Characteristics of air-water vertical two-phase flow across a sudden expansion

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Abstract. *The pressure loss and void fraction changes of an air-water flow in a vertical pipe with a sudden area expansion have been investigated experimentally. The expansion is defined when the two-phase flow passes from a 13 to a 19.5 mm pipe. Pressure was measured in 15 upstream and 17 downstream stations through a series of pressure taps. In addition electro-resistivity probes were used to measure void fraction at 27 different locations. The experiments were aimed at analysing the transitions flow patterns and the void fraction increase as the flow passes the sudden expansion section. The sudden increase was followed downstream by a gradual relaxation to a fully developed value further downstream.*

Keywords. *Vertical two-phase flow, sudden expansion, resistivity probes, transition flow patterns, measurements, air-water mixture.*

1. Introduction

Two-phase air-water flows in vertical pipes are a common occurrence in technology. In fact, many industrial processes and equipment including chemical reactors, power generation units, oil wells and pipelines operate with two-phase mixtures. Of course, depending on the gas-liquid interactions resulting from the complex interactions that take place as a function of the flow rates, of the physical properties of the mixture constituents and of the pipe characteristics, different flow configurations may arise.

Classical textbooks frequently identify five different flow patterns for vertical upwards co-current flows. These are: bubbly, slug, churn, wispy annular and annular flows. Very often, these phases are very difficult to distinguish through naked eye due to, for example, the high velocities present in the flow, reflection and refraction at multiple interfaces, break up of coalescence of phases, and so on. More than that, since the distinction between two different flow patterns is sometimes very subjective, various possible denominations could, in fact, be given to a certain phase distribution. This is a great complicating factor for the analysis of two-phase flows since physical and mathematical models are often developed for a known flow pattern. Thus, if one is to understand the basic behavior of a two-phase flow, an important entry datum is the characteristic flow pattern. Only then any momentum or heat transfer model can be developed.

Clearly, all above mentioned difficulties are further aggravated for flows that develop subjected to sharp accidents (see e.g. Schmidt and Friedel (1997), Bertola (2003), Ahmed at al. (2003, 2004)). The purpose of the present work is to investigate the changes in properties of a two-dimensional flow that undergoes a sharp expansion in pipe diameter. Of particular interest of the research is the assessment of occurring changes in the liquid holdup and in the pressure drops as a function of the increase in flow area. Thus, the present work will present experimentally determined parameters for a vertical two phase flow in a pipe with a sudden expansion. The parameters are the pressure loss and the void fraction changes. Special emphasis is placed on identifying the transitions flow patterns as a function of local parameters.

Patrick and Swanson (1959) were apparently the first to address this problem. They conducted an experimental investigation of an air-water system to obtain information on the effect of expansion and contraction of flow area on the relative velocities of the two phases. They found that the relative velocity and therefore the mean void fraction of the mixture changed following either an expansion or a contraction. The order of magnitude of the change, however, was not great and could be predicted by a semi-theoretical equation. The phase distribution was obtained by the use of a radiation attenuation traversing technique.

Two-phase flow for a vertical bubbly flow in a pipe with a sudden expansion was studied by Rinne and Loth (1996). Using fiber-optic probes, the local void fraction, bubble velocity, bubble frequency, bubble chord length and size, and local interfacial area concentration were determined in a pipe with a sudden expansion from a 40 mm to a 90 mm diameter. The main concern of the authors was the determination of the local interfacial area concentration, the ratio of the total surface area of all bubbles in a reference volume to the size of that volume. Different bubble shapes were used to evaluate the surface area. The calculated distribution of bubble sizes depended on the chord length resulting from the product of measured bubble velocity and bubble residence time at the probe tip.

The changes in void fraction in pipes with a sudden contraction were experimentally studied by Fossa and Guglielmini (1998). The experiments, however, were conducted for a horizontal pipe. To find the void fraction, the instantaneous measurements of the electrical impedance of an air-water mixture was made. The instrumentation consisted of basically two ring electrode pairs set on the internal wall of the pipe. Plug and slug flow regimes were investigated. Measurements were taken at five different stations.

