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PRESSURE DROP AND GAS HOLDUP MEASUREMENTS IN AIR-WATER FLOW IN 180° RETURN BENDS

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Abstract. *Gas-liquid flows in curved tubes are found in a number of applications, such as heat exchangers and transport pipes. The present work deals with air-water flow in 180° tube bends (curvatures 2R/d of 6.1, 8.7, and 12.2) that connects two 5-m long 26-mm ID horizontal tubes made from borosilicate glass. The bend lies in the vertical position and the two-phase flow can be set as upward or downward. The behavior of the static pressure upstream and downstream of the bend was measured for a wide range of flow patterns, as was the pressure drop and gas holdup change associated with the bend itself. The frictional pressure drop in the bend was calculated, resulting in a preliminary pressure drop correlation for the bend segment. The distribution of the phases in the bend was investigated with a high-speed camera.*

Keywords: *two-phase flow, return bend, frictional pressure drop, gas holdup*

1. INTRODUCTION

Gas-liquid flows in return bends are found in various applications, including heat exchangers, transport pipes and separators. A better assessment of pressure drop in singularities, such as return bends, elbows, T-junctions etc., is required in order to accurately design two-phase flow equipment in general. Substantial experimental research has been conducted on two-phase flow in return bends, as a large number of works dealt with phase-change in small curvature radii bends focusing on cooling applications (Traviss and Rohsenow, 1971; Geary, 1975; Chen *et al.*, 2004; Padilla *et al.*, 2009). Other works on return bends involved visual observations of air-water flows (Usui *et al.*, 1980; Hoang and Davis, 1984; Wang *et al.*, 2008) and gas-liquid refrigerant flows (Padilla *et al.*, 2012; da Silva Lima and Thome, 2012), which also discussed in detail the hydrodynamics of two-phase flow in bends.

The present work deals with the characterization of an air-water two-phase flow in a 180° tube bend connecting two 5-m long, 26.4-mm ID horizontal tubes. The bend lies in the vertical position and the flow can be set as upward or downward (i.e., entering from the top or bottom tube). The behavior of the static pressure downstream and upstream of the return bend was measured for a wide range of flow patterns, as was the pressure drop and change in gas holdup associated with the return bend itself. Experiments were carried out with bend curvatures 2R/d of 6.1, 8.7, and 12.2 in both upward and downward directions. Superficial velocities of the phases were set for each test condition, varying from 0 to 40 m/s for the gas, and 0.05, 0.2 and 1 m/s for the liquid. Experimental gas holdup data have been compared with correlations proposed by Chexal *et al.* (1991); Smith (1969); Premoli *et al.* (1971). Frictional pressure drop in the bend has been assessed based on the total pressure drop change and gas holdup measurements at the inlet and outlet positions of the bend, and compared with correlations from Chisholm (1983); Chen *et al.* (2004); Domanski and Hermes (2008); Padilla *et al.* (2009). A preliminary frictional pressure drop correlation for downward flow in the bend segment has been proposed. The phase distribution and the behavior of the flowing phases in the bend were investigated with a high-speed camera.

2. EXPERIMENTAL WORK

2.1 Experimental setup

An experimental apparatus was built for the purpose of this research and is represented schematically in Fig. 1. The setup – a two-phase flow rig – consists of two individual fluid flow lines equipped with inlet flow mixers (1) where the two phases are introduced. The air-water mixture flows from either of the two mixers through a 26.4-mm ID horizontal borosilicate glass tube. The test section consists of a 180° tube bend connecting the two horizontal tubes, which are approximately 5 m long.

The water line comprises of a thermostatic bath (2), a centrifugal pump (3) controlled by a frequency inverter, a gate valve and a by-pass line, and a Coriolis mass flow meter (4). The air line is attached to a main compressed air line, which

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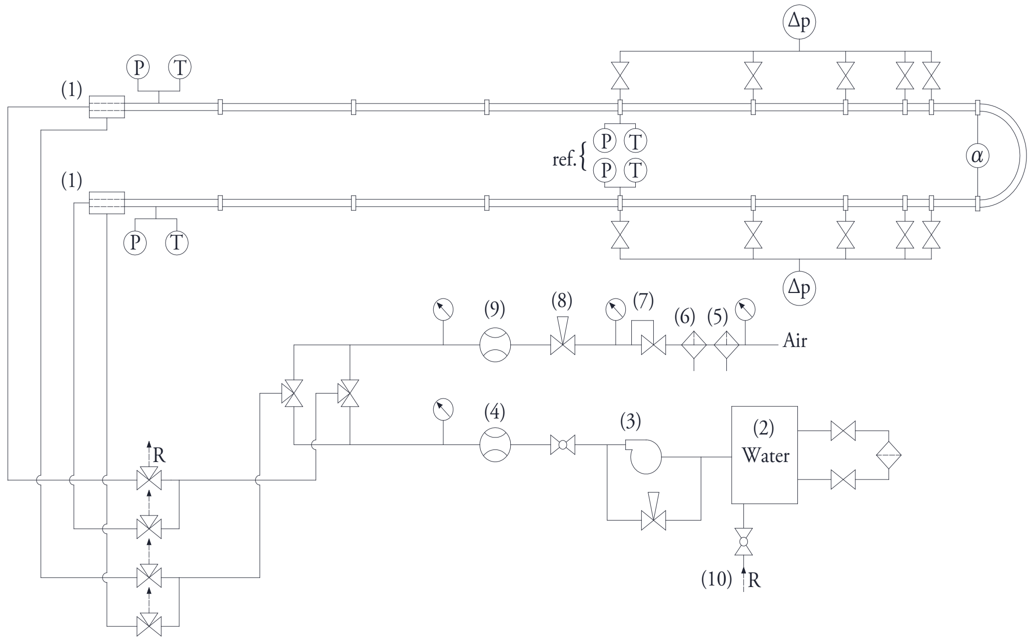

Figure 1: Schematic view of the experimental apparatus.

consists of the following: a particulate filter (5), a coalescent filter (6), a pressure regulator (7), a micrometric valve (8), and a hot wire anemometer-based mass flow meter (9).

