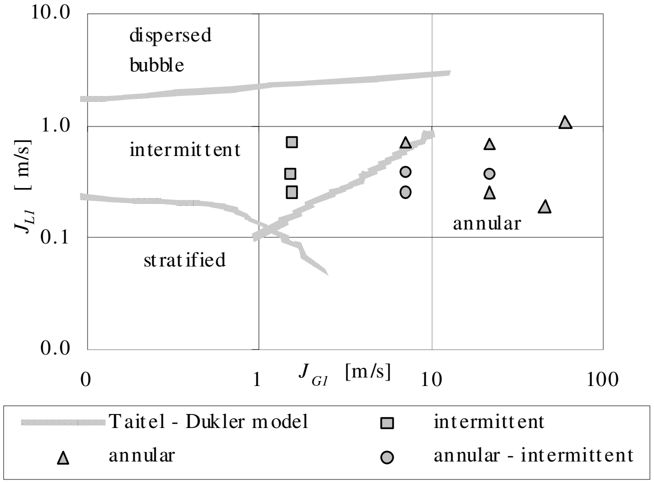

Figure 3 Observed flow patterns at the inlet tube and Taitel – Dukler flow pattern prediction

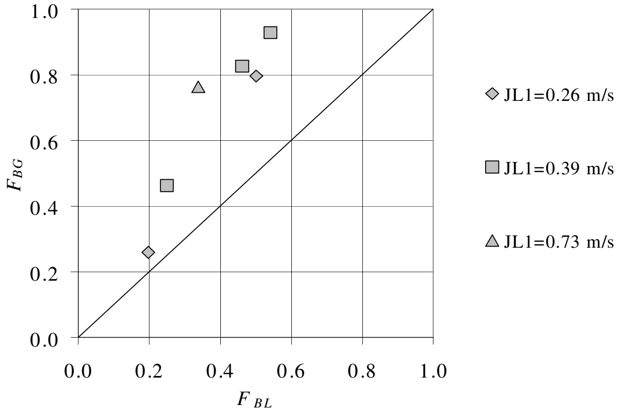

Figure 4 Phase separation for J_{G1} = 1.6 m/s

ANALYSIS OF EXPERIMENTAL PRESSURE DROPS

Pressure drops Δp_{12} and Δp_{13} have been evaluated by extrapolation of the pressure distribution along the T-junction. Experimental pressure drops in single-phase flow have been used in order to evaluate the coefficients k_{12} and k_{13}, whose values are reported versus the extraction ratio and compared with the prediction of the reference [3] polynomial best fit in figure 8; as far as k_{12} is concerned, a good agreement has been found, while significant discrepancies have been observed for k_{13} when W_3/W_1 is higher than 0.6. Possible causes of the disagreement are the effects of measurement uncertainty, geometric parameters and constructive details of the junction and the influence of flow parameters that are not considered in the polynomial best fit, such as the Reynolds number.

With reference to the two-phase tests, the dependence of pressure drops on the extraction ratio has been analyzed [10] and experimental pressure drops have been compared with the prediction of different models.

