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POLISH ACADEMY OF SCIENCES

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

118

WYDAWNICTWO IMP PAN

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ISSN 0079-3205

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 118, 2006, 3-14

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Local void fraction and liquid turbulence measurements of two-phase flow downstream of a sudden expansion

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Abstract

The flow structure of horizontal air-oil two-phase flow downstream of a sudden area expansion has been experimentally investigated using hot-film anemometry. The time averaged local profiles of the void fraction, mean liquid velocity and the liquid turbulence intensity for elongated bubble flow downstream of the expansion are presented in this paper. The development of the flow pattern downstream of the expansion was investigated using direct observations of the flow using a high speed video camera. The sudden expansion was found to have a strong effect on the phase redistribution immediately downstream of the expansion. However, the "fully developed" flow regime and void fraction are found to be dependent only on the downstream flow parameters.

Keywords: Two-phase flow; Sudden expansion; Void fraction; Turbulence

1 Introduction

Two-phase flow commonly occurs in many engineering applications, such as heat exchangers, steam generators, chemical reactors, oil transportation and many processing equipment. In all these systems, the two-phase flow can occur in complex geometries such as sudden area changes, orifices, bends and valves under a variety of different flow conditions. In order to design such systems, it is important to understand the effect of these piping components on the two-phase flow parameters such as pressure, void fraction and flow pattern. While there have been a large number of studies on gas-liquid flows in constant area pipes, there

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are limited studies on two-phase flow across sudden area expansions [1-8]. Most previous experimental investigations have focused on vertical bubbly flow [1-3]. There are fewer experimental investigations for two-phase flow across horizontal sudden expansions [4-7]. Aloui and Souhar [4, 5] reported experimental data for bubbly flow over a horizontal flat channel with a sudden expansion as an application to plate heat exchangers. The experiments were performed at relatively low mass qualities and no information on the change in the flow pattern were reported. An attempt was made to incorporate interfacial transfer terms, such as the interfacial drag, according to the flow regime, but the flow pattern transition across the sudden expansion section was not considered. More recently, Yang et al. [6] and Ahmed et al. [7] reported the flow pattern changes downstream of a sudden area expansion. In these studies, the flow pattern transitions immediately downstream of the sudden expansion was found to depend on the upstream flow pattern and the expansion area ratio. The flow in this developing region strongly influences the pressure recovery across the sudden expansion [8]

The objective of this study is to investigate the development of the two-phase flow parameters downstream of a sudden expansion. In particular, the flow pattern, local void fraction distribution and liquid velocity and turbulence intensity downstream of the expansion are investigated. In this paper, experimental results for the local void fraction, liquid velocity and turbulence intensity downstream of a horizontal sudden area expansion are presented and discussed.

2 Experimental facilities

The experiments were performed in an air-oil two-phase flow loop shown schematically in Fig. 1. The density and the dynamic viscosity of the oil are 973.5 kg/m^3 and 0.036 Pa·s, respectively. The air and oil are mixed through an annular mixer, with oil flowing on the outside of an inner perforated pipe. Air flows in the inner pipe and enters the oil stream through 380 holes of 0.8 mm diameter. The air-oil mixture passes through the horizontal test section, which has a total length of 3.5 m. A sudden expansion test section with an area ratio of 0.25 is used in this study. The section upstream of the sudden expansion has a diameter of 12.7 mm and length of 1.1 m, while the downstream section has a diameter of 25.4 mm and length of 2.4 m. These lengths were found to be sufficient to obtain fully developed flow on both sides of the sudden expansion. The entire test section is made of Lexan polycarbonate tubing to allow for complete flow visualization. Flow patterns were identified by visual observation with the aid of a high-speed video camera (up to 1,000 frames/s). Two turbine flow meters in parallel and four rotameters in a bank are used to measure the oil and air volume flow rates, respectively. The pressure and temperature of the air were measured at the inlet