The two inlet flow mixers (1) are attached to the ends of the horizontal sections through a set of three-way valves, so it is possible to set the air-water mixture to flow upwards or downwards through the return bend. As the flow exits the loop, both fluids are separated in a hydrocyclone; air is released to the atmosphere and water returns to the thermostatic bath.

Absolute pressure was measured at points located 1.85 m downstream and upstream of the return bend. Pressure drop was measured at the bend itself and along the 1.85-m segments between shorter sections of 0.11, 0.22, 0.51, and 1.01 m in length. The influence of the bend on the behavior of flow parameters (gas holdup, pressure drop) has been investigated using bends with different curvature radii ($2R/d$ = 6.1, 8.7, and 12.2). Temperature was measured in the test section to ensure an isothermal condition.

Gas holdup was evaluated by two non-intrusive capacitance sensors positioned at the straight portions of the tube bend segment, as seen in Fig. 2. The technique consists in measuring the electrical capacitance of the flow, which is known to vary according to the gas holdup. The electronics and sensors were designed and built according to Libert *et al.* (2011). Each sensor is made up of two electrodes mounted flushed on the outer wall of the tube, thus constituting a capacitor in which the dielectric is formed by the air-water flow and the wall.

Both gas holdup sensors were calibrated using a closed borosilicate glass pipe section inside of which specified amounts of water were placed, generating known values of gas holdup. This stratified regime calibration procedure is alternative to the linear relationship between voltage and holdup, which is known to give errors up to 18% (De Kerpel *et al.*, 2013). The calibration curve has been normalized with respect to voltage signals corresponding to gas holdup values of 1 and 0, i.e. pipe full of water or full of air, respectively. Thus, the calibration curve accounts for small variations in electrical properties of both fluids due to contamination or small changes in temperature.

2.2 Experimental procedure

The experimental procedure is described as follows. The test rig is initialized by turning the thermostatic bath on and setting the valve system so only air enters the test section. The pressure regulator and the micrometric valve are set to generate a flow of air inside the test section. After the test section is completely free of liquid water, voltage signals of both gas holdup sensors are read and stored for calibration (signal normalization) purposes. The valves are then set to a position where only water enters the test section and the pump is turned on. A shut-off valve (10) located downstream the test section is partially closed, thus generating an increase of pressure inside the test section. Following that, any air bubbles inside the tubing connecting the pressure transducers to the test section are purged out of the system. Then, the shut-off is opened after the system has been purged, and voltage signals of both gas holdup sensors are again read and stored.

After performing the previous procedures, experiments can be carried out. As the pump is turned on and the pressure

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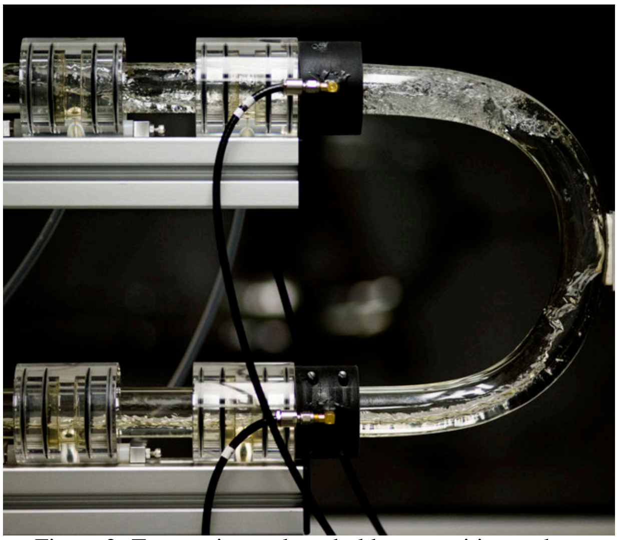

Figure 2: Test section and gas holdup capacitive probes.

regulator is opened, mass fluxes of air and water are set by adjusting the valves and pump speed. Mass fluxes of each phase are measured individually upstream of the inlet mixer. Only a few minutes are required for the flow rates to stabilize in the test section at each condition. Superficial air velocities were varied between 0.2 and 40 m/s for three nominal values of superficial water velocity (0.05, 0.2 and 1 m/s) covering the stratified, plug, slug and annular flow patterns. As the majority of flow conditions involve intermittent flow patterns, the sampling interval needs to be significantly larger than the characteristic time scales of the flow patterns (e.g., slug and wave periods). The sampling interval used in the present study varied from 30 s to 5 min depending on the condition, at a 10 kHz sampling rate.

2.3 Frictional pressure drop in the bend

The frictional pressure drop in the bend was estimated by applying the conservation of momentum in a control volume between the inlet and outlet of the bend as follows,

$$\Delta p_{f,b} = \Delta p + G^2 \left(\frac{1}{\rho'_{out}} - \frac{1}{\rho'_{in}} \right) \pm \bar{\rho} g 2R, \tag{1}$$

where Δp is the total measured pressure drop, G is the total mass flux and g is the gravitational acceleration. The positive sign of the gravitational term corresponds to upward flow in the bend, while the negative signal corresponds to downward flow. The momentum density, ρ', is defined as,

$$\rho' = \left[\frac{(1-x)^2}{\rho_l(1-\alpha)} + \frac{x^2}{\rho_g \alpha} \right]^{-1} \tag{2}$$

and is evaluated by using actual gas holdup values α measured at the inlet and outlet of the bend. The average density of the mixture in the bend, $\bar{\rho}$, is taken as the average value of the mixture densities at the inlet and outlet of the bend, which is given by,