Hibiki et al. (2004) discussed the structure of downward bubbly flows in vertical pipes. The authors proposed an approximate radial phase distribution pattern map based on available data of some flow parameters such as void fraction, interfacial area concentration, interfacial velocity and bubble Sauter mean diameter. The one-dimensional drift-flux model for a downward two-phase flow and the correlation of the interfacial area concentration were compared with the downward flow data.

2. The expression of Petrick and Swanson

Petrick and Swanson (1959) showed that the relative velocity and hence the mean void fraction of an air and water mixture change following an expansion. Fhurthermore, these authors proposed a semi-theoretical expression through which the flow changes could be predicted.

For a two-phase mixture, the liquid phase velocity, (also known as the 'slip ratio') can be written in terms of the mass quality and the void fraction as

$$\frac{u_g}{u_f} = \frac{x}{1-x}\frac{1-a}{a}\frac{r_f}{r_g} \tag{1}$$

For an adiabatic system, where the quality is a constant, the void fraction will only change if the slip ratio changes. Considering that the flow undergoes a sudden change in pipe area, then, the following relation holds

$$\frac{a_1}{1-a_1}\frac{1-a_2}{a_2} = \frac{x_1}{1-x_1}\frac{1-x_2}{x_2}\frac{r_{f1}}{r_{g1}}\frac{r_{g2}}{r_{f2}}\frac{u_{f1}}{u_{g1}}\frac{u_{g2}}{u_{f2}} \tag{2}$$

With the postulation of an adiabatic system, $x_1 = x_2$ and $r f_1 = r f_2$, so that it results

$$\frac{a_1}{1-a_1}\frac{1-a_2}{a_2} = \frac{r_{g2}}{r_{g1}}\frac{u_{f1}}{u_{g1}}\frac{u_{g2}}{u_{f2}} \tag{3}$$

Petrick and Swanson then took

$$\frac{u_g}{u_f} = K u_{wo}^N \tag{4}$$

But,

$$W = u_{wo} A r, \quad u_{wo} = \frac{W}{A r} = \frac{k'''}{A} \tag{5}$$

The result is that slip ratio can be evaluated from

$$\frac{u_g}{u_f} = \frac{K'''}{A^N} \tag{6}$$

$$\frac{1}{r} = \frac{RT}{PM} \tag{7}$$

so that

$$r_g = K'P \tag{8}$$

Substitution of Eqs. (6) and (8) into Equation (3), gives

$$a_2 = \frac{1}{\left(\frac{P_2}{P_1}\right)\left(\frac{A_1}{A_2}\right)^N \left[\frac{1-a_1}{a_1}\right]+1} \tag{9}$$

where N has to be determined experimentally.

In their experiment, Petrick and Swanson found $N = 0.2$. The static pressure ratio had to be included because of the large changes in specific volumes of the gas phase at lower pressures.

3. Experimental setup

The experimental setup will be described next.

The test loop consisted of two acrylic pipes with 13 and 19.5 mm internal diameter and lengths of 90 and 90 mm respectively. These diameters were chosen so as to keep the experiment within a laboratory scale.

The test section was designed so as to submit the flow to a sudden expansion or to a sudden contraction.

At its present configuration, the loop only operates for upward two-phase flow experiments. The air supply was provided by a compressor fitted with a pressure regulating valve. The water was supplied by a regular centrifugal pump fitted with a settling chamber to avoid flow intermittence. The supplied air and water were introduced into the test section through an injection unit. A 2 mm diameter pipe with multiple holes set across de pipe diameter served as the bubble generator. The liquid and air flow rates were measured with two rotameters. Figure 1 shows an actual photograph of the rig. The general experimental set up in show in Figure 2.

Figure 1. Experimental Setup.

4. Instrumentation

Electro-resistivity sensors built from small needles were simultaneously developed by Neal and Bankoff (1963) and by Nassos (1963). In these studies, almost all efforts were dedicated to the development of the experimental technique rather than to the investigation on the nature of some particular type of flow. Neal and Bankoff used a Nitrogen-Mercury system, whereas Nassos carried out measurements in an air-water system. Chesters et al. (1980) were the first to employ the resistivity technique in gas-liquid non-confined flows with a certain degree of success. The authors used electro-resistivity sensors together with laser-Doppler anemometry to describe the characteristics of the liquid and of the gas phases in a bubble plume.

