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EXPERIMENTAL STUDY OF TWO-PHASE FLOW IN LARGE-DIAMETER ANNULAR DUCTS

Alex Roger Almeida Colmanetti, alex.colmanetti@usp.br
Oscar Mauricio Hernandez Rodriguez, oscarmhr@sc.usp.br
Sao Carlos School of Engineering , University of Sao Paulo
Av. Trabalhador São Carlense, 400
13566-590, Sao Carlos, SP, Brazil

Marcelo Souza de Castro, mcastro@fem.unicamp.br
School of Mechanical Engineering, University of Campinas, Brazil

Tor Kindsbekken Kjeldby, tbkj@statoil.com
Peter W. J. Derks, pede@statoil.com
STATOIL

Abstract. *Gas-liquid flows in annular ducts are present in many industrial applications, e.g., in directional oil wells. However, even global characteristics of these flows such as flow patterns or two-phase pressure gradient are so far not fully understood. The common design approach of annular ducts used for transport of gas-liquid mixtures has been based on the hydraulic-diameter concept. The limitations of this method have been leading to significant oversizing. This experimental study aims to evaluate the conditions for which this approach is suitable and present new data on vertical gas-liquid flows in an annular geometry. An experimental setup of 10.5 m length was constructed for this work. The investigation was conducted using air and water as working fluids. Comparable experiments were performed in: (i) a reference pipe setup and (ii) a duct of concentric annular configuration. Identical values of the equivalent hydraulic diameter were applied. Flow pattern, pressure drop and void fraction data were obtained for both configurations. The data will be of large importance for development of new models for flow-pattern transition and closure correlations, which are essential for optimized design of oil wells.*

Keywords: *two-phase flow, gas-liquid flow, annular duct, hydraulic diameter, flow patterns, pressure gradient.*

1. INTRODUCTION

Flows in annular ducts are observed in the oil industry in directional wells with sand screen, vertical wells with electrical submersible pumps (ESPs) as well as gas-liquid inline separators. Some characteristics regarding two-phase flow in annular ducts require better understanding, such as flow patterns, phase distribution, effects of oil viscosity, droplet-size distribution and effect of inclination. These are necessary for correct modeling of two-phase pressure drop and void fraction, which are important for optimized projects and construction of oil wells.

This work presents an experimental investigation on two-phase flow in a large diameter annular duct. Pressure-drop and void-fraction data were acquired in two different apparatus connected to the same fluids supply line: the annular duct and a reference pipe setup, both with the same hydraulic diameter. The experiments were conducted at the Laboratory of Thermal and Fluids Engineering (LETeF) of the São Carlos School of Engineering of the University of São Paulo - USP.

2. LITERATURE REVIEW

Works on multiphase flows in annular ducts are scanty. Most of the papers present discussions on flow patterns in gas-liquid pipe flows. One may cite the work of Kelessidis and Dukler (1989), where techniques for flow regime transitions in upward gas-liquid flow in concentric and eccentric annular ducts are presented. Caetano et al. (1992) carried on the work of Kelessidis and Dukler, performed experiments, developed correlations and proposed a classification of flow patterns. Flow-pattern maps and experimental data for pressure drop and volumetric fraction was presented. It was concluded that the hydraulic-diameter concept is not always suitable for modeling the flow in annular ducts. Figure 1 shows the flow patterns observed by Caetano et al. (1992).

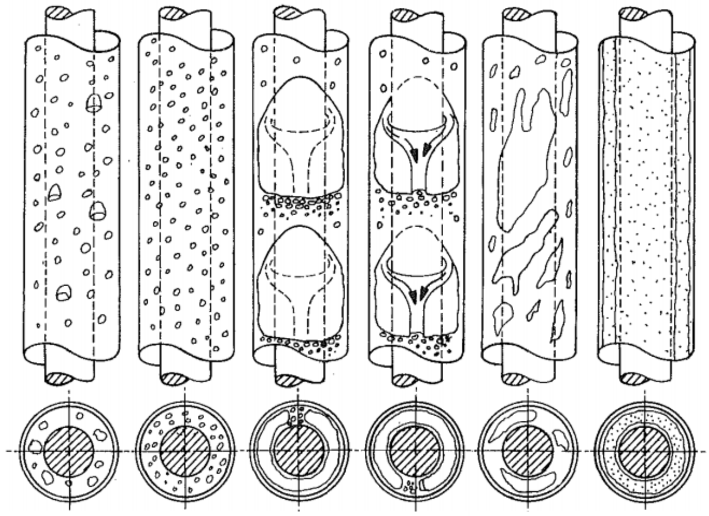

Figure 1. Annular-duct flow patterns in gas-liquid flow observed by Caetano et al. (1992).