$$\rho = \rho_g \alpha + \rho_l (1-\alpha). \tag{3}$$

3. RESULTS AND DISCUSSION

3.1 Pressure distribution

Figure 3 depicts the pressure distribution as function of distance for upward flow at a superficial liquid velocity, j_l, of 0.2 m/s. The superficial gas velocities j_g were varied from 0.2 to 30 m/s. The pressure and the distance are written with respect to the absolute pressure and the axial position of the point at which the absolute pressure is measured furthest upstream from the bend (see reference point in the diagram of Fig. 1). The bend is located at around 1.85 m downstream of this reference point, which corresponds to the fifth marker in each curve. The markers have been distinguished by flow pattern, i.e., plug, slug and annular flow. The region close to the bend is affected by its presence, noted by a change in pressure gradient (better detailed in Fig 3b). The flow is affected not only downstream the tube bend, but also upstream; for lower gas flow rates, there is also a small increase in pressure that reaches an equivalent length of approximately 15 diameters upstream. At low flow rates, countercurrent flow was observed in the bend, as the gas flow lacked the required momentum to lift the liquid continuously along the bend. In this way, a flow behavior resembling that of churn flow in a vertical pipe was observed during upward flow in the bend at low (Fig. 4) and intermediate flow rates. This oscillatory behavior of the liquid phase in the bend, as will be seen, influences significantly the frictional pressure drop contribution in the bend. Nevertheless, these effects vanish when the gas flow rate increases, and the flow pattern changes from slug to annular in the upstream section. In annular flow, the pressure gradient remains fairly constant along the horizontal tube length, indicating a minor influence of the bend on the flow behavior in the straight section. The influence of the bend on the flow is seen in Fig. 5, which depicts the phase distribution in the bend of different test conditions, each corresponding to a well-defined flow regime in the horizontal tube section.

Figure 6 shows the pressure distribution for the downward flow condition, for the same gas superficial velocities. In this case, the gravitational and the frictional components of pressure gradient have opposite signs. The gravitational

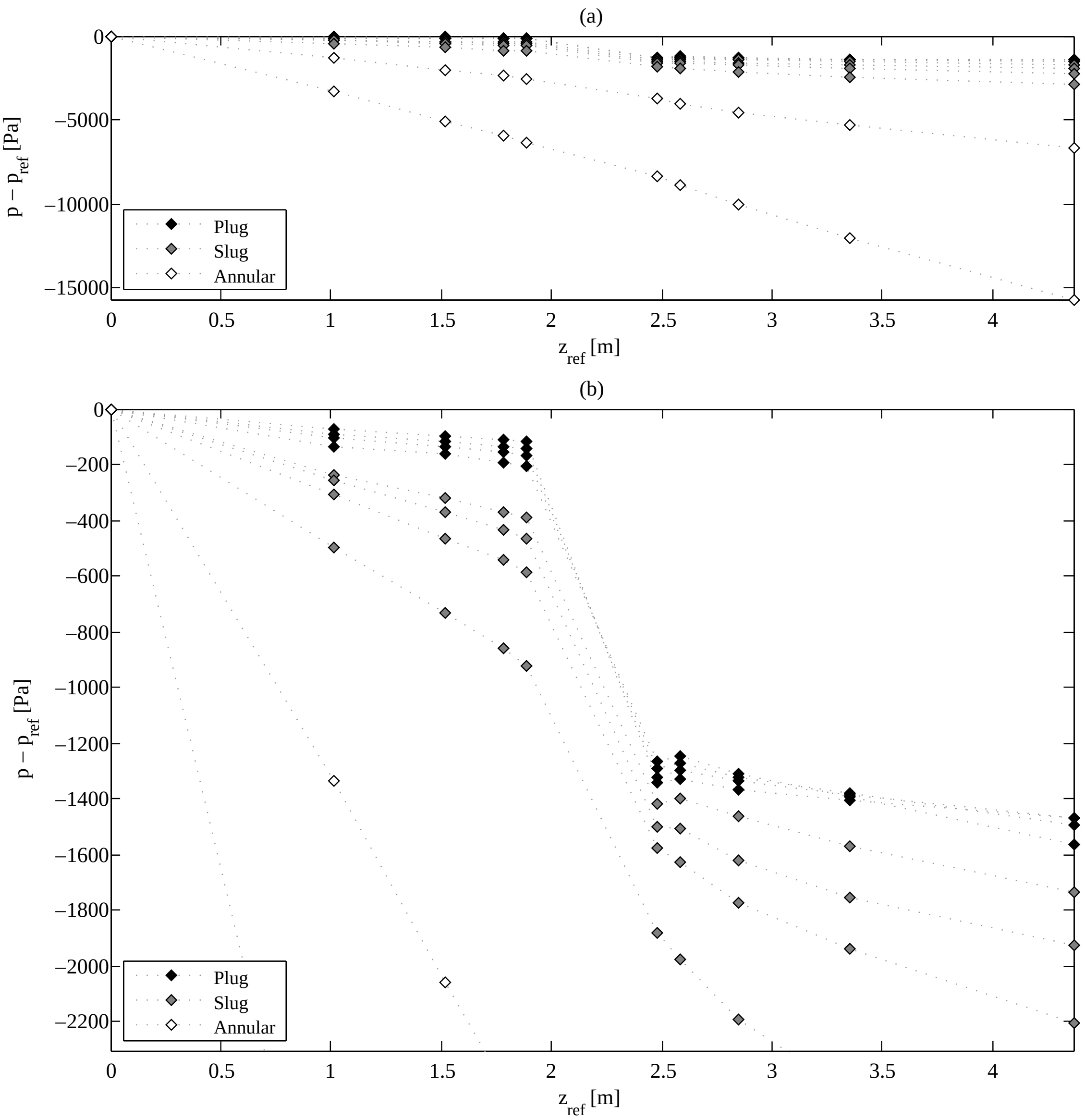

Figure 3: (a) Pressure distribution in upward flow condition, j_l = 0.2 m/s and j_g = 0.2 - 30 m/s; (b) Detailed view of pressure distributions for low gas flow rates of plot (a).