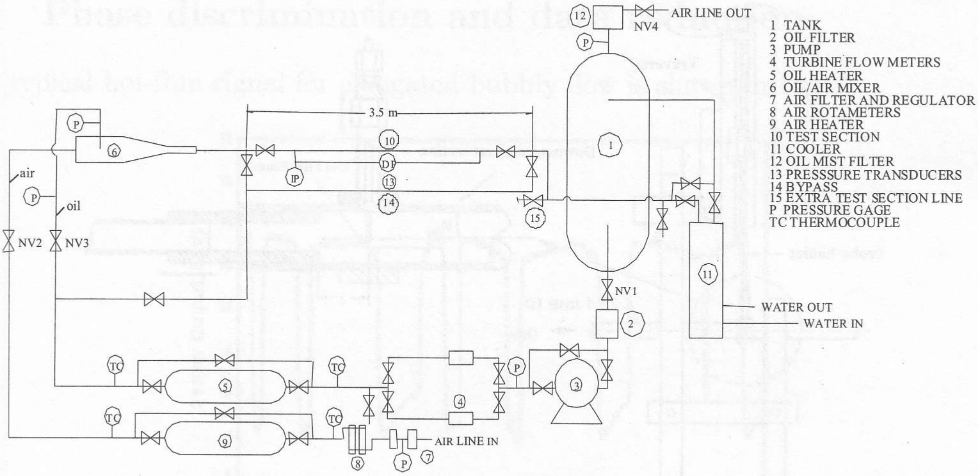

Figure 1. Schematic of oil-air two-phase loop.

of the test section in order to determine the mass flow rate of air. The upstream flow regimes for the results presented here were plug and slug flows while the downstream flow regime was elongated bubble flow. The axial variation of the average void fraction was measured using ring capacitance sensors located along the test section, the details of which are described in Ahmed [8].

Time averaged local profiles of the void fraction, mean liquid velocity and the liquid turbulence intensity were measured downstream of the expansion using hot-film anemometry. Measurements at different axial positions were obtained by changing the axial position (z) of the upstream pipe relative to the expansion section, as shown schematically in Fig. 2. A cylindrical TSI 1210-60W hot-film probe was used with a DISA 55M10 Constant Temperature Anemometer (CTA) bridge. The hot-film is mounted on a traverse which allows measurements at different radial positions with an accuracy of ± 0.01mm. The overheat ratio was set to 1.09, and is consistent with other reported HFA measurements in two-phase flow [3]. The hot-film signals were sampled at 5 kHz into a dedicated personal computer through a PCI-6034E A/D converter. The spectra showed that the highest frequency in all cases was below 1.5 kHz. A 300-second sampling time was taken to obtain statistically steady results.

The hot-film calibration was performed by placing the probe at the pipe center-line, at a distance of 60 diameters downstream of the sudden expansion. The center-line velocity was estimated from the measured oil flow rate using the laminar velocity profile. Typical calibration curves obtained over a 2 hour period are shown in Fig. 3, where the liquid Reynolds number was in the range 50 to 1200. Due to the relatively low value of the overheat ratio, the hot-film calibration

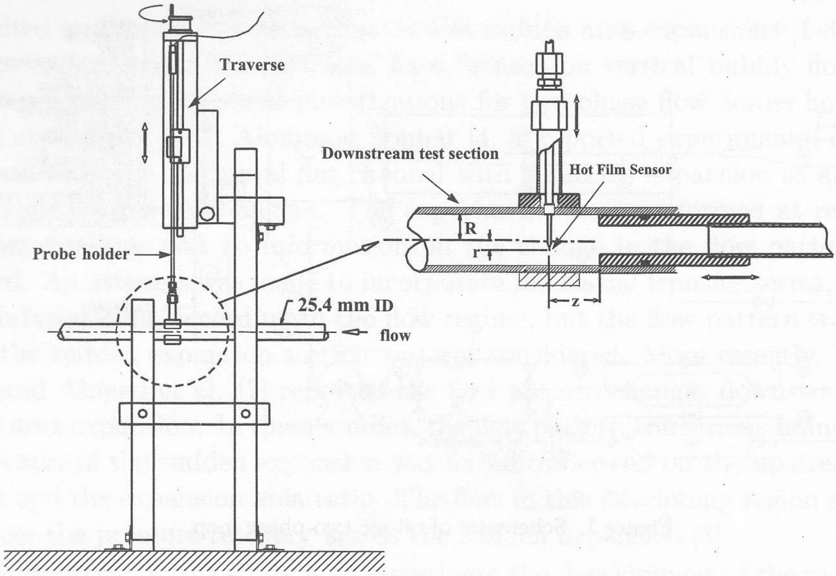

Figure 2. Schematic diagram of the hot-film set-up.

is very sensitive to variations in the fluid temperature. The temperature rise over the two hour period, however, is less than 0.4 ^{o}C and the corresponding drift in the calibration is less than ± 5% over the time period taken to complete a velocity profile as shown in Fig. 3.