Blanco et. al. (2008) carried out a literature review and proposed a methodology for generation of flow-pattern transition boundaries in upward-vertical and horizontal gas-liquid flow in an annular-duct geometry. For upward vertical flow the transition models of Caetano et al. (1992), Hasan and Kabir (1992) and Kelessidis and Dukler (1989) were used. In the case of horizontal flows, the model of Rodriguez et al. (2006) was used to predict the stratified and wavy-stratified flow-pattern transition, but extended to include the modeling of the occupied perimeters and areas in the annular geometry. Ekberg's et al. (1999) data were used for all other flow patterns. The predictions were compared with experimental data from Caetano et al. (1992), Kelessidis and Dukler (1989) and Ekberg et al. (1999) and found consistent with the experimental data.

Julia and Hibiki (2011) proposed a new model for flow-pattern transition in vertical annular-duct flow. Special attention was given to the transition from slug flow to churn flow and also from churn flow to annular flow. The drift-flux model was used to predict the void fraction. Two new models were developed for the transition from slug flow to churn flow. The first was intended for small diameter annular-duct geometries, where the torus-shaped Taylor bubble is evenly distributed over the flowing cross section, and the second for annular ducts of large diameter, where the Taylor bubble can be highly asymmetric. The authors argued that their models were more refined than those already available in the literature, except for the transition model for churn to annular flow which did not yield better prediction when compared with models from the literature.

Ortiz-Vidal (2010), Ortiz-Vidal et al. (2012) and Mendes (2012) worked with an inverted shroud gas-liquid separator. The equipment was made of three concentric tubes, the intermediate one closed at the bottom end, allowing for segregation of the liquid phase. The authors studied flow patterns and gas-liquid separation efficiency using air, water and viscous oil as working fluids. They observed the following patterns in horizontal flow: stratified, wavy stratified, slug flow and elongated bubbles. In inclined ducts, only the elongated bubble and slug flow patterns were observed.

Carvalho (2013) used the same setup as Mendes (2012) to obtain pressure drop and void fraction data in upward vertical and inclined bubbly air-water flow. The pressure drop was measured using a differential pressure transducer and void fraction was measured using the quick-closing-valve technique (QCV). The acquired data were compared with predictions of a one-dimensional drift-flux model developed for circular tubes and adapted to annular-duct geometry by applying the hydraulic-diameter concept.

3. EXPERIMENTAL METHODOLOGY

The experimental work presented here was performed in the multiphase flow loop of LETeF. There are two test lines of 10.5 m length of which the inclination can vary from 0° to 90°, relative to the horizontal. It is possible to generate single, two and three-phase flow in the setup. The setup has the necessary instrumentation for flow measurement, with positive displacement flow meters for liquids, thermocouples for liquids and air temperature measurements, characterization of flow patterns by visualization, global measurements of pressure drop with differential pressure transducers and in-situ volumetric fraction by quick-closing valves technique (QCV). The air is supplied by an air compressor and air tanks are used to maintain the flow steady. The air flow is controlled via electrically controlled globe valves and measured with turbine flow meters, pressure transducers and thermocouples (Fig. 2).