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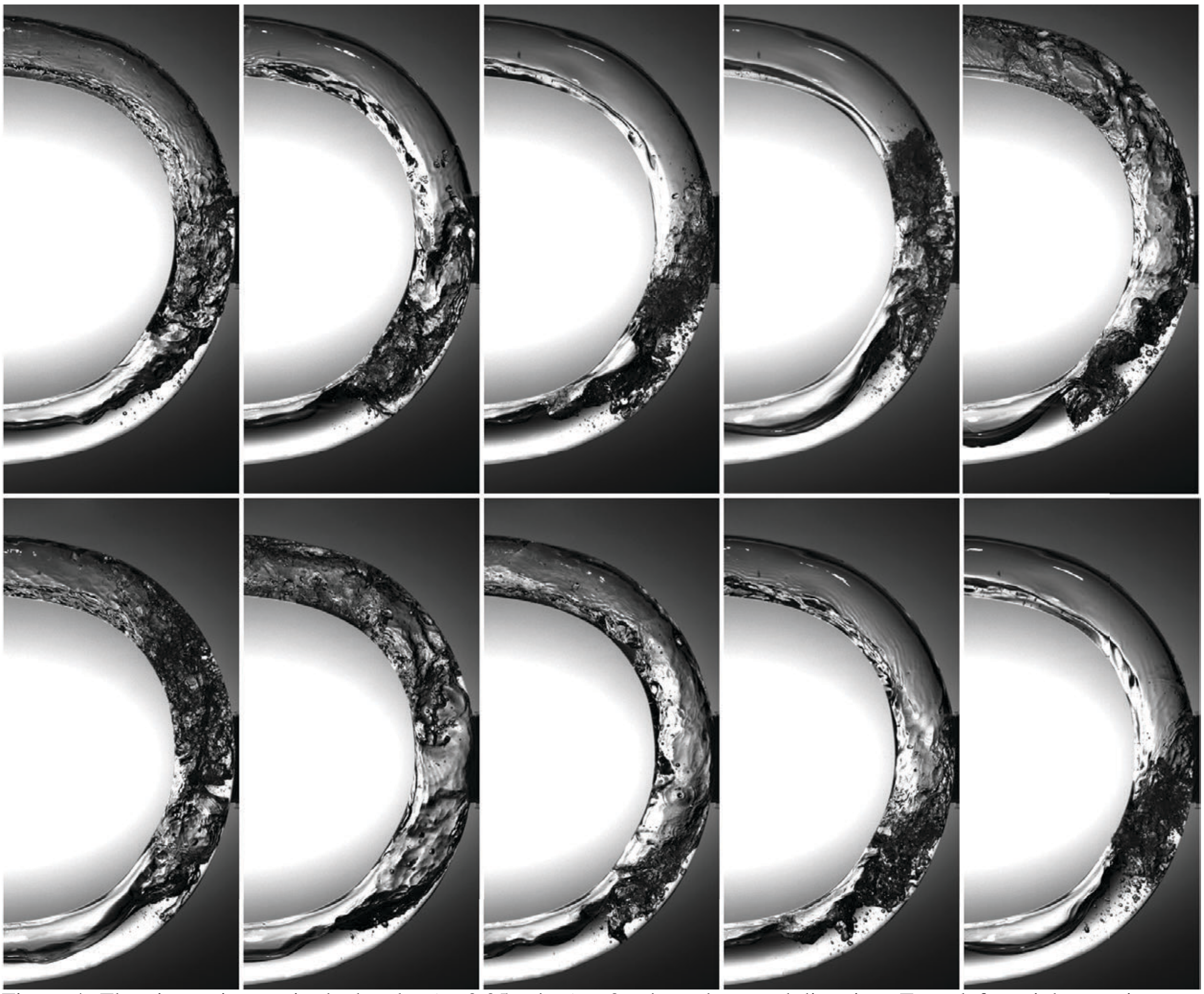

Figure 4: Flow intermittency in the bend – j_l= 0.05 m/s, j_l = 2 m/s, and upward direction. From left to right, starting at the top, images were taken with a 0.07 s time interval between each other.

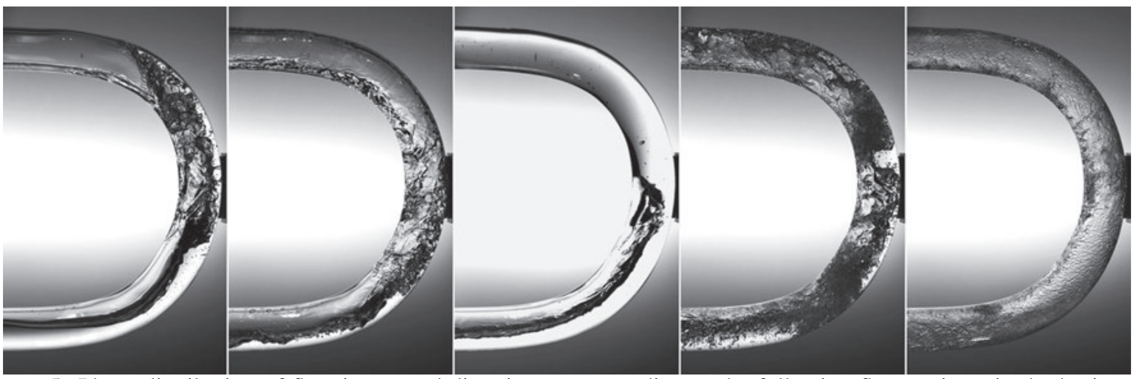

Figure 5: Phase distribution of flow in upward direction corresponding to the following flow regimes in the horizontal segment: stratified, wavy, plug, slug, and annular (from left to right).

component dominates the frictional component for low gas flow rates, resulting in an increase of pressure downstream the bend. Also for lower gas flow rates (Fig. 6b), a small increase in pressure occurs upstream, starting at approximately 15 diameters upstream the bend (z = 1.52 m). As the gas flow rate increases and friction becomes higher, the pressure loss is increased. Downstream of the bend, the effect of the tube bend on pressure drop is not well defined as it seems to extend beyond the measuring stations and becomes negligible when j_g reaches the boundary between slug and annular

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flow regimes.