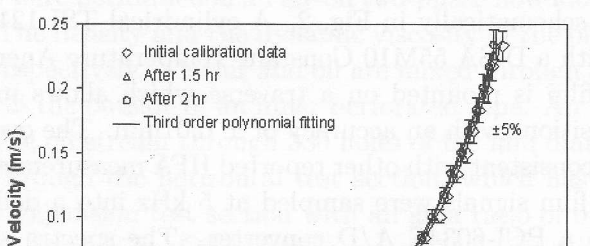

Figure 3. Hot-film calibration curves obtained over a 2 hour period.

3 Phase discrimination and data reduction

A typical hot-film signal for elongated bubbly flow is shown in Fig. 4.

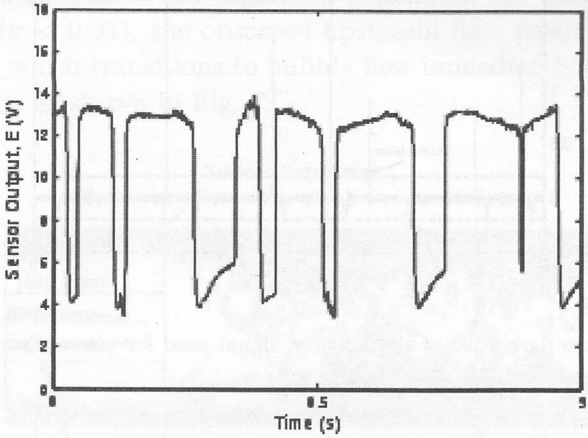

Figure 4. Typical hot-film signal in elongated bubble two-phase flow.

In order to discriminate between the phases, it is necessary to estimate a threshold voltage that distinguishes the signal between the two phases. As discussed by Bel-Fdhila [3], the threshold is applied to the time derivative of the voltage signal, (dE/dt) instead of the voltage signal, E. This method was found to more clearly identify the liquid-gas interfaces with respect to the high turbulence intensity. In the present case of elongated bubbly flow, the corresponding time derivative of the hot-film signal is shown in Fig. 5. The threshold levels were adjusted at $dE/dt = \pm 0.25$ volt/s as shown in Fig. 5 to identify the gas-liquid interfaces. For a gas bubble (n) the time when the bubble hits the sensor (t_n^H) and the time when the bubble leaves the sensor (t_n^L) were identified using the thresholds as shown in Fig. 5. After removing the signal that corresponds to the bubbles, the discretized hot-film signal for the liquid phase is presented in Fig. 6.

The total time that the probe is in the gas phase is used to determine the local time averaged void fraction as

$$\alpha(r) = \frac{1}{T} \sum_{n=1}^{N} \left(t_n^L - t_n^H \right)$$

where N indicates the number of gas bubbles passing the sensor probe in the total sampling time, T. A continuous signal corresponding to the liquid phase was obtained by replacing the signal between t_n^H and t_n^L with an average value between $E_{t_n^L}$ and $E_{t_n^H}$. This did not affect the value of the mean liquid velocity or

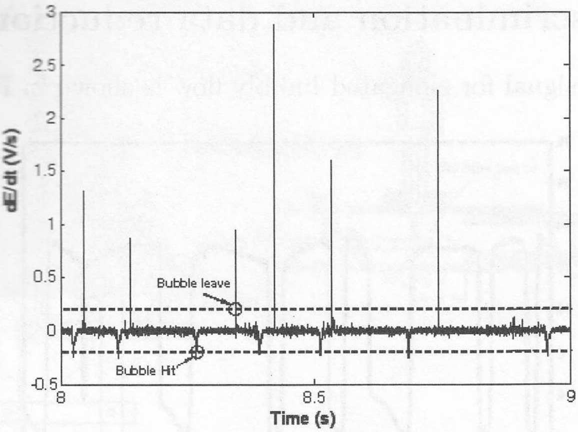

Figure 5. Time derivative of the hot-film signal used for phase discrimination.