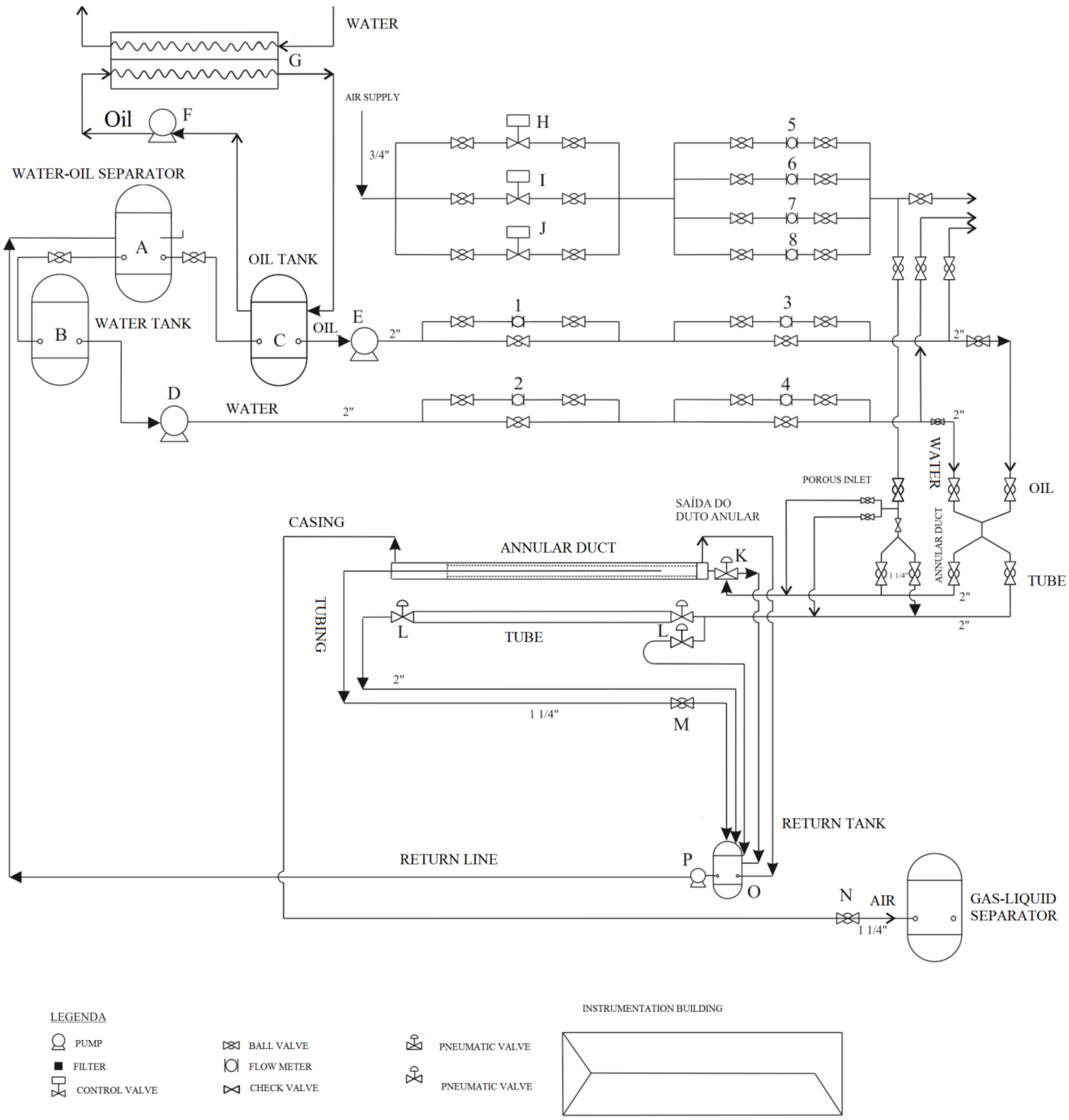

Figure 2. Experimental setup.

Data acquisition from all instruments is obtained using a National Instruments® data acquisition system in combination with a LabVIEW® based software. This system also controls the water and oil pumps, pneumatic valve and air flow rate. The experiments were carried out in the vertical position (90° from horizontal) in both test lines: annular duct and reference pipe setup. The annular duct is a set of three concentric tubes of different diameter, two PVC tubes and the outermost made of glass. There is another setup made of glass tubes besides it with equivalent hydraulic diameter. The annular duct and the reference tube layouts are presented in Figs. 3 and 4.

There is one pneumatic directional valve (Fig. 3) in the annular duct inlet, which is used to inject the fluids into the test section and to deflect them to a by-pass line when the fast closing valves are engaged, this to avoid pressure buildup in upstream piping. Two Endress-Hauser® differential pressure transducers with an uncertainty of 0.075% of the range were installed in parallel to measure different ranges of pressure drop (Fig. 3). Furthermore, four thermocouples were installed in the test section to measure the temperature and two pressure transducers to monitor the gage pressure inside the test section and ensure operational safety.

The dimensions of the concentric tubes are:

External tube: o.d. = 165 mm, i.d. = 155 mm (glass)
Internal tube: o.d. = 60 mm, i.d. = 53.4 mm (PVC)

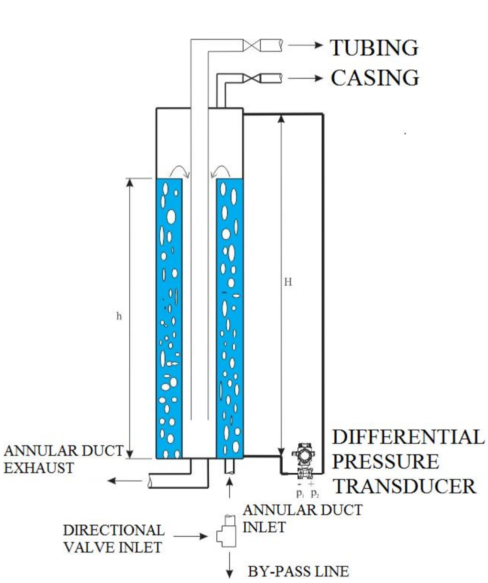

Figure 3. Annular duct configuration.

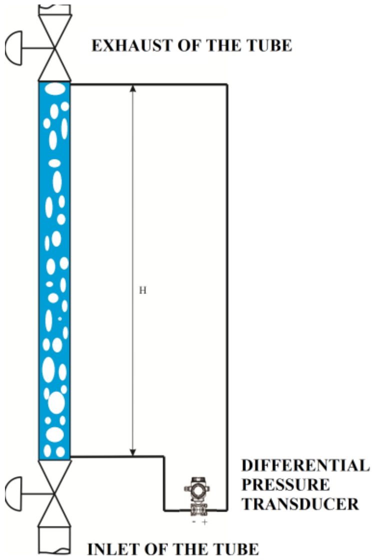

Figure 4. Reference pipe configuration.

According to Caetano et.al (1992), two geometrical parameters must be defined to study flows in annular ducts: annular tube diameter ratio (*K*) and eccentricity (*e*), as presented in Fig. 5. To calculate the diameter ratio and eccentricity it is necessary to define the following dimensions: D_T - external diameter of the internal tube, D_C - internal diameter of the external tube and *DBC* – distance from the center of the internal tube to the center of the external tube (related to eccentricity). In practical application, D_T would refer to the external diameter of the tubing and D_C to the internal diameter of the casing. In this work D_C = 155 mm, D_T = 60 mm and *DBC* = 0 mm, leading to a concentric annular duct with K = 0.4 and e = 0.