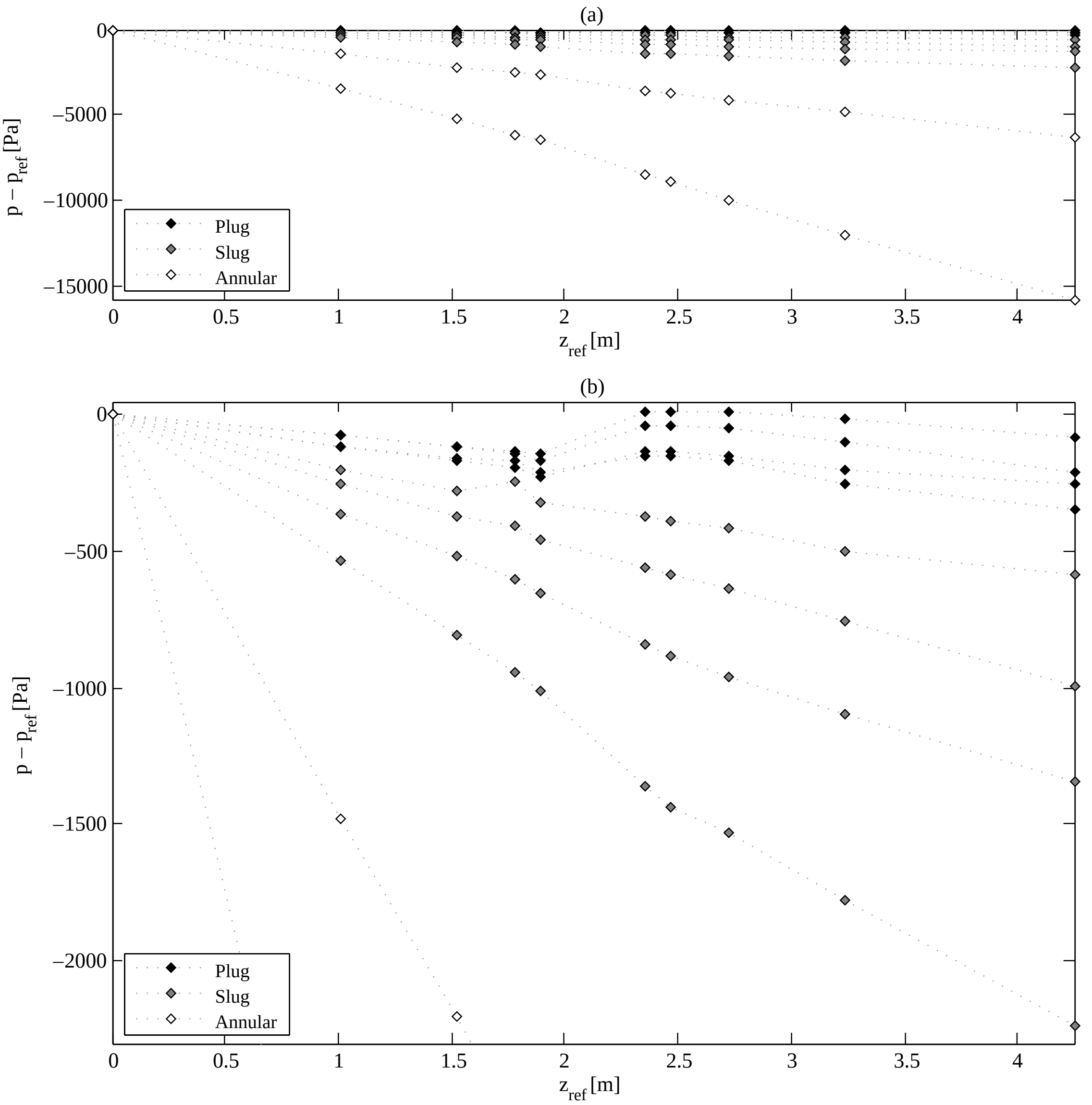

Figure 6: (a) Pressure distribution in downward flow condition, j_l = 0.2 m/s and j_g = 0.2 - 30 m/s; (b) Detailed view of pressure distributions for low gas flow rates of plot (a).

3.2 Gas holdup

Gas holdup values of the sensors positioned at the top and bottom of the bend (inlet or outlet, depending on the flow direction) are shown in Fig. 7 for each flow condition and different curvature radii. Each color of the markers represents a bend curvature radius. Flow in the upward direction seems more affected by the tube bend than in the downward direction, as gas holdup values differ significantly between the inlet and the outlet. This effect is stronger at lower gas flow rates, for the same reasons discussed previously for the pressure distribution. Nevertheless, gas holdup tends to remain more uniform between the inlet and outlet when liquid flow rate is increased, or when gas flow rate is increased. As the liquid flow rate increases, the higher flow inertia reduces the influence of the body forces associated with the bend. When the gas flow increases, it gives rise to a less intermittent flow condition as it approaches the boundary between slug and annular flow, which also makes the flow less affected by the bend. For the annular flow regime, when j_g = 20 m/s and j_l = 0.05

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and 0.2 m/s, gas holdup values are almost the same.

For downward flow and j_l equal to 0.05 m/s, a hydraulic jump was observed downstream the bend for low gas flow rates. At this condition, the gas holdup at the outlet (bottom) is seen to decrease slowly with time, accelerating the air phase and generating small disturbances at the stratified flow interface. As the gas holdup decreases, the small waves increased in amplitude until a large wave reaches the tube upper wall, generating a single slug of liquid that propagated along the test section. This phenomenon was observed for superficial gas velocities less than 4 m/s; for values greater than 4 m/s, gas holdup values remained constant between the inlet and outlet positions.

Figure 7 also shows that gas holdup values at the bottom position of the bend differ according a the curvature radius, while values at the upper position remain fairly constant.

In Fig. 8 the values of gas holdup at the inlet of the bend in both directions have been compared with correlations proposed by Chexal *et al.* (1991); Smith (1969); Premoli *et al.* (1971). For the upward flow direction (Fig. 10a) a better agreement between the experimental and predicted values is given by the correlation of Chexal *et al.* (1991), while in the downward condition this correlation only provides a good fit for high values of j_g.