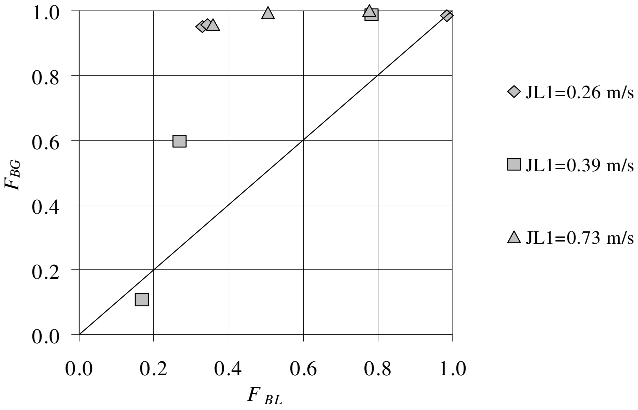

Figure 5 Phase separation for J_{G1} = 7.3 m/s

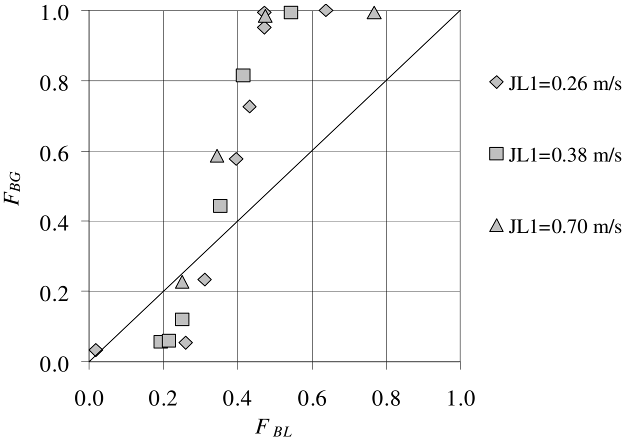

Figure 6 Phase separation for J_{G1} = 22.3 m/s

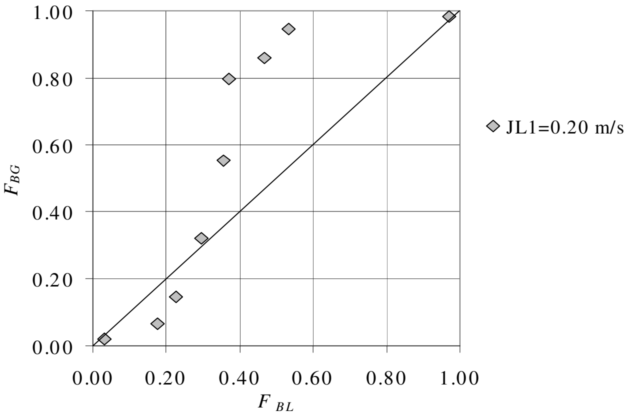

Figure 7 Phase separation for J_{G1} = 47.0 m/s

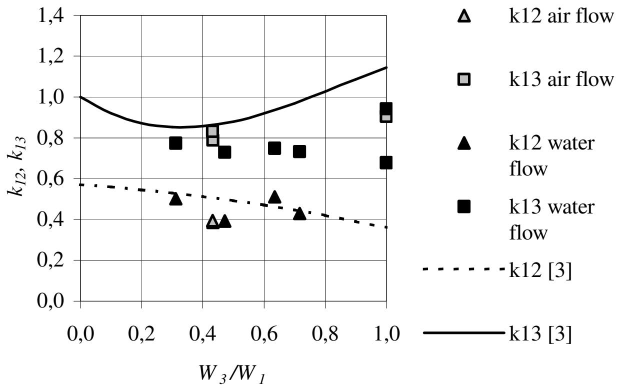

Figure 8 Experimental values of k_{12} and k_{13} in single-phase flow and the values predicted by reference [3] correlation

A comparison between the experimental pressure drop values and the prediction of Separated Flow Model (SFM) with k_{12} and k_{13} evaluated by the reference [3] polynomial best fit is shown in figures 9a and 9b.

Taking into account the extrapolation difficulty in the case of low pressure drop, only the tests with regular and linear pressure profile and with pressure drops higher than 10 mbar have been considered in the comparison. Part of the experimental points show a good agreement with the predicted values, while significant discrepancies occur for Δp_{13} when the pressure change is higher than 50 mbar.

For comparison purpose also the prediction by means of the homogeneous model is reported; figure 9b shows that such a model predicts Δp_{13} data better than the SFM at higher flow rate and pressure drop.

Experimental pressure drops are compared with the predictions of the RSM model in figures 10a and 10b. The predictions for Δp_{12} of RSM model are less accurate than the SFM model ones. As far as the prediction of Δp_{13} is concerned, the RSM model is less accurate at low values of Δp_{13}, but it is better at high values of Δp_{13}.

A corrective factor, that depends on the W_3 / W_1 ratio

$$F_{irr} = 0.038 + 2.16(W_3 / W_1) \tag{4}$$

has been determined by the least square method to correct the irreversible component of the pressure variation, in order to improve the prediction of Δp_{13} by means of the the SFM model. As it is shown in figure 11, there is a good agreement between the present experimental data and Δp_{13} calculated with the corrective factor.

The Chisholm correlation, with the reversible pressure drop evaluated accordingly to the SFM model [6], strongly overestimates the present experimental data: the mean value of the coefficient C_{13}^{*} in the present tests is about 33, while its value should be reduced to 8.7 in order to reduce the discrepancies between experimental and calculated values.