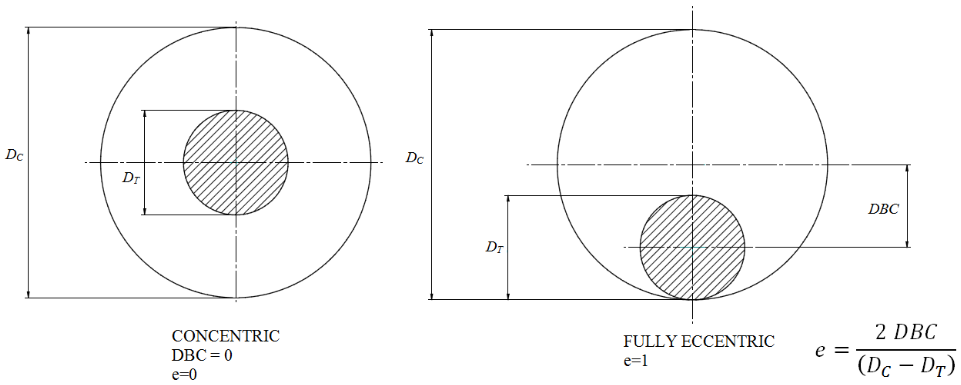

Figure 5. Annular duct parameters defined by Caetano et.al (1992).

The glass tube of the reference pipe setup has an internal diameter equivalent to the hydraulic diameter of the annular duct (95 mm) and is installed on the same metal structure and next to the annular duct. The reference pipe setup has three pneumatic quick-closing-valves to measure liquid holdup, and to deviate the flow to a by-pass line when measuring holdup. The same differential pressure transducers are used both for measuring pressure drop in the annular duct setup as well as in the circular cross section reference pipe (reference pipe setup). The setup also has thermocouples and pressure transducers. Relief valves are located at the inlet and the outlet of each setup to ensure operational safety.

The two setups are necessary in order to enable the direct comparison of the experimental data and evaluate the limitations of the hydraulic diameter concept. Flow pattern characterization, void fraction and two-phase pressure-drop data were obtained for both geometries at similar flow conditions.

Pressure taps are located at several points along the annular duct and reference pipe setup. The pressure drop measurements are conducted at equivalent axial positions for both geometries (Figs. 6 and 7).

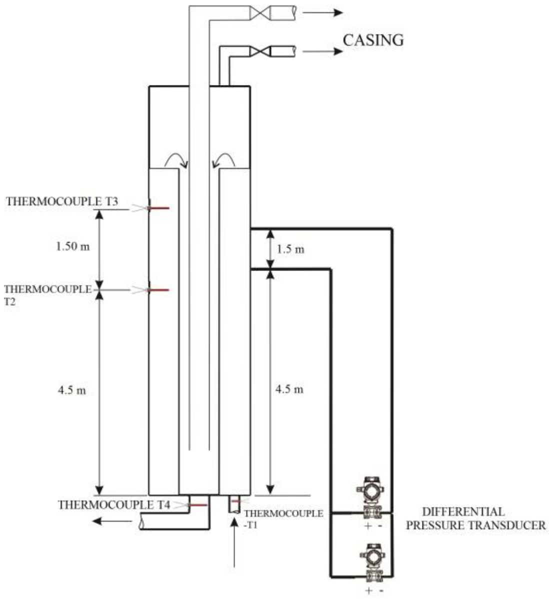

Figure 6. Pressure taps in the annular duct.

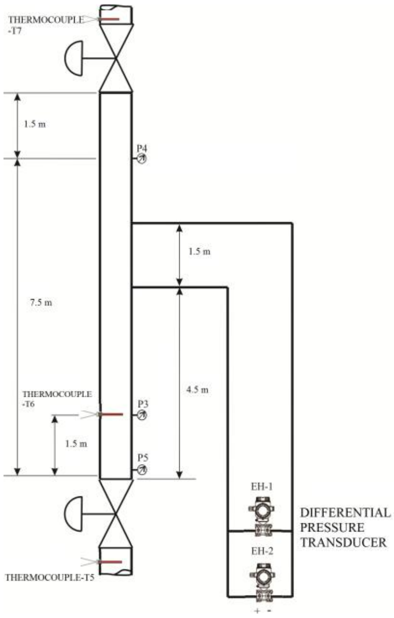

Figure 7. Pressure taps in the reference pipe setup.

The objectives of this experimental study are the measurement of two-phase pressure drop and void fraction in different geometries, annular duct and reference pipe, using equivalent hydraulic diameters. In order to ensure reliable pressure drop measurements, the setup was validated using single-phase water flow and the results were compared with classical single-phase flow models.

4. LITERATURE MODELS FOR TUBES

In this section, the models used to predict pressure drop in single-phase flow and pressure drop and holdup in two-phase flow are presented.