3.3 Frictional pressure drop in the bend

Frictional pressure drop in the bend, $\Delta p_{f,b}$, was evaluated according to Eq. 1 for all flow conditions. These values are shown in Fig. 9 and were compared with the correlations proposed by Chisholm (1983); Chen *et al.* (2004); Domanski and Hermes (2008); Padilla *et al.* (2009). The conditions where flow was set in the upward direction of the bend are represented by a triangular marker pointing up, while for the downward direction a triangular marker poiting down was used. In this figure, which presents nine different plots, rows represent different curvature radii used, and columns represent different liquid superficial velocities j_l.

3.3.1 Upward flow

In the upward direction, as a result of the occurrence of countercurrent flow in the bend, low values and positive values of frictional pressure drop are observed, i.e. the average wall shear stress is approximately zero or has the same direction of the net flow, respectively. This effect on wall shear streess seems to occur for the majority of flow conditions, since in general the absolute values of pressure drop in the upward direction are substantially lower than in the downward direction. Nevertheless, these values are almost the same for a few conditions observed, with j_l = 1 m/s and $2R/d$ = 6.1.

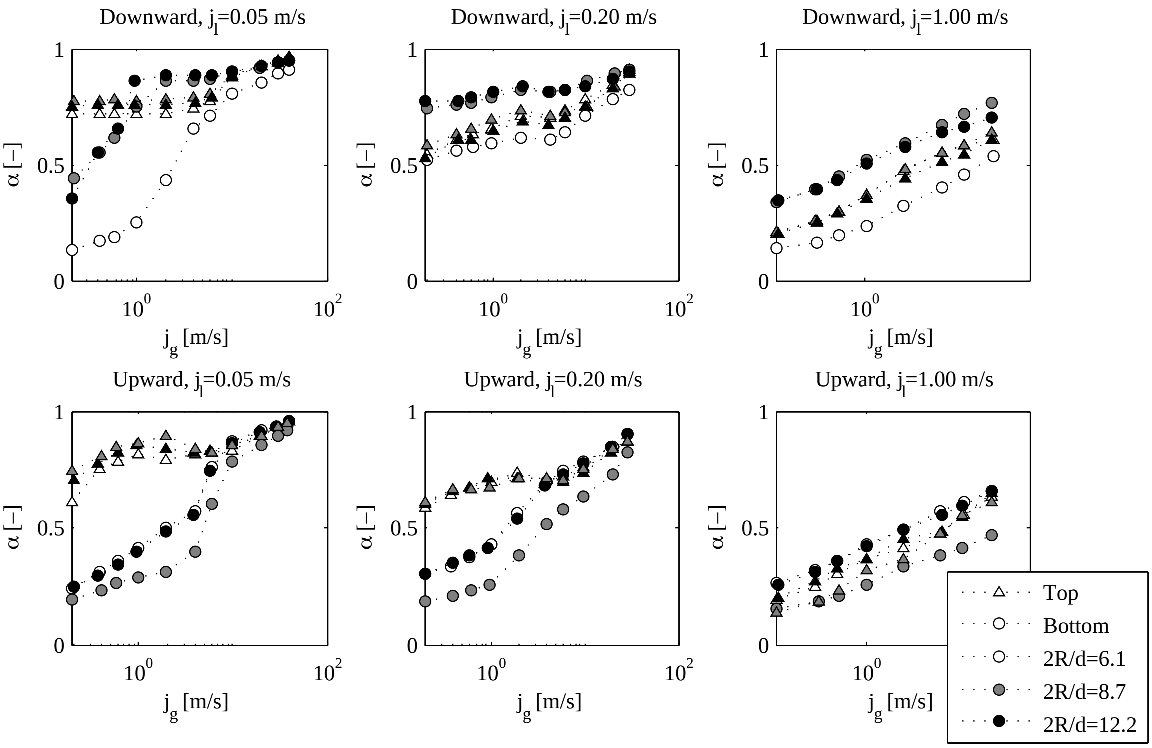

Figure 7: Measured gas holdup values at top and bottom positions of the bend for every flow condition and curvature radius $2R/d$ = 6.1, 8.7, and 12.2.

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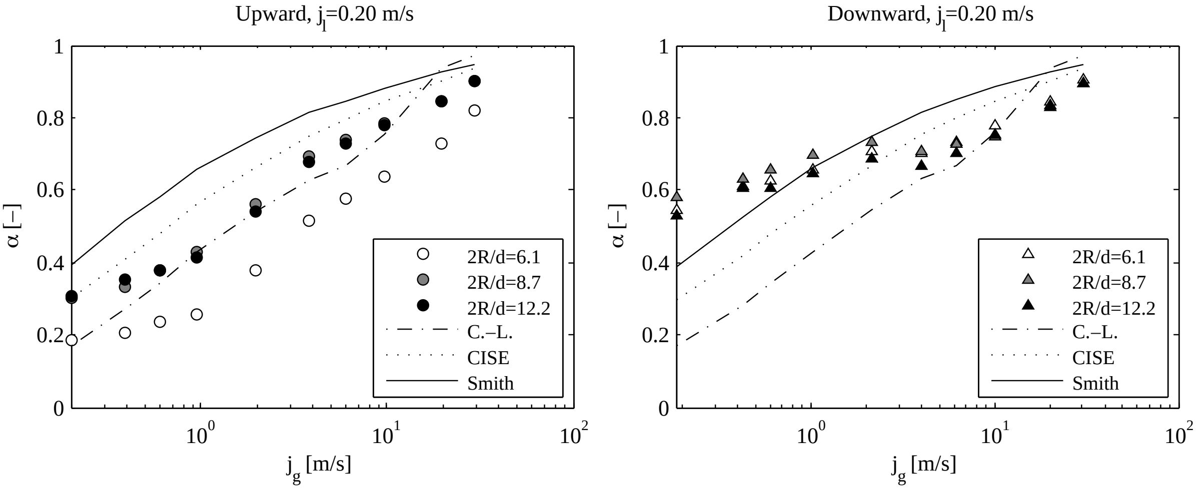

(a) upward direction (b) downward direction

Figure 8: Gas holdup values at the inlet for upward (a) and downward (b) direction, j_l = 0.2 m/s, compared with correlations proposed by Chexal *et al.* (1991); Smith (1969); Premoli *et al.* (1971).