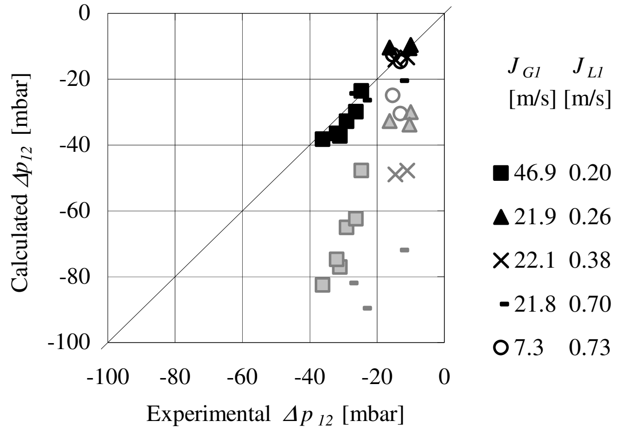

Figure 9a Comparison between experimental Δp_{12} and the separated flow model prediction; grey points refer to the homogeneous model

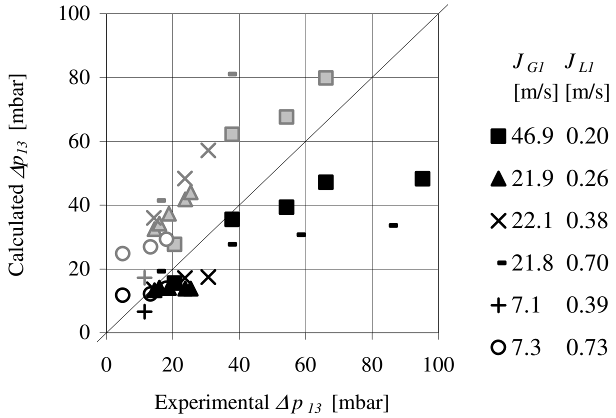

Figure 9b Comparison between experimental Δp_{13} and the separated flow model prediction; grey points refer to homogeneous model

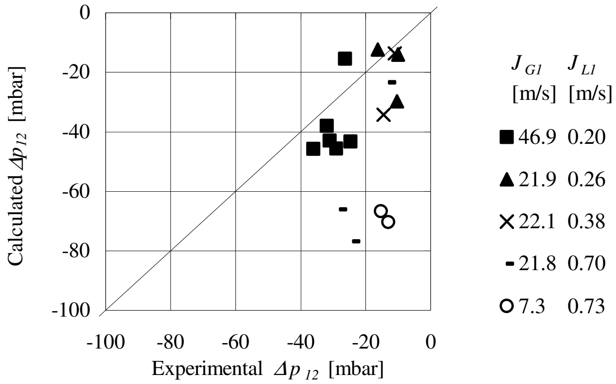

Figure 10a Comparison between experimental Δp_{12} and the Reimann-Seeger model (RSM) prediction

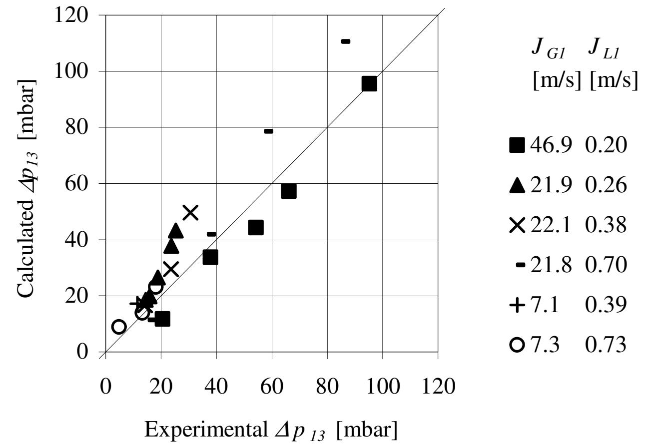

Figure 10b Comparison between experimental Δp_{13} and the Reimann-Seeger (RSM) model prediction

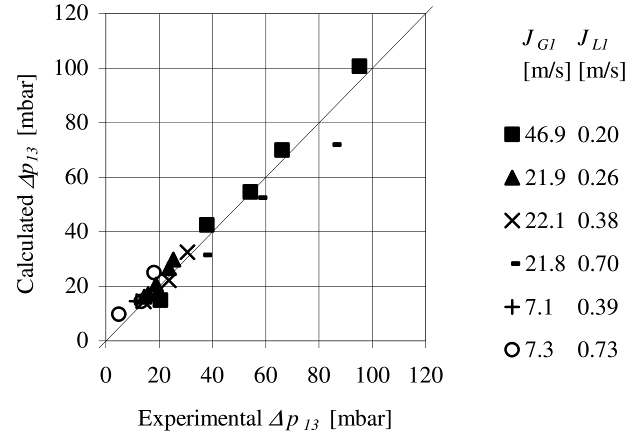

Figure 11 Comparison between experimental Δp_{13} and the SFM model prediction with the F_{irr} factor (eq. 4)