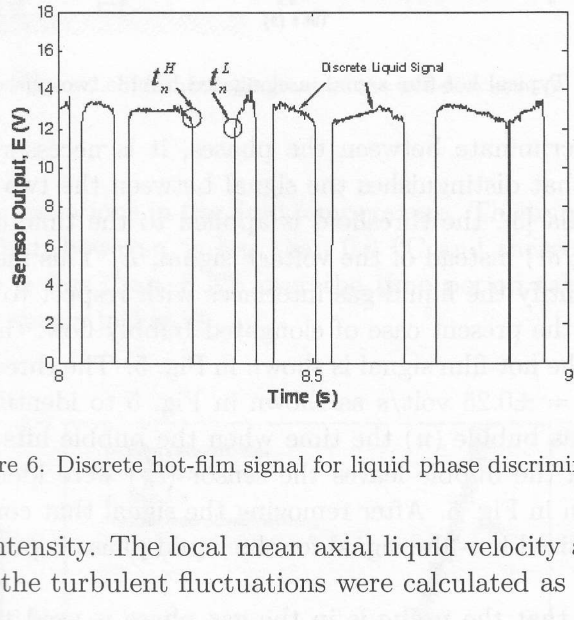

Figure 6. Discrete hot-film signal for liquid phase discrimination.

the turbulence intensity. The local mean axial liquid velocity and the root mean square values of the turbulent fluctuations were calculated as

$$U_{mean}(r) = \frac{1}{T} \sum_{k=1}^{N} u_k(r,t) \, ,$$

$$u'(r) = \sqrt{\frac{1}{N} \left[\sum_{k=1}^{N} \left[u_k(r,t) - U_{mean}(r) \right]^2 \right]}$$

where $u_k(r,t)$ is the instantaneous axial velocity for the k_{th} data point in the liquid phase, and N is the total number of data points in the liquid phase of the digital sample, $k = 1$ to N.

4 Results and discussion

The flow patterns can change across the sudden expansion, and the transitions immediately downstream of the expansion depend on the upstream flow regime. At low quality ($x < 0.04$), the observed upstream flow patterns were elongated bubble and slug which transitions to bubbly flow immediately downstream of the sudden expansion as shown in Fig. 7.

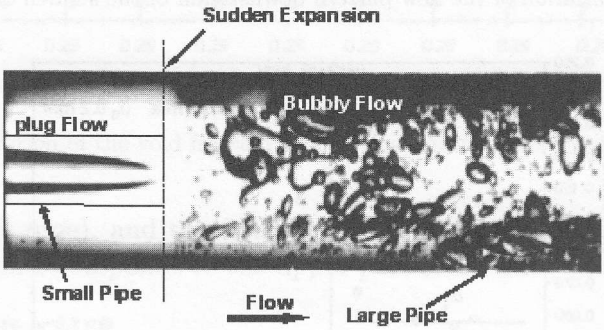

Figure 7. Bubble break-up across sudden expansion.

Data for liquid and gas superficial velocity $J_L = 0.675$ m/s and $J_G = 0.2$ m/s are presented here. The detailed observations of the two-phase flow in the vicinity of the sudden expansion using the high speed video camera show two interesting phenomena: bubble break-up and coalescence. In this case, as the air slugs enter the downstream expansion section, there is break-up of the slug into smaller bubbles which are distributed more uniformly due to the strong recirculatory motions immediately downstream of the expansion. The break-up and redistribution of the bubbles occur up to a downstream distance of approximately z/D=7 from the sudden expansion where D is the diameter of the downstream pipe. As the two-phase flow develops along the axial direction, the bubbles migrate to the upper part of the pipe due to the buoyancy effect, where coalescence takes place. The images at different axial locations along the test section using the high-speed video camera are shown in Fig. 8.

The variation of the cross-sectional averaged void fraction across the sudden expansion section for this representative case is shown in Fig. 9. The void fraction increase from a value of about 0.04 far upstream to about 0.07 at the closest measurement location to the sudden expansion section. This is an indication of an increase in the slip due to the reduction in the pressure gradient as the flow approaches the sudden expansion. There is a sharp increase in the void fraction just downstream of the sudden expansion, followed by a gradual decrease to a constant value of about 0.11 far downstream from the expansion. The fow pattern

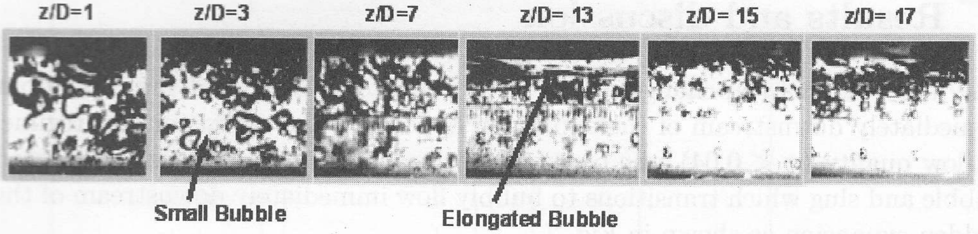

Figure 8. Variation of the flow pattern downstream of the sudden expansion.