4.1 SINGLE-PHASE FLOW MODEL

Neglecting wall roughness, the frictional pressure gradient in single-phase flow

$$-\left(\frac{\mathrm{dp}}{\mathrm{dz}}\right)_{\mathrm{F}} = \frac{f\rho \mathrm{J}^2}{2\,\mathrm{D}} \tag{4.1}$$

is predicted using the Blasius' friction factor correlation (White, 2006):

$$f = 0.316\mathrm{Re}^{-0.25} \tag{4.2}$$

$$\mathrm{Re} = \frac{\mathrm{DJ\rho}}{\mu} \tag{4.3}$$

Here, f is the Darcy's friction factor, ρ is the water density, μ is the water dynamic viscosity, D is the hydraulic diameter of the channel (95mm), Re is Reynolds number and J is the water superficial velocity. The frictional pressure drop is found by multiplying Eq. (4.1) by the distance between the pressure taps (L), in the case of this experimental work $L=3m$.

4.2 TWO-PHASE FLOW MODEL - DRIFT-FLUX MODEL

The drift-flux model takes into account the slip between the phases. It depends on two parameters that must be experimentally obtained: the void-fraction-weighted average drift velocity ($\tilde{V}_{gj}$) and the distribution parameter (C_0).

$$\tilde{V}_{gj} = \frac{\langle \alpha V_{gj} \rangle}{\langle \alpha \rangle} \tag{4.5}$$

$$C_0 = \frac{\langle \alpha J \rangle}{\langle \alpha \rangle \langle J \rangle} \tag{4.6}$$

Here < > denotes spatial average, α is the void fraction given by Eq. (4.7), J is the mixture velocity and V_{gj} is the drift flux.

$$\alpha = \frac{\frac{J_g}{J}}{C_0 + \frac{\tilde{V}_{gj}}{J}} \tag{4.7}$$

Hibiki and Ishii (2003) suggest the following values for C_0 and $\tilde{V}_{gj}$ in upward-vertical churn flows, which is the flow pattern observed in the experiments in the annular duct in this paper.

$$C_0 = 1.2 - 0.2\sqrt{\frac{\rho_g}{\rho_L}} \tag{4.8}$$

$$\tilde{V}_{gj} = \sqrt{2}\left(\frac{g\sigma\Delta\rho}{\rho_L^2}\right)^{1/4} \tag{4.9}$$

where g is gravity (9.81 m/s²), σ is the surface tension (0.025 N/m), ρ_g is the gas density dependent of the air pressure and temperature inside the experimental setup, ρ_L is the liquid density (1000 kg/m³), $\Delta\rho$ is the density difference between phases, J_g is the superficial gas velocity, J_L is superficial liquid velocity and J is the mixture volumetric flux, C_0 the distribution parameter and $\tilde{V}_{gj}$ is the void-fraction-weighted average drift velocity. The liquid holdup (β) and the void fraction sum to unity:

$$\beta = 1 - \alpha \tag{4.10}$$

5. RESULTS

In this section the experimental data on single-phase and two-phase flows pressure drop and void fraction for annular duct and reference pipe setups of the lab are presented.

5.1 SINGLE-PHASE FLOW

The experiments carried out in the reference pipe setup show that measured pressure drops are in good agreement with classical single phase flow pressure drop predictions (Section 4.1). Point spreading lower than ±10% was observed (Fig. 8) and the average relative error (ARE) was lower than 7%. Only low mean velocities were tested due to limitations in the liquid flow rate capacity Therefore, the error is acceptable as the measured pressure drop in this test section was lower than 50 Pa. Two differential pressure transducers, with different ranges, were used in those experiments to ensure low error in the measurements.

On the other hand, the pressure drop measured in the annular duct, using standard equivalent hydraulic diameter of 95 mm (Eq. 5.1), did not agree with that predicted by the single-phase flow model with the concept of hydraulic and most of the data are within the -50% limit line, and an average relative error (ARE) larger than 40% was calculated (Fig. 9). The experimental data of single-phase flow in annular ducts were compared with predictions given with Sas-Jaworky and Reed’s (1998) hydraulic diameter concept (Eq. 5.2), which takes into account curvature effects. With this it was found deviation around ±20% and average relative error (ARE) of 5.5%, which indicates the reliability of the experimental setup for these experiments (Fig. 10).

$$D_{h,standard} = D_C - D_T \tag{5.1}$$

$$D_{h,Sas-Jaworsky} = \frac{(D_C^2 + D_T^2) - \frac{(D_C^2 - D_T^2)}{ln\left(\frac{D_C}{D_T}\right)}}{D_C - D_T} \tag{5.2}$$

where D_C is the internal diameter of the external pipe (155mm) and D_T is the external diameter of the internal pipe (60mm), they form the annular duct. Please refer to Fig. 5 for more information.