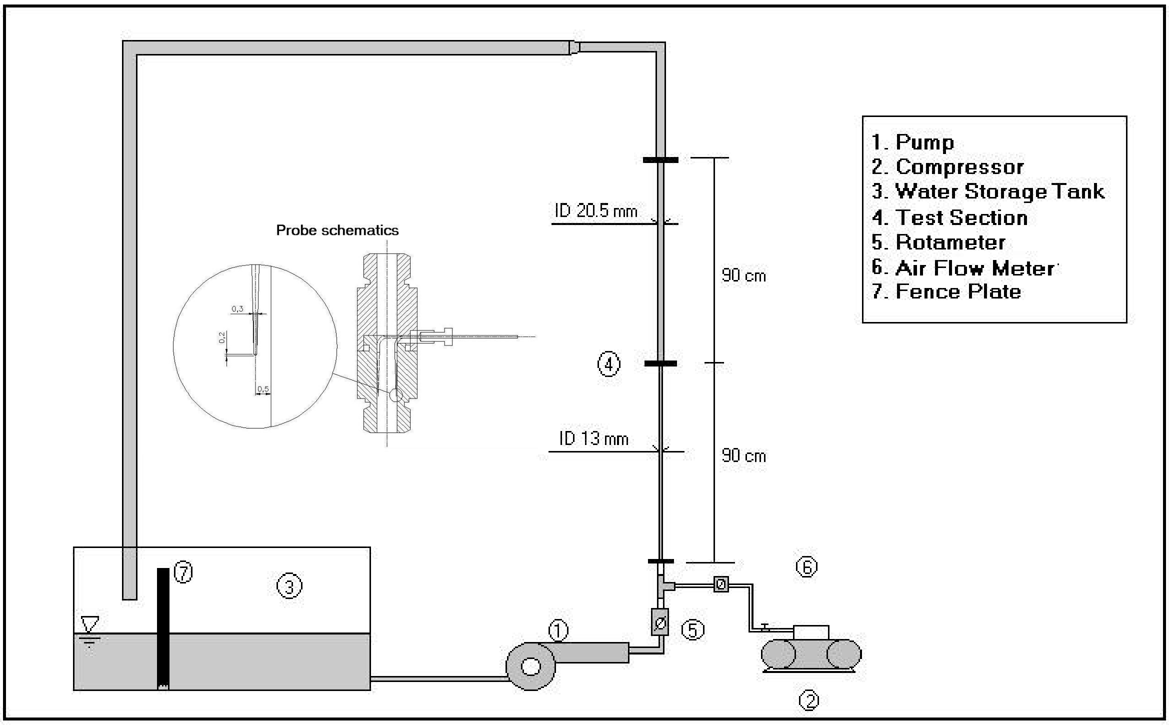


Figure 2. Experimental rig.

Tacke et al. (1985), studying gas stirred steel making processes, used the electro-resistivity sensor technique to make some measurements of the gas phase properties in air-water, Helium-water and Nitrogen-Mercury systems. Castillejos and Brimacombe (1975), also aiming at the application of the bubble plume phenomenon in the steel making industry, developed a comprehensive instrumentation based on the resistivity technique to investigate the problem. In 1988, Teyssedou et al. presented a new AC probe system, together with an analysis of the effect of the geometry of the sensor tip and of other parameters on the performance of the system. More recently, Kocamustafaogullari and Wang (1991), Leung et al.(1992) and Liu and Bankoff (1993) used resistivity sensors to determine local time-averaged mean gas fraction, interfacial area concentration, bubble rise velocity and bubble pierced length in internal bubbly flows.

The working principle of the experimental technique is based on the difference between the electrical conductivity (resistivity) of the phases. Since the electrical conductivity of water is much higher than that of air, it is assumed, for practical purposes, that only the continuous phase (liquid) is capable of conducting electrical current. Accordingly to Herringe and Davis (1974), resistivity sensors are the most suitable technique for measurements in two-phase mixtures where the continuous phase is conductive. The main adversity of the technique is the existence of an in-stream sensor, which affects the structure of the flow.

In a double channel system (whether AC or DC supply), the difference in electrical resistivity between the phases can be sensed by the electrodes in the two-phase flow so that parameters like the local time-averaged mean gas fraction, the rise velocity and the pierced length of bubbles can be obtained through an analysis of the output signal.

The measuring system used in this work has been fully described in Barbosa and Bradbury (1996) and in Barbosa (1997); for any detailed information on the system the reader is, therefore, referred to those works. Next we will just briefly comment on the features of the probes.

Co-axial probes were chosen to be used here. In fact, due to its symmetric geometry, the co-axial probe interference on the flow is recognized as being weaker than that of a parallel probe of nearly equal dimensions. The measuring probes were constructed with the following features: i) 0.2 mm diameter stainless steel internal wire (upstream electrode); ii) 0.4 mm OD and 0.2 mm ID hypodermic tubing (downstream electrode); iii) length of electrodes free of insulation equal to 0.1 mm; and iv) distance between electrodes equal to 1.5 ± 0.15 mm.

The data acquisition and analysis system consisted of a microcomputer with an interface data acquisition board, an oscilloscope, a signal conditioner module and the electro-resistivity probes.

The mean gas fraction at a point in the flow is a time-averaged property given by,

$$f(r,x) = \frac{1}{T}\int_0^T I(r,x,t)\,dt \tag{10}$$

where T is the total sampling time, I is the digital output signal from the conditioning module and r and x are the co-ordinates. The output signal, I, consists of a series of pulses which correspond to the transit of bubbles through the probe. Further details concerning the output signal, I, are available in Barbosa and Bradbury (1996) and in Barbosa (1997).

The data were acquired at a sampling rate of approximately 2.5 kHz and about 50 sampling blocks of 10,000 readings (Barbosa and Bradbury (1996), Barbosa (1997)) were shown to be sufficient to describe the flow at each measured point. In fact, in Barbosa (1997), the shape, size and velocity of the ris ing bubbles was detailed studied; also, the influence of the injection geometry on plume development and the existence of any lateral wandering motion of the plume were investigated.

The probe calibration was carried out in a vertical pipe with 30 mm diameter and 1000 mm length. After the pipe had been filled with water taken from the tank and the probe had been placed in position, a large bubble was carefully introduced at its bottom through a syringe. As the bubble raised and hit the probe, the recordings from a Panasonic video camera were digitalized and analyzed. The pictures which were taken at a frequency of 60 frames per second were then compared with the signal of the conditioning module. The resistance of the flow in the conditioning module was then set so as to furnish the same response in both systems.

An uncertainty analysis of the data was performed according to the procedure described in Kline (1985). Typically the uncertainty associated with the mean gas fraction measurements was: f = 0.00035 precision, 0 bias (P=0.95).

5. Measurements

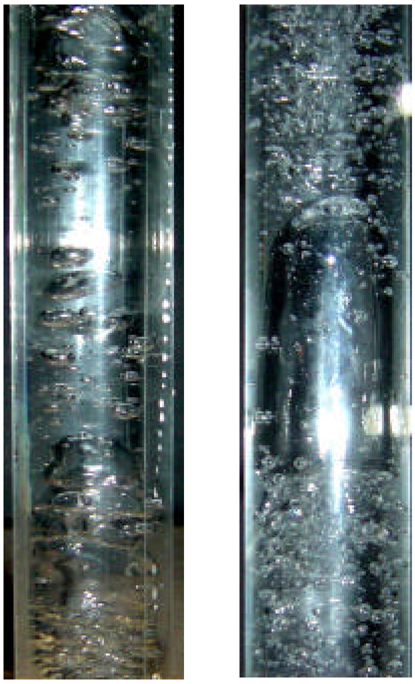
Before quantitative measurements were made, a flow visualization study was performed. For the experiment conditions, the liquid and the gas flow rates were fixed at 6 l/min (10 10^{-5} m^3/s) and 2 l/min (3.3 10^{-5} m^3/s) respectively. Table 1 indicates the experimental conditions.

Table 1. Volumetric flux.

Volumetric flux	J_g (gas) (m/s)	J_l (liquid) (m/s)
Upstream expansion, ID = 13 mm	0.248	0.7518
Downstream expansion, ID = 19 mm	0.1166	0.3498

For the flow conditions considered here, the flow was observed to pass from bubbly to churn flow after the abrupt change in pipe diameter.

Figure 3 illustrates the flow pattern.



(a) (b)

Figure 3. Flow pattern. (a) Bubbly flow, (b) slug flow.

The void fraction distribution was measured in 27 different stations, 8 upstream of the sudden expansion, the other 19 stations downstream of the sudden change. The actual position of the measuring stations will become clear in next figures.

Local void fraction distributions for different measuring stations are presented in Figs. 4 and 5 for two upstream stations and four downstream stations.

As the flow approaches the sudden expansion, the void fraction is observed to increase. As noted by other authors, this is indicative that of an increase in slip due to the reduction in pressure gradient as the flow approaches the sudden expansion. The graphs also show that the increase in void fraction is followed by a gradual decrease towards a constant value.

Far upstream of the sudden change (z = -788 *mm*), the void fraction shows a parabolic distribution. Close to the change, at station (z = -138 *mm*) the void fraction profile assumes a flatter a shape.

All the downstream void fraction profile exhibits a top-hat profile, with this shape becoming more pronounced for higer values of *z*.

The variation of void fraction with section length is show in Fig. 6. The variation in void fraction is obtained through a numeric integration of the void fraction profiles. The pressure distribution is show nest in Fig.7.

Petrick and Swanson (1959) have observed that shortly downstream of an expansion, a sharp increase in void fraction may occur. Still, according to these authors this is due to the formation of a jet over the few inches past the transition and to the creation of air pockets. The jet then dissipates into a very turbulent region, after which a regular pattern is established. The severity of the jet effects were identified with the mixture quality, fluid velocity and area enlargement. For expansions with a small area enlargement, low fluid velocities and mixture quality, severe transition regions were not observed. Thus, given the conditions of the present experiment, Fig. 6 seems to be coherent: no sharp zone of flow transition was observed and a region of stablished flow ($a \cong 0.52$) pattern was observed.

The changes in pressure along the measuring section were almost due to the hydrostatic effects.

The predicted value of a_2 according to Eq. 8 is 0.44. This furnishes a value of 0.41 for the slip ratio. However, we see from Fig. 6 that the actual value of a_2 is 0.53. That results in a value for the slip velocity of 0.29. These results are summarized in Table2.

The implication is that for present findings, N = 0.7, a value much higher than the one found by Petrick and Swanson (1959).

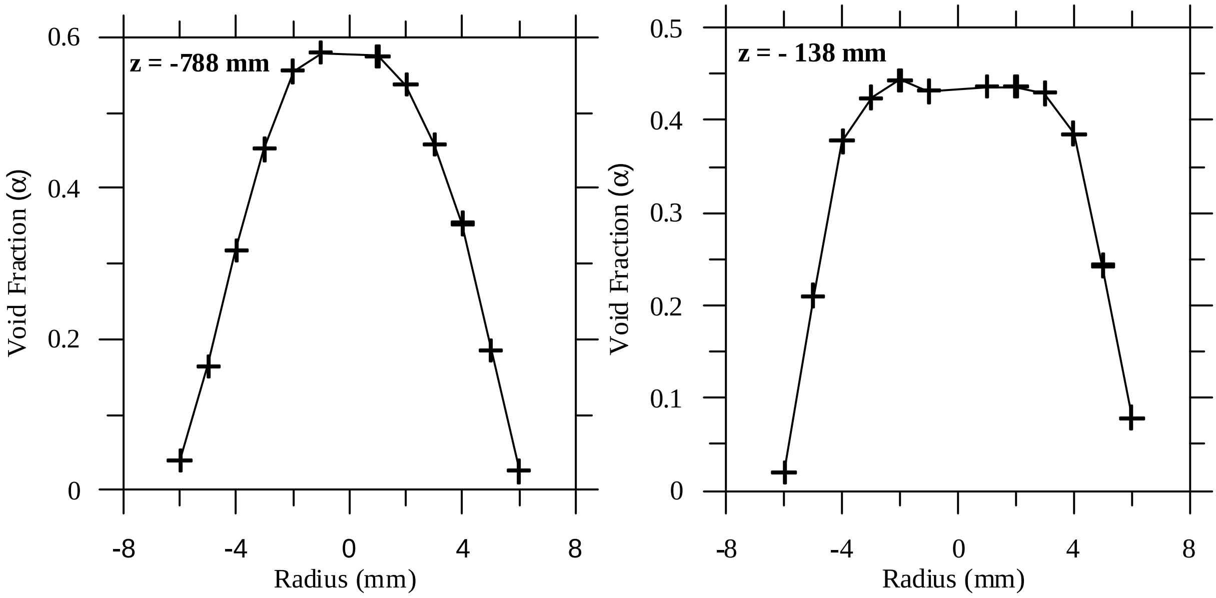


Figure 4. Local void fraction profiles upstream of sudden change in diameter.

