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THE EFFECT OF A SUDDEN CONTRACTION ON GAS-LIQUID FLOW IN A PIPE AT A SLIGHT UPWARD INCLINATION

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1. INTRODUCTION

Though there have been significant studies of gas/liquid flows in pipes, there is much less research on the effect of fittings or singularities