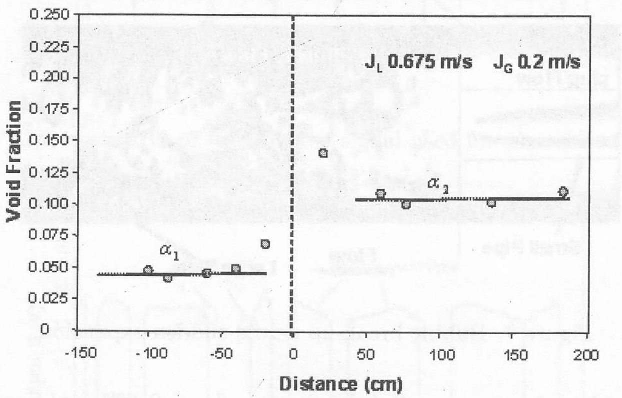

Figure 9. Void fraction distribution along the sudden expansion.

and void fraction in the "fully developed" region downstream of the expansion was found to be well predicted by traditional models such as [9, 10], indicating that the two-phase flow in this region is independent of its initial formation. The flow in the immediate vicinity of the sudden expansion and in the developing region, however, is strongly depends on both the upstream flow and the sudden expansion.

The local radial void fraction profiles in the vertical orientation along the pipe axis are presented in Fig. 10. The void fraction profiles remain approximately uniform up to an axial location of $z/D = 7$ where bubble break-up and mixing takes place. As the two-phase flow develops downstream of the expansion, the void fraction profile changes from the nearly-uniform shape to a profile that is higher in the upper half and nearly zero in the lower half. This reflects the migration of the bubbles to the upper half of the pipe. There is no significant change in the void fraction profiles beyond $z/D = 13$, which indicates that relaxation of the two-phase flow is complete at this axial location.

The liquid velocity profiles (Fig. 11) can be divided into two regions. The first region corresponds to where the void fraction is approximately zero (in the

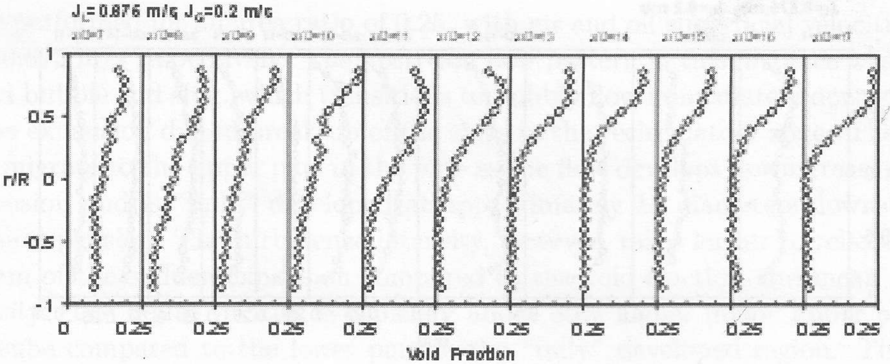

Figure 10. Variation of the void fraction profiles downstream of the sudden expansion.

lower part of the pipe), and the flow is mainly liquid with very small bubbles. The second region corresponds to the upper part of the tube with a much higher

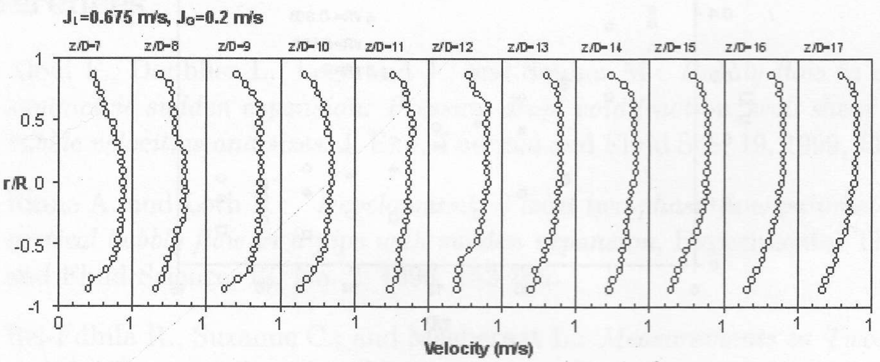

Figure 11. Variation of the liquid velocity profiles downstream of the sudden expansion.

void fraction. The liquid velocity profile shows that initially the velocity is higher in the lower half of the pipe ($z/D = 7$), and as the flow develops the velocity tends to higher values in the upper half of the pipe. In the fully developed region ($z/D > 13$), the average velocity in the upper part of the pipe is approximately 30 % higher than the lower part.

The turbulence intensity profiles along the pipe are shown in Fig. 12. The turbulence intensity is higher in the region of higher void fraction, which can be attributed to the enhancement of the turbulence due to the gas bubbles. As the flow develops downstream, the profiles are relatively unchanged beyond $z/D = 13$, with the turbulence intensity slightly higher in the top part of the pipe than the bottom. The variation of the liquid turbulence intensity at the centerline and in the upper ($r/R = 0.86$) and lower ($r/R = -0.86$) parts of the

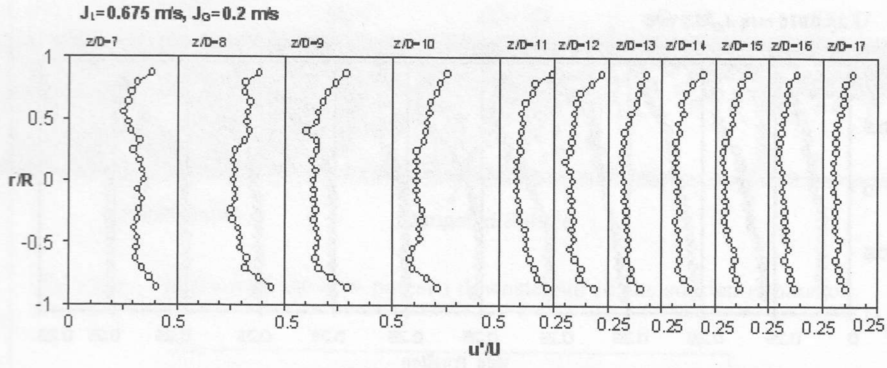

Figure 12. Variation of the turbulence intensity downstream of the sudden expansion.

tube downstream of the sudden expansion are shown in Fig. 13. The turbulence

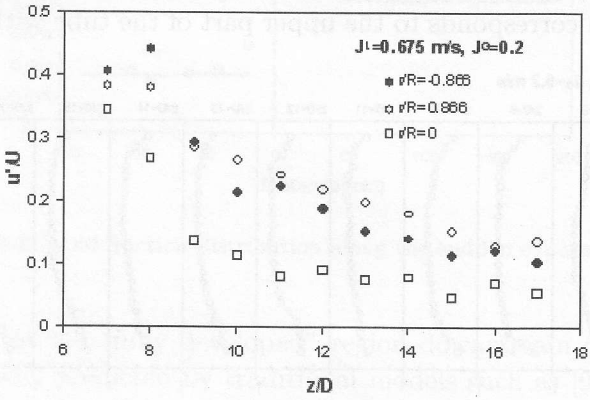

Figure 13. Variation of the turbulence intensity downstream of the sudden expansion.

intensity along the centerline decreases rapidly from about 35% at $z/D = 7$ to approximately a constant value of about 5% at $z/D = 15$. There is a similar decrease in the turbulence intensity in the upper and lower parts of the pipe, although it does not appear to reach a steady value up to z/D=15. This indicates that the relaxation of the turbulence takes longer than either the void fraction or the mean liquid velocity.

5 Conclusions

The flow pattern observations along with the void fraction, liquid velocity and turbulence intensity measurements were used to characterize the development of air-oil two-phase flow downstream of a sudden area expansion. The measurements were performed for an area ratio of 0.25, with air and oil superficial velocities 0.2 and 0.675 m/s respectively. The upstream flow pattern in this instance was elongated bubble and slug, which transitions to bubbly flow immediately downstream of the expansion due to break-up of the slugs in the recirculatory zone. The bubbles migrate to the upper part of the pipe as the flow develops downstream of the expansion and is "fully" developed at approximately 13 diameters downstream of the expansion. The turbulence intensity, however, takes longer to relax downstream of the sudden expansion compared to the void fraction and mean liquid velocity. The liquid velocity is typically about 30% higher in the upper part of the tube compared to the lower part in the "fully" developed region. There is a corresponding increase in the turbulence intensity, which can be attributed to the enhancement due to the presence of the gas bubbles.

Received 30 October 2005

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