In order to better assess the effect of the curvature radius on the frictional pressure drop, the same data presented in Fig. 9 has been graphed as an average pressure gradient, and is shown in Fig. 10. In general, the absolute value of frictional pressure gradient increases substantially as superficial velocity of gas increases. The effect of different bend curvature radii is more evident at high liquid flow rates, in the slug flow regime.

3.3.2 Downward flow

Figure 10b shows the frictional pressure drop in the bend for downward flow. In this case, the frictional pressure drop values are all negative. Similarly as proposed by Lockhart and Martinelli (1949), pressure drop at the bend can be written in terms of a two-phase multiplier,

$$\Delta p_{f,b} = \phi^2_{b,g} \cdot \Delta p_{f,b,g}, \tag{4}$$

where the two-phase multiplier $\phi^2_{b,g}$ is related to a Martinelli parameter for the tube bend segment, X_b^2, defined as,

$$X_b^2 = \frac{\Delta p_{f,b,l}}{\Delta p_{f,b,g}}. \tag{5}$$

Eq. 5 represents the ratio of single-phase frictional pressure drop in the bend corresponding to each phase, and can be assessed using the correlation suggested by Idelchik (1992). The above-mentioned relationship for $\phi^2_{b,g}$ in terms of X_b^2 can be expressed by the following equation:

$$\phi^2_{b,g} = AX_b^2 + BX_b + 1. \tag{6}$$

In an initial approach, only a data set corresponding to the curvature radius of 8.7 and the downward flow condition was used to evaluate the coefficients A and B of Eq. 6. For both coefficients, a power function of a modified Froude number is proposed. Thus,

$$A = k \cdot Fr^n_{b,l}, \tag{7}$$

where,

$$Fr_{b,l} = \frac{\rho_l j_l^2}{(\rho_l - \rho_g) g R}, \tag{8}$$

and R is the curvature radius. The coefficients, which have been regressed from the experimental data for downward flow, are presented in Tab. 1.

Figure 11 shows the two-phase multiplier, $\phi^2_{b,g}$, correlation (solid line) together with the experimental data, for which the color markers represent different liquid Froude numbers.

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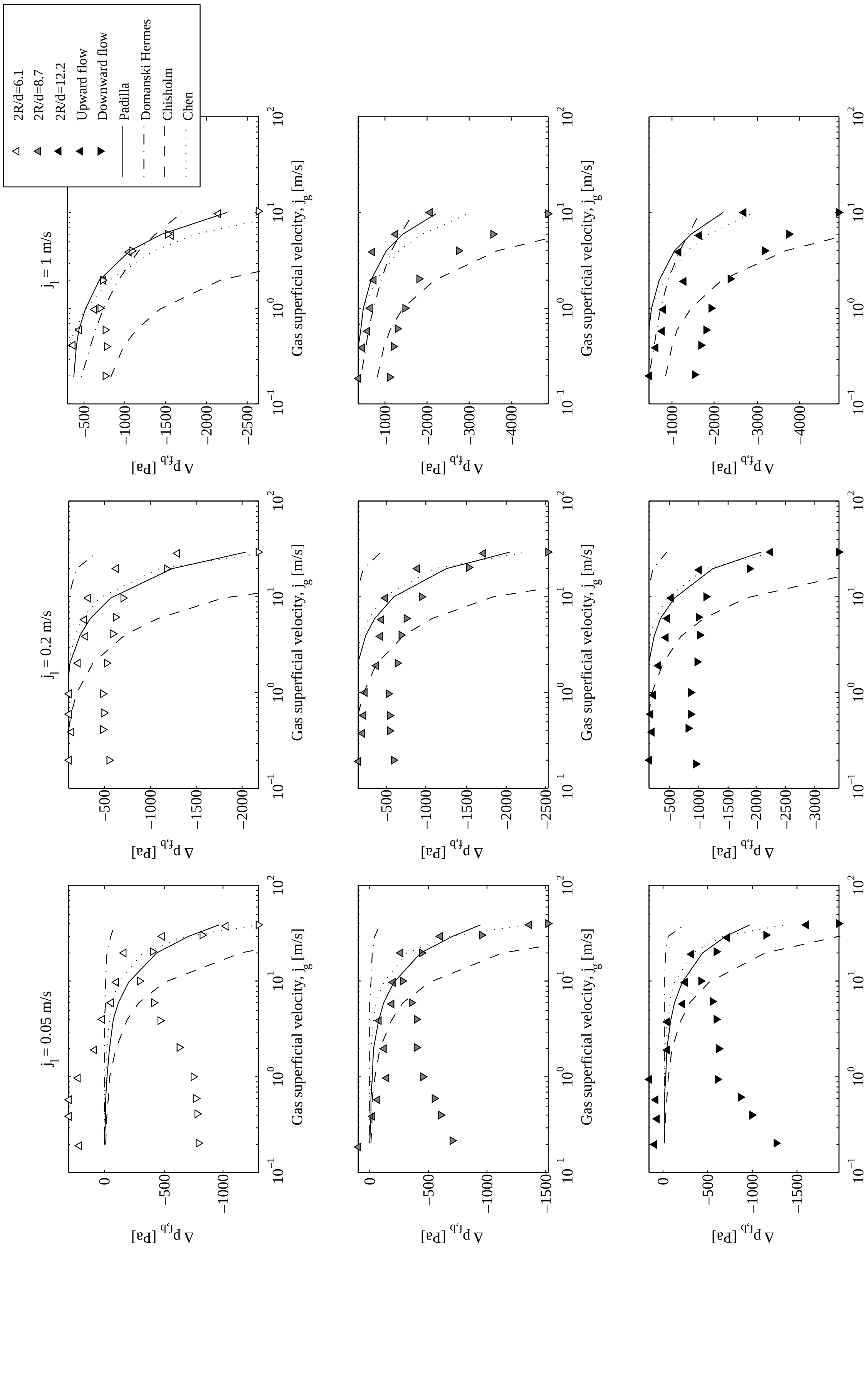

Figure 9: Frictional pressure drop in the bend for upward and downward flow direction, curvature radii $2R/d$ of 6.1, 8.1 and 12.2, compared with correlations proposed by Chisholm (1983); Chen *et al.* (2004); Domanski and Hermes (2008); Padilla *et al.* (2009).

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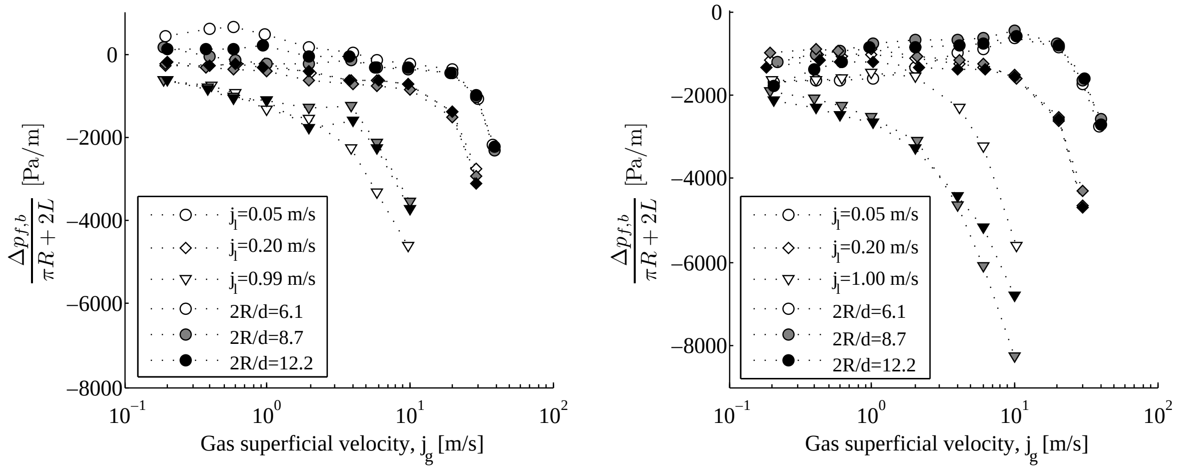

(a) upward direction (b) downward direction

Figure 10: Frictional pressure gradient in the bend for both flow directions.

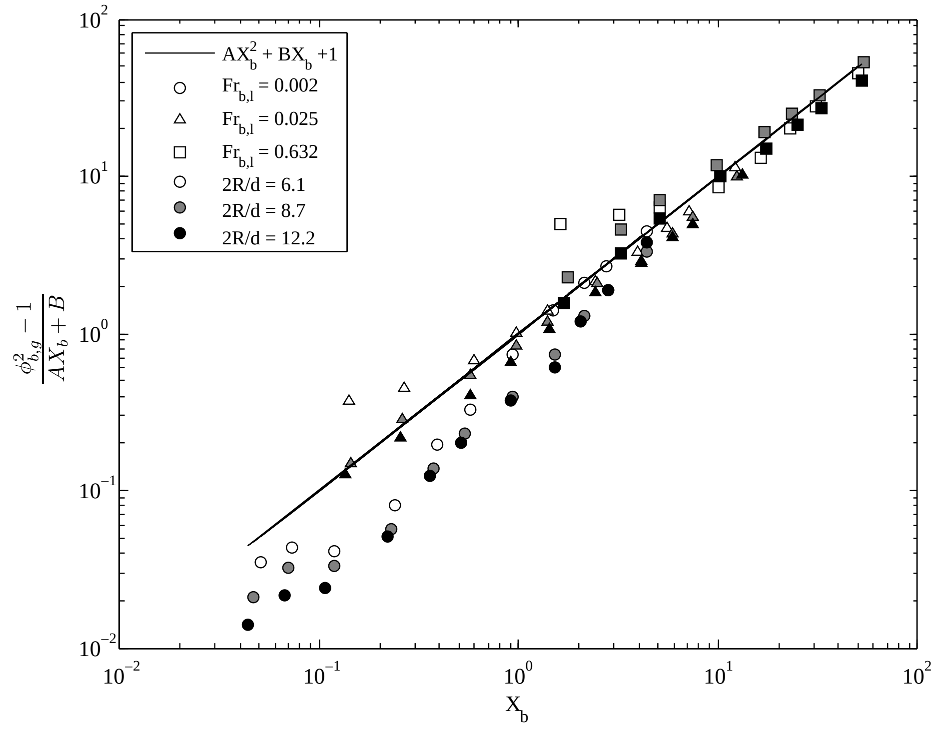

Figure 11: Two-phase multiplier calculated from frictional pressure drop values and estimated by the proposed correlation.

Table 1: Coefficients of Eq. 7.

Coefficient	k	n
A	4.4	-0.8
B	0	-

4. CONCLUSIONS

An experimental apparatus was built in order to evaluate the two-phase air-water flows in 180° bends. Pressure and gas holdup measurements were presented for a wide range of flow rates and flow regimes, for two orientations and three curvature radii. Frictional pressure drop in the bend has been evaluated and a two-phase multiplier correlation proposed for downward flow direction.

According to the measurements of pressure and gas holdup, and the frictional pressure drop analysis, it has been seen that the annular flow regime at the bend is highly subjected to frictional effects and less to the centrifugal and gravitational effects. However, intermittent flow regimes are very influenced by the tube bend especially in the upward flow direction, when gravity plays an important role and countercurrent flow occurs.

5. ACKNOWLEDGEMENTS

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