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EXPERIMENTAL STUDY OF GAS-LIQUID FLOW IN VERTICAL 180º NON-CIRCULAR RETURN BENDS

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Abstract. *Gas-liquid flows are commonly present in industrial processes. Also, the presence of bends is quite common in lines through which gas and liquid phases flow. However, until now there just a few works devoted to the observed phenomena of gas-liquid flow in such configuration. One of the major problems observed in bends in the presence of combined action of gravitational, centrifugal, and buoyancy forces. The force balance tends to produce complications such as the formation of stationary elongated bubbles in the curve. Also, the phenomena of stationary bubbles are observed in the impeller of centrifugal pumps when dealing with gas-liquid flows with high gas volume fractions. Therefore, this work presents an experimental analysis of gas-liquid flows through a vertical 180° Non-circular return bends. The study was carried out in a 180º curved duct of rectangular section, made of acrylic, with a diameter of 40 x 30 mm. The rectangular cross-section facilitates image acquisition. Compressed air, tap water, and mineral oil were the working fluids. Images of the stationary bubble were collected in a wide range of experimental tests. Data on liquid film thickness, elongated bubble length, and bubble diameter at the entrance, exit, and return to the system were collected. The data might be used to improve models to predict gas-liquid flow characteristics in bends and in other equipment where the centrifugal field is important as in centrifugal pumps.*

Keywords: *Two-phase flow, gas-liquid flow, 180° bend, elongated bubbles, film thickness.*

1. INTRODUCTION AND LITERATURE REVIEW

Two-phase flows have a significant number of applications and are commonly found in several industrial activities, among which are the chemical industry, the power generation industry, and the oil and gas industry. In the latter, the interest is focused on the presence of bends is quite common in lines through which gas and liquid phases flow, in a better understanding of changes in flow patterns and phenomena that occur inside vertical, horizontal, and inclined pipes, as well as equipment in the oil industry. Shoham, (2006)

One of the major problems observed in bends in the presence of combined action of centrifugal and buoyancy forces. The force balance tends to produce complications such as the formation of stationary elongated bubbles in the curve. Also, the phenomena of stationary bubbles are observed in the impeller of centrifugal pumps when dealing with gas-liquid flows with high gas volume fractions. Therefore, this work presents an experimental analysis of gas-liquid flows through a vertical 180° Non-circular return bends.

However, until now there just a few works devoted to the observed phenomena of gas-liquid flow in such configuration. USUI et al., (1980) carried out experiments regarding the flow behavior, the average void fraction, and the pressure drop of air-water two-phase flow that flows upwards through a C-shaped curve in the vertical plane. The curved test section of the transparent acrylic resin tube varied in four versions of (a) 90 mm, (b) 132.5 mm, and (c) 180 mm bend radii with a 16 mm inner diameter tube and (d) radius of 135 with 24 mm diameter tube. The combined action of gravity and the centrifugal force acting on the two-phase flow is expressed in terms of a modified Froude number that represents the balance of radial forces between those acting on the liquid and the gas phases of the flow that passes through the vertical reclined U curve. The average void fraction in the curved test section was determined and correlated empirically with the pressure drop, using a series of non-dimensional numbers.

Gardner and Neller, (1969) carried out a precursor work in the amount of the study of two-phase flows in curves using experimental studies of air-water flows applied in a 90-degree curve. In this way, the modified Froude number (Fr_θ) was noted by the authors to simulate the effect of competition between the centrifugal and gravitational forces along the curve. The modified Froude number (Fr_θ) is defined according to (1).

$$Fr_\theta = \frac{J_m^2}{Rg\sin\theta} \tag{1}$$

where $\boldsymbol{J_m}$ is the surface velocity of the mixture, $\boldsymbol{R}$ is the radius of curvature of the pipe, $\boldsymbol{g}$ is gravity and $\boldsymbol{\theta}$ is the angle is the angular position along the curve from horizontal.

Quantitatively, the flow is classified from the value calculated for the modified Froude number (Fr_θ), obtaining three types of classification. When:

- ✓ **Fr<1:** the gravitational force has a higher value and the gas phase flows through the outer region of the curve,
- ✓ **Fr=1:** both phases remain in radial equilibrium and tend to maintain their trajectories,
- ✓ **Fr>1:** the centrifugal force is greater and the liquid phase flows through the outside of the curve, that is, the gas phase will flow through the internal region of the curve.