Table 2. Slip ratio.

Pipe	a (measured)	Slip ratio	a (Petrick and Swanson)	Slip ratio
Upstream expansion, ID = 13 mm	0.4	0.49	---	---
Downstream expansion, ID = 19 mm	---	---	0.44	0.41
Downstream expansion, ID = 19 mm	0.53	0.29	---	---

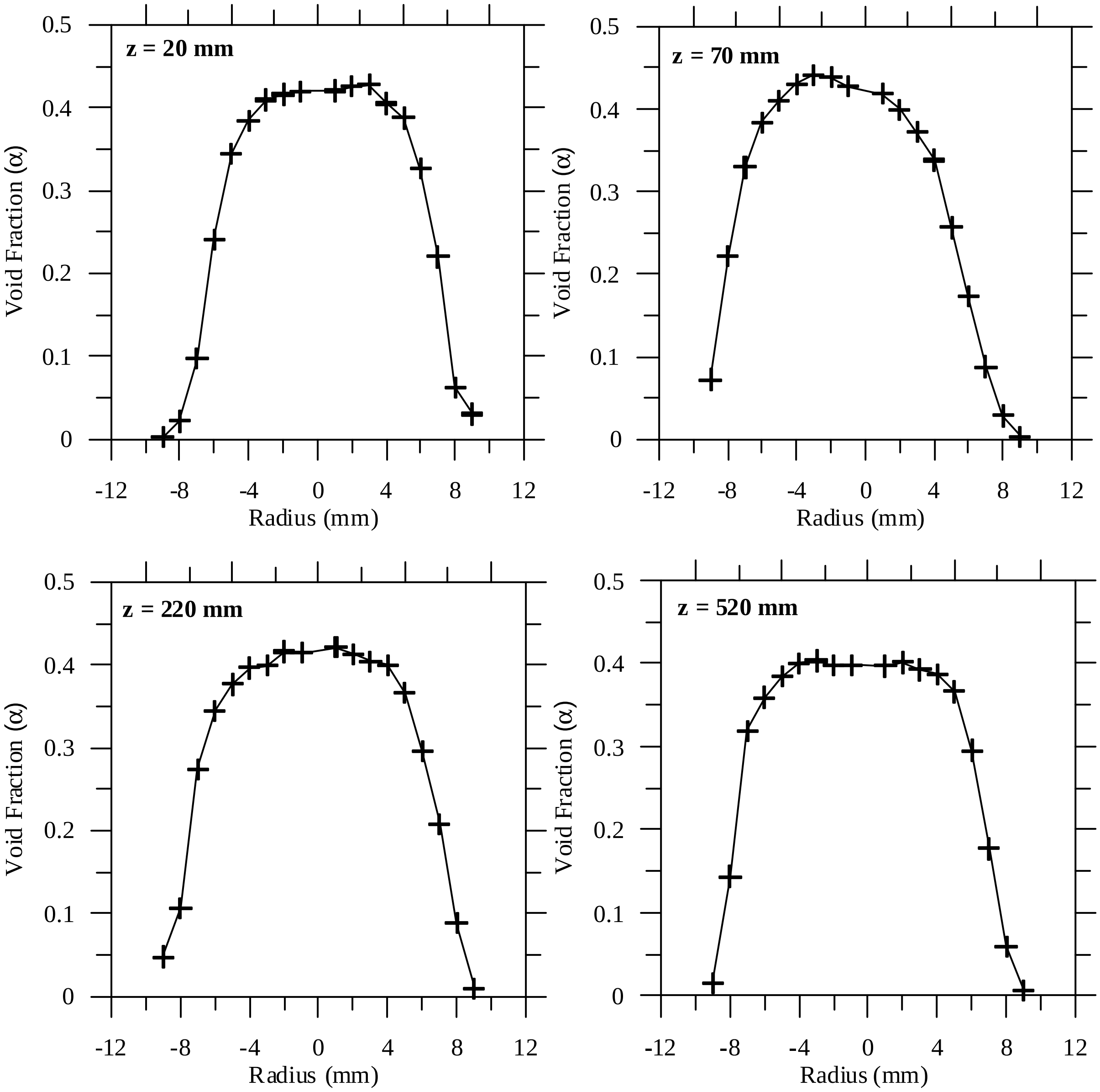


Figure 5. Local void fraction profiles downstream of sudden change in diameter.

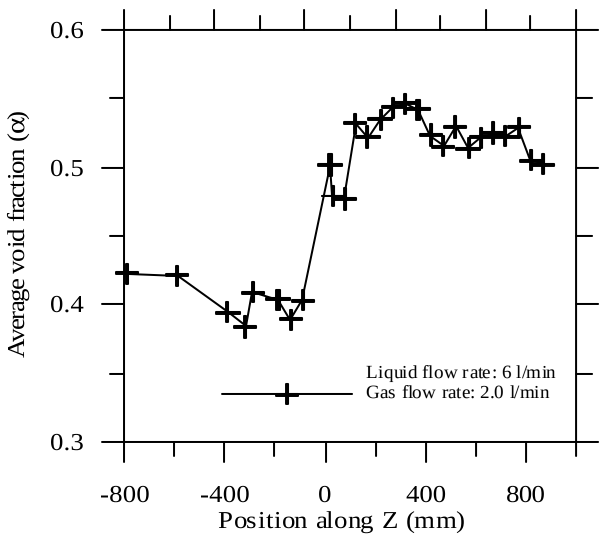


Figure 6. Void fraction variation with section length.

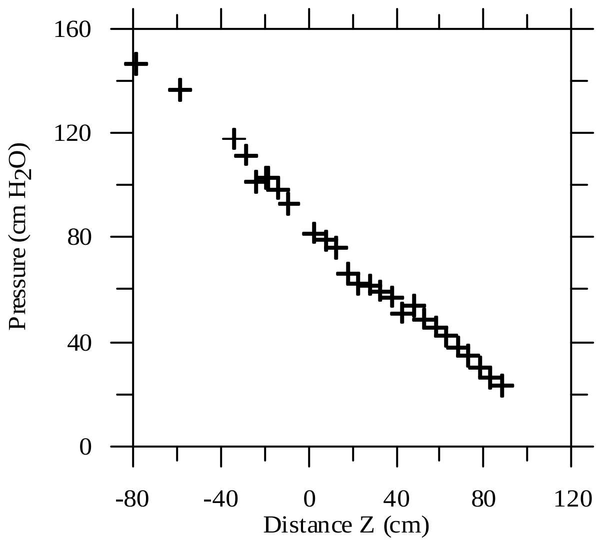


Figure 7. Pressure distribution.

6. Final remarks

The pressure loss and void fraction changes of air-water flow in a vertical pipe with a sudden area expansion have been investigated experimentally. The expansion is defined when the two-phase flow passes from a 13 mm to a 19.5 pipe. Pressure was measured in 15 upstream and 17 downstream stations through a series of pressure taps. In addition electro-resistivity probes were used to measure void fraction in 27 different locations. The experiments were aimed at analysing the transitions flow patterns and the void fraction decrease as the flow passes the sudden expansion section. The sudden increase was followed downstream by a gradual relaxation to a fully developed value further downstream. Upstream values of the void fraction were observed be about 0.4; downstream values were of0.53. The downstream value predicted by the correlation of Petrick and Swanson (1959) for the void fraction was 0.44. Thus according to the present analysis, the power coefficient of Petrick and Swanson (1959), *N*, was found to be $N = 0.7$, a value much higher than the 0.2 that is quoted by those authors.

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Nomeclature

A	Cross-sectional flow area
ID	Internal diameter [mm]
u	Fluid velocity [m/s]
α	Void fraction
χ	Mixture quality, ratio of massflow of gas to total mass flow rate of both phases.
W	Flow rate, [Kg/s]
T	Absolute temperature, ^{O}R
P	Pressuere, [N/m^2]
M	Molecular weight
N	Expoent in Equation (4)
ρ	Fluid density, [Kg/m^3]

Subscripts

f	Liquid phase
g	gaseous phase
w_0	Liquid phase flowing alone in conduit
1,2	Position

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