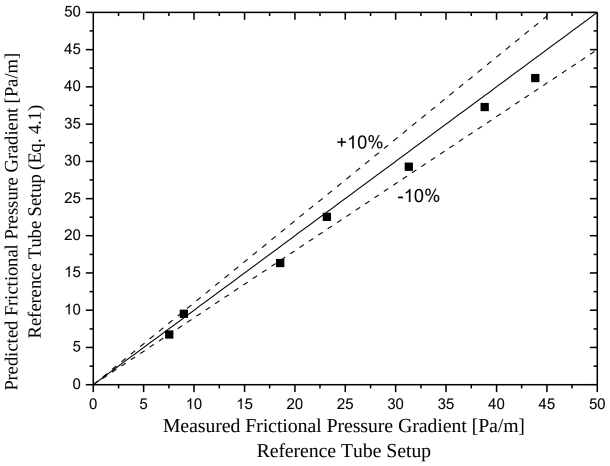

Figure 8. Single phase flow experiments – reference pipe setup.

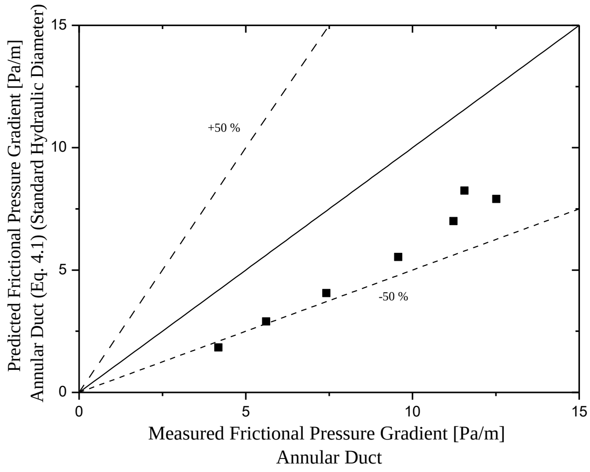

Figure 9. Single phase flow experiments - annular duct.

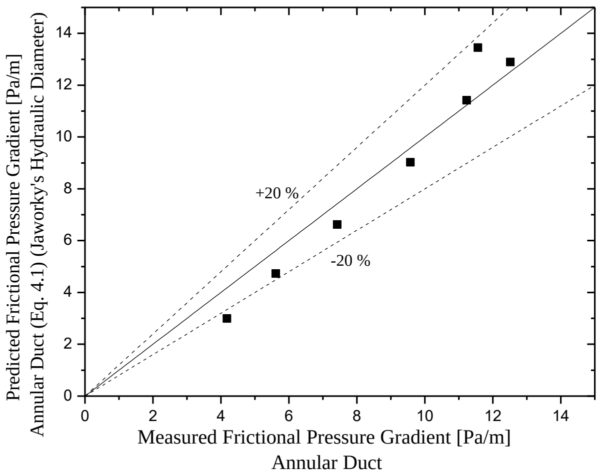

Figure 10. Single phase flow experiments - annular duct.

Table 1. Average relative error in single phase flow.

Channel Geometry	dp/dz ARE [%]
Reference pipe, single phase flow	6.9
Annular duct, single phase flow ($D_{h,\ standard}$)	> 40
Annular duct, single phase flow ($D_{h,\ Sas\text{-}Jaworsky}$)	5.5

Where the Average Relative Error (ARE) is defined as:

$$ARE = \frac{1}{N}\sum_i^N \sqrt{\left(\frac{\frac{dp}{dz}_{model} - \frac{dp}{dz}_{experimental}}{\frac{dp}{dz}_{experimental}}\right)^2} \tag{5.3}$$

where $\frac{dp}{dz}_{model}$ is the pressure gradient predicted by the drift-flux model , $\frac{dp}{dz}_{experimental}$ is the measured pressure gradient and N is the number of experiments.

5.2 TWO-PHASE FLOW EXPERIMENTS

Global measurements of pressure drop and holdup were done in upward-vertical two-phase flow in the reference pipe setup and in the annular duct. The experiments were performed at several air and water superficial velocities. The slug flow pattern was observed in the reference pipe setup while the churn flow pattern was observed in the annular duct. The acquired experimental points were plotted in flow maps given by Taitel et al. (1980) correlations using fluids and ducts properties used in the experimental work at the laboratory, these flow maps are presented in Figs. 11 and 12. At a first glance, the flow map for the reference pipe setup was correlated with the experimental observation of slug flow pattern. On the other hand, for the flow map created for the annular duct, it predicts slug flow where churn flow was observed in the experimental work. More data are necessary to improve the conclusion on flow patterns and this will be subject of further experiments.

The Average Relative Error (ARE), given by Eq. (5.1) with each experimental parameter (pressure drop or holdup), was used to compare the experimental data with predictions based on the drift-flux model. Two parameters were evaluated in this section: total pressure gradient and holdup ($1 - \alpha$).