The liquid and gas superficial velocities, J_{SL} and J_{SG}, are determined as the volumetric flow of the phase divided by the cross-sectional area of the tube, according to (2). Thus, J_{SL} and J_{SG} denote the average speed that each phase would have if it flowed alone in the pipe.

$$J_{SL}=\frac{q_L}{A_T}\ ;\ J_{SG}=\frac{q_G}{A_T} \tag{2}$$

The mixture velocity, J_M, is given by the sum of the superficial velocities of each phase, according to (3).

$$J_M = J_{SL} + J_{SG} \tag{3}$$

USUI et al., (1983) present the behavior of the flow and distribution of phases in the two-phase air-water flow around the inverted U curvature. In their work, experimental results are presented on the flow behavior, phases distribution, average void fraction, and slip ratio in the two-phase air-water flow. The curved test section was of 24 mm i.d. Using a riser, an inverted U-curve with a 96 mm radius being fed from below was analyzed. The local void fraction distributions were measured along a diameter located in the central plane of the curve and across the entire cross-section of the tube, such distribution mechanisms were denoted because of centrifugal and gravitational forces.

Hoang and Davis, (1984) carried out experimental observations of the flow structure and pressure gradient of water-air two-phase flow within 180-degree circular tube curves, with a radius of 25.4 mm and a central line radius of 50.8 mm and 76.2 mm. Within the curve, the pressure distributions observed reflected the onset of the effects of rotation and phase separation, while secondary flow effects were apparent in the void fraction distributions at the outlet.

Takemura et al., (1986) presented in his work experimental results on the flow behavior, pressure drop characteristics, and joule heating drying characteristics for the two-phase flow of water and gas through U-shaped tubes and inverted U in the vertical plane. The height of the straight vertical section of the test tube is 4100 mm and two radii of curvature, 116 mm and 435 mm, were chosen for the experiments. The test tubes used are made of transparent acrylic resin for the flow behavior test and stainless steel for the other tests, with an internal diameter of 18 mm in the first and 18.5 mm in the last. Being carried out under atmospheric pressure condition due to the valve opening at the top. On the other hand, during the experiments with helium in two-phase water-gas flow, the pressure in the separator was maintained at 16 bar by the pressure control valve. The main objectives of the study were the pressure drop between the inlet and outlet of the test tube for the two-phase flow is shown in comparison with that of the single-phase water flow.

Sakamoto et al. (2004) carried out experimental work in a horizontal 180º bend using air-water as the working fluid. The diameter and radius of curvature of the bend were 24 and 135 mm, respectively. They employed conductance probe void fraction measurement to analyze the liquid film thickness and an L-shaped stainless steel sampling tube to measure the local droplet flow rate. They reported the distributions of annular liquid film thickness and the local drop flow rate in the gas core in a straight pipe and at the end of three U-bends at horizontal to horizontal (upward), vertical upward, 45º upward to the horizontal positions. They claimed that the local flow rate of droplets in the gas core in horizontal pipe flow reaches a minimum near the lower wall of the pipe and a maximum near the upper wall.

A critical review of the literature, concerning liquid film thickness in bends, has revealed that the present state of understanding of liquid film thickness distribution in return bends is limited to two-phase gas-liquid flow in small diameter pipes with air-water as working fluids. On the matter of large diameter pipes, the only data that was reported in the work of Abdulkadir et al. (2012). In their work, an experimental investigation on the behavior of film fraction in a vertical 180º bend using air and water as working fluids was carried out. The diameter and radius of curvature of the bend are 127 and 381 mm, respectively. They carried out measurements of cross-sectional film fraction using conductance ring probes placed at 17 pipe diameters upstream of the bend, 45º, 90º, and 135º into the bends and 21 pipe diameters downstream of the bend. The probe was placed 17D upstream as a compromise between being a well-developed flow as far from the mixer as possible and not too close to the start of the bend. The same applies to the 21D on the outlet. The choice of the measurement locations is justified by the conclusions drawn by Golan and Stenning (1969). They reported that the effect of the bend on phase distribution disappeared by 10D downstream of the end of the bend for the inverted U-bend case. However, obtaining an estimation of liquid film thickness from film fraction data obtained from the conductance ring probe will lead to an oversimplification of the results. This is because using the film fraction results to obtain liquid film thickness will be based on the assumption of an ideal annular flow in which the liquid flows as a smooth thin film on the pipe wall with the gas in the center. The authors concluded that the average film fraction is higher in straight pipes than in bends. And that the condition for which the liquid goes to the outside or inside of the bend can be identified based on a modified form of Froude number, proposed by Oshinowo and Charles (1974).

Recently, Abdulkadir et al., (2014) made an experimental study of the behavior of air-water two-phase annular flow through a 180º vertical return curve using an electrical conductance technique to measure film thickness. The measurements were made using probes placed before, inside the curve (45º, 90º, 135º) and after the curve. The curve was made of transparent acrylic resin, with a diameter of 127 mm and a curvature ratio (R/D) of 3. The superficial velocity of the air and liquid varied from 3.5 to 16.1 m/s and from 0.02 to 0.2 m/s, respectively. The flow patterns were identified using the characteristic signatures of probability density function (PDF) graphs of the time series of the average fraction of the film. The study also found that, at low superficial air velocities, the film fraction for the riser was generally greater than for the downward flow. For low liquid and gas flow rates, the film breaks at the 45º curve due to gravity drainage.

This work has the main objective to experimentally analyze gas-liquid flows in 180° vertical bends to analyze the flow structure at this point and the influence of liquid viscosity in the bubble shape, liquid film thickness, etc. In this way, the formation of an elongated bubble present in most of the experiments carried out is presented. The formation of the elongated bubble resulted in a region with no bubble development, where we can observe smaller bubbles adhering to the larger bubble. Furthermore, at the exit of the duct, we can appreciate the formation of liquid film and bubbles being dragged out of the system, which generates a recirculation process. Undeniably, a correct forecast of this type of flow is essential for the design of adequate piping projects and phase separation equipment, as mentioned above.

2. EXPERIMENTAL SETUP

The study was carried out in a 180º curved duct of 40 x 30 mm rectangular section, made of acrylic, to obtain results that can be simulated, evaluated, and validated with existing models or empirical correlations from the literature. The complete scheme of the experimental apparatus can be seen in Figure 1. The green line represents the gas phase, the blue line the liquid phase (oil or water) and the red one is the mixture.

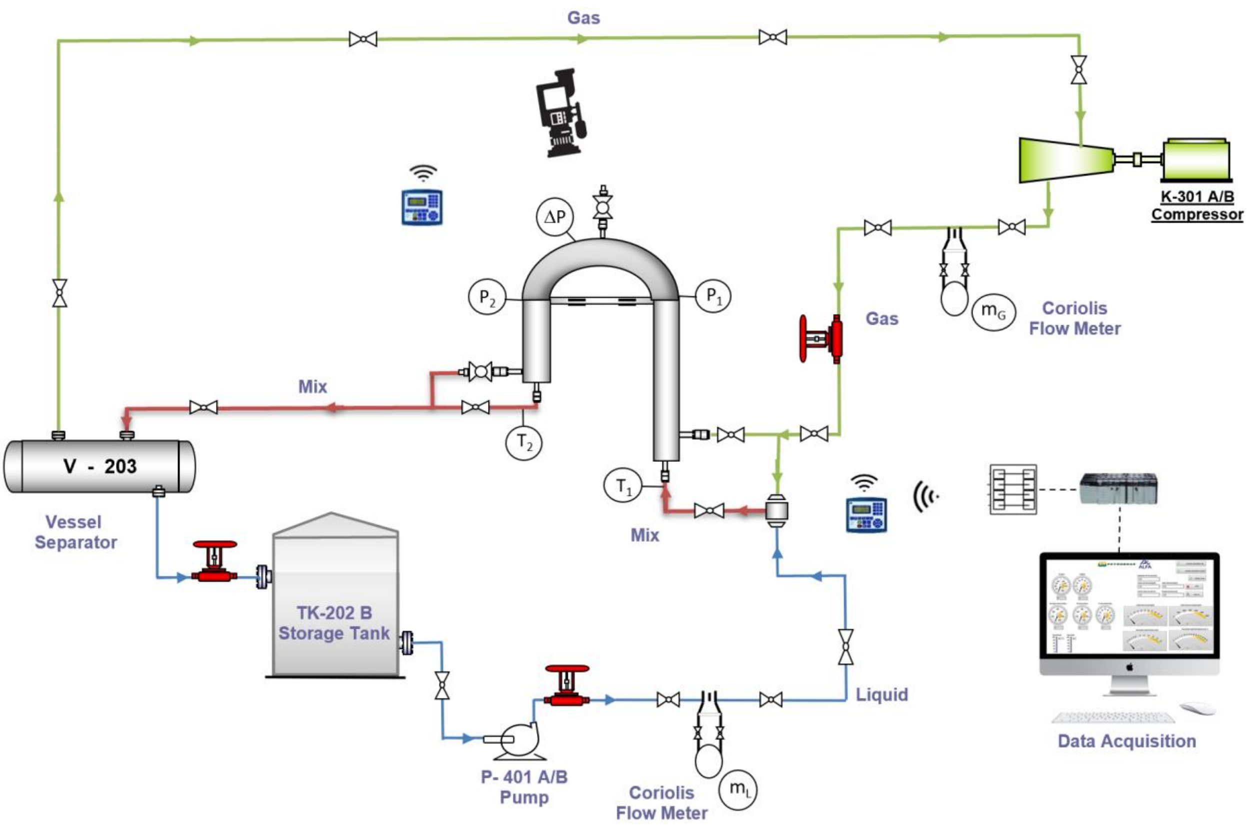

Figure 1. Experimental setup sketch of the curved duct.

The experiment is a closed circuit for liquid circulation and gas injection to build a mixture of two different fluids (Water-Air and Oil-Air). The apparatus consists of a liquid tank, also used as the gas-liquid separator, a gear pump for Water/Oil, and a compressor for the gas phase. Variable speed driver controls pump frequency, Coriolis flowmeters are used for gas and liquid flow measurement, pressure and temperature transducers are used to correct gas and liquid phases properties, a data acquisition system with LabVIEW based software were used for experimental das acquisition. Tap water, compressed air, and mineral oil (19 cP) were the working fluids.

During the experimental rounds, pressure variation from 0.2 to 2 bar was used, with gas mass flow rates ranging from 0.05 to 5.5 kg/h and liquid mass flow rates between 200 to 2540 kg/h. The measurements were made at room temperature (approximately 24 ºC) and with an average fluid temperature of 26 °C.

During multiphase flow experiments, as the phenomena were quite slow, a high-definition camera was used to film the flow for post-analysis of the different observed flow patterns, and also characteristics of the liquid film, elongated bubble, and bubbles diameter.

3. RESULTS

In total, 340 experimental tests were performed using two different two-phase mixtures (Oil-Air and Water-Air). The data were analyzed in two phases for both cases: image treatment and analytically. In the first part, the phenomenology that happened in the curved duct was observed. From the total of the tests mentioned, four different conditions were observed: I) elongated bubble formation for Oil-air, II) elongated bubble formation for Water-air, III) no elongated bubble formation for Oil-air, and IV) non-formation elongated bubble for water-air. And for the cases that had a bubble formation measurements of film thickness and bubble shape were done.

In the second case, the average values of all tests were calculated individually from the data acquired by the Labview laboratory software, and with these average values, it was possible to calculate other variables that allowed a better understanding of phenomenology and some possible relationships and trends in parameters used.

Figure 2 and Figure 3 show the elongated bubble formation in the curvature of the tube through the time for some experiments for both water-air and oil-air cases, respectively.

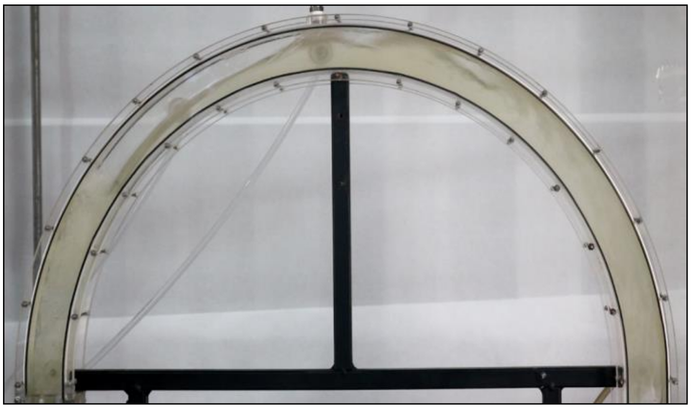

Figure 2. Air-Water flow through vertical 180° bend and stationary elongated bubble formation.

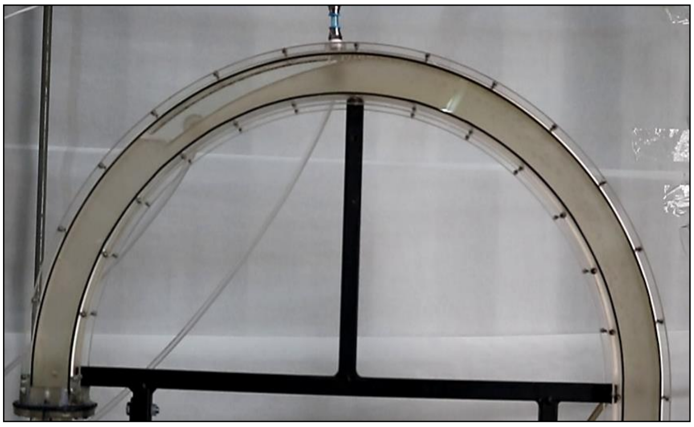

Figure 3. Air-Oil flow through vertical 180° bend and stationary elongated bubble formation.

In the cases where the stationary elongated bubble was observed the time evolution of the bubble was acquired and the liquid film thickness, the characteristics of the elongated bubbles as the point of start and end, and gas bubbles at the entrance and exit of the pipe were measured. It was observed that the characteristics of the bubble are a function of the Froude and Reynolds mixture numbers.

Furthermore, this gas bubble occupies a significant portion of the curved duct, in the area of the curve. Restricting the area available for the flow of liquid. The gas-liquid interface of this gaseous structure is deformable and presents some instability when the liquid continues to flow below the bubble through the liquid film.

There is also a region of intense recirculation downstream of the stationary bubble. This region is characterized by an accumulation of small bubbles that come off the larger structure around the end of the stationary bubble.

According to Estevam (2002) working with centrifugal pumps, when the coalescence of bubbles occurs, a larger bubble begins to originate, generating two regions in the channel: one composed of the air bubble and the other of the liquid film that continues to flow into the remaining space of the channel. A drag force acts on this bubble that seeks to move along the channel, a centrifugal force, of low intensity due to the low density of the air, which accelerates the liquid film more than the air bubble, and a force of centrifugal thrust that tends to hinder the displacement of this bubble. When the balance between the drag force and the centrifugal thrust occurs, this bubble will be stationary within the channel. Associated with this, the acceleration of the liquid film will remove small air bubbles from this stationary bubble, which, depending on their diameters, will flow out of the channel or will be retained, forming a mixing region. In terms of flow regime, there will be a region in the channel with the stratified flow and another with the flow in dispersed bubbles.

The thickness of the liquid film was also found through images with values ranging from 3 to 28 mm for the Oil-Air case and values from 2 to 31 mm for the Water-Air case. The beginning and end of the bubbles are a function of the liquid and gas superficial velocity. Also, differences were observed in the film thickness, elongated bubble characteristics, and bubbles diameters as a function of the liquid viscosity. Finally, the mixture region at the tail of the bubble presents different behavior when oil or water is the liquid phase, being more turbulent and with smaller bubbles with the last case.

In all experiments the gas phase, lighter phase flow through the external region of the duct showing that. In the observed cases, the buoyancy effect is higher than the centrifugal forces.

Other analyses, results, and discussions for the experiments will be presented in further works.

4. CONCLUSIONS

Air-water and air-oil two-phase flows in 180° vertical return bends were experimentally observed. The presence of an elongated stationary bubble was observed in several pairs of air and liquid superficial velocities. Data on liquid film thickness, elongated bubble characteristics, and bubble diameters were acquired.

The data might be used for the improvement of gas-liquid models in curves and for the analysis of gas-liquid flows where centrifugal fields are present.

It was noted that the formation of the stationary elongated bubble occurred mostly at low gas flows in the bubble pattern, for the different flows. In oil-air experiments, superficial velocities are higher than in water-air for bubble formation. This fact can be related to the viscosity of the oil, which ends up generating some resistance to flow requiring higher inertia in the formation of the elongated bubble. Also, as it presents higher liquid superficial velocities, the time for the formation of the complete bubble is shorter in oil-air experiments than in water-air experiments.

The formation of the bubble will depend on: (i) the intensity of the centrifugal field acting on the channel; (ii) the size of the discrete bubble of gas entering the channel; (iii) operational variables (liquid flow, temperature, pressure and void fraction), and (iv) fluid properties (surface tension, viscosity, and density of the liquid). The formation depends on the values of these variables and the relationship between the forces acting in the phases.

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