CONCLUSIONS

An experimental research to investigate the two-phase flow in a T-junction has been carried out at the Thermal-hydraulic Laboratory of Dipartimento di Energetica of Politecnico di Torino; it allowed to highlight specific aspects and problems related to the measurement of low flow rates for different flow patterns, of the phase split and pressure drops in the junction.

The results refer to intermittent slug and annular- annular dispersed flow patterns at the junction inlet. Many measurements of phase split have been performed at different values of air and water velocities and extraction ratio. The measurement of pressure change from the inlet to the run pipe and to the branch pipe was generally rather difficult at low flow rate; in such conditions it is not easy to determine extrapolated values for the pressure drops at the T junction location.

Both single-phase and two-phase pressure drops have been compared with models prediction. The comparison confirmed that the accuracy of the Separated Flow Model (SFM) is only partially satisfactory. The comparison of experimental data with the Reimann-Seeger model (RSM), the Chisholm correlation and the SFM model showed that the most accurate prediction of Δp_{12} is given by the SFM model, while the RSM model gives a better agreement with the experimental Δp_{13} at higher values. Furthermore, the predictions of the SFM model have been improved by applying a corrective factor linearly dependent on W_3/W_1 to the irreversible component of Δp_{13}. The pressure drops evaluated by the Chisholm correlation are much higher than the present experimental ones.

Finally useful suggestions for the future emerged:

- further experimental investigations also on single-phase flow of water and air are needed
- the effect of the geometry (pipe diameter, T-junction plane, angles between pipes) have to be further studied
- further work is needed before pressure drops prediction method for general conditions can be devised.

Acknowledgment

The authors wish to thank R. Costantino, G. Di Giusto, A. Quaranta and P. Squillari for their support in the facility set-up and for the help to carrying out the experimental campaign.

REFERENCES

[1] Azzopardi B. J. and Whalley P. B., The effect of flow patterns on two-phase flow in a T junction, *Int. J. Multiphase Flow,* vol. 8, pp. 491-507, 1982.

[2] Oranje L., Handling two-phase condensate flow in offshore pipeline systems, *Oil and Gas J.*, vol. 81, pp. 128-138 C, 1983.

[3] Buell J. R., Soliman H. M., Sims G. E., Two-phase pressure drop and phase separation at a horizontal tee junction, *Int. J. Multiphase Flow,* vol. 20, pp. 819-836, 1994.

[4] Jones R., Wren E., Baker G., Azzopardi B. J., The split of slug flow at a small diameter horizontal T-junction, *Procs. of Fifth World Conference on Experimental Heat Transfer, Fluid Mechanics, and Thermodynamics*, Vol. II, pp. 1561-1566, 2001.

[5] Walters L. C., Soliman H. M., Sims G. E., Two-phase pressure drop and phase distribution at reduced tee junctions, *Int. J. Multiphase Flow*, vol. 24, pp.775-792, 1998.

[6] Reimann J. and Seeger W., Two-phase flow in a T-Junction with a horizontal inlet, part II: pressure differences, *Int. J. Multiphase Flow,* vol. 12, pp. 587-608, 1986.

[7] Rouhani Z., Modified correlations for void and two-phase pressure drop, AE-RTV-841, 1969.

[8] Wojtan L., Ursenbacher T., Thome J.R., Interfacial measurements in stratified types of flow. Part II: Measurements for R-22 and R-410A, *Int. J. Multiphase Flow*, vol. 30, pp. 125-137, 2004.

[9] Taitel Y. and Dukler A.E., A Model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow, *AIChE Journal*, Vol. 22, No. 1, pp. 47-55, 1976.

[10] Bertani C., Malandrone M., Panella B., Quaranta A., Squillari P., Pressure drop and phase separation in a horizontal T-junction, *Procs. XXIV Congresso Nazionale sulla Trasmissione del Calore (National Heat Transfer Conference),* pp. 267-274 Napoli (Italy), 21-23 June 2006.