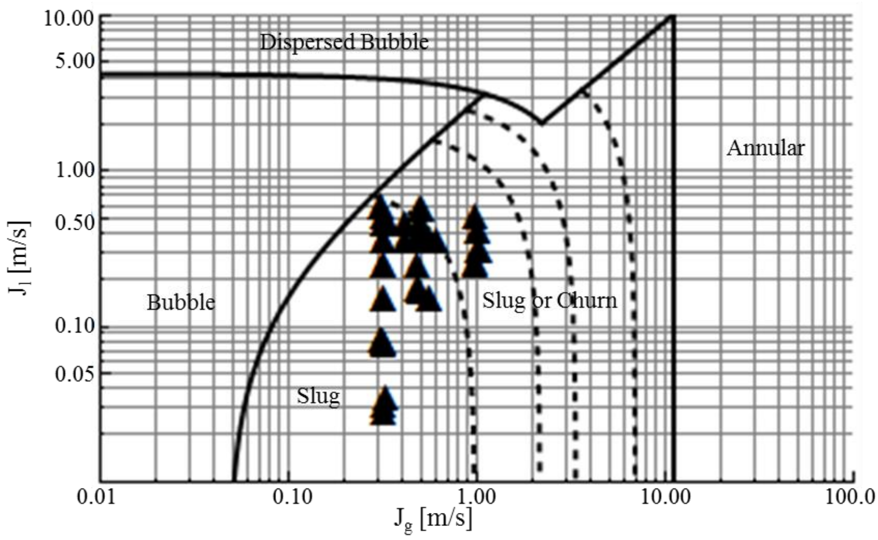

Figure 11. Experimental data (black triangles) acquired in the reference pipe setup plotted in a classical flow map of Taitel et al. (1980).

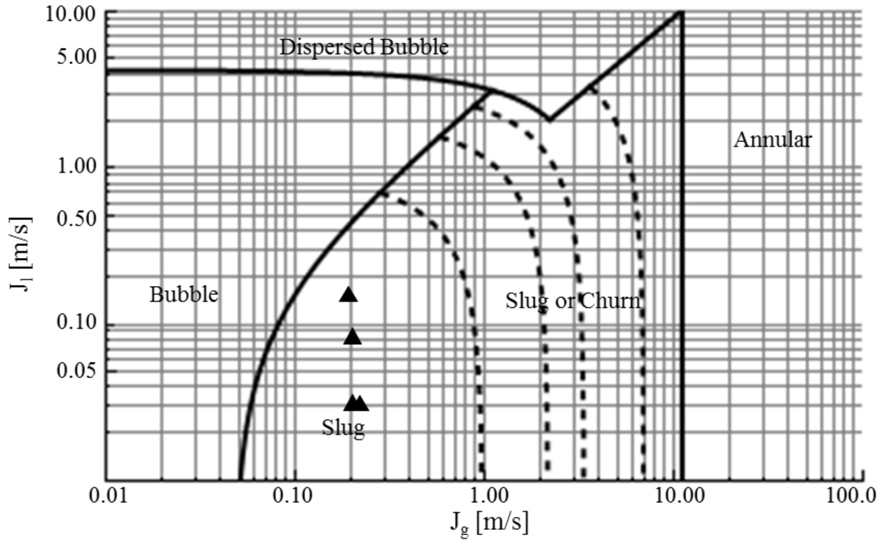

Figure 12. Experimental data acquired in the annular duct setup plotted in a classical flow map of Taitel et al. (1980).

The measured pressure drop and liquid holdup in the annular duct and reference pipe setups were compared with predictions of the drift-flux model using values of C_0 and $\tilde{V}_{gj}$ as suggested by Hibiki and Ishii (2003). These constants are appropriate for upward-vertical two-phase flow in big vertical tubes. A point spreading of ±10% and ARE of 4% were found for the reference pipe setup, when a comparison between the measured and predicted pressure drop was done (Fig. 13.a). The same was found when the experimental liquid holdup was compared to predictions (Fig. 13.b).

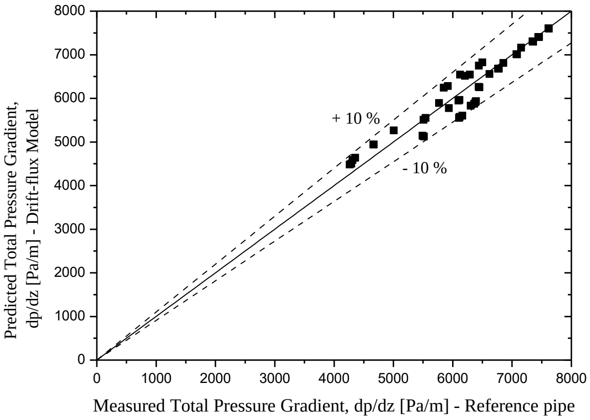

Figure 13.a. Slug flow model performance - total pressure gradient in the reference pipe setup

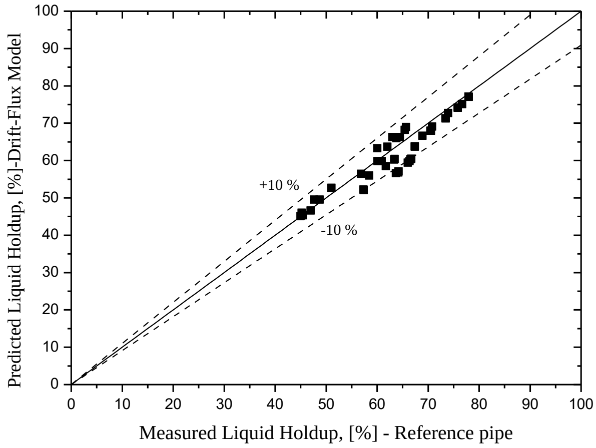

Figure 13.b. Slug flow model performance – liquid holdup ($1-\alpha$) in the reference pipe setup

However, a point spreading of ±20% was observed in the annular duct when the experimental pressure drop and liquid holdup were compared with predictions (Figs. 14.a and 14.b). An ARE of 13.8% (Tab. 2) was found in the annular duct when experimental pressure-drop and drift-flux predictions were compared. Almost the same was observed for the experimental liquid holdup and holdup predictions. All the predictions were done using the standard concept of hydraulic diameter. Other concepts of hydraulic diameter for two-phase flow will be subject of further study.

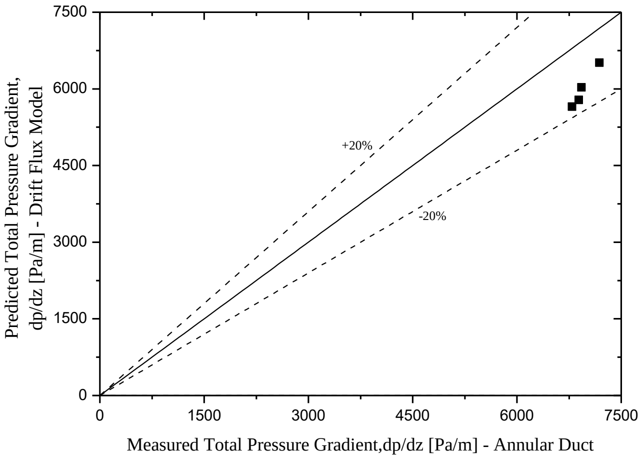

Figure 14.a. Comparison between measured total pressure gradient and drift-flux predictions in the annular duct.

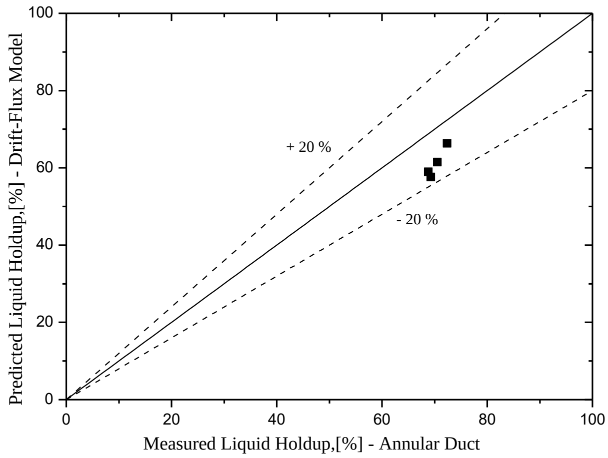

Figure 14.b. Comparison between measured liquid holdup (1-α) and drift-flux prediction in the annular duct.

Table 2. Average relative error in two-phase flow measurements.

Channel Geometry	dp/dz	$1-\alpha$
	ARE [%]	ARE [%]
Reference pipe, two-phase flow	3.9	4.4
Annular duct, two-phase flow	13.8	13.0

6. CONCLUSIONS

The results of the single-phase flow experiments in the reference pipe setup were compared with pipe correlations shown that the experimental setup is validated. The pressure drop measured in single-phase flow was in good agreement with predictions of a classical model (Darcy's Law), with average relative error (ARE) of 7%. The same was observed for single-phase flow in the annular duct setup where the predictions of pressure drop with Sas-Jaworsky and Reed's hydraulic diameter concept (Eq. 5.2) presented an ARE of 5.5%, however when the standard concept of hydraulic diameter was used, an ARE larger than 40% was found. It suggests that the standard hydraulic diameter concept (Eq. 5.1) is not appropriate to model the pressure drop in such geometry, not capturing all the effects present in annular-duct flows even in single-phase flow.

The liquid holdup and pressure drop measured in two-phase flow in the reference pipe had a quite good agreement with the drift-flux model predictions with parameters given by Hibiki and Ishii (2003). An ARE of 3.9% was found for pressure drop in two-phase flow in the reference pipe. A significantly higher ARE of 13.8% was found for pressure drop in two-phase flow in annular-duct flow. The respective liquid-holdup predictions presented similar average relative errors.

These results show that the pressure-drop and liquid-holdup predictions in the annular-duct flow are not as good as those observed in the reference-pipe flow. The higher error observed in the annular-duct-flow condition could be associated with the hydraulic diameter concept or the drift-flux parameters (void-fraction-weighted average drift velocity ($\tilde{V}_{gj}$) and the distribution parameter (C_0)). It is necessary to acquire more data, including Taylor-Bubble velocity in slug flow, for the development of new drift-flux parameters more suitable for annular-duct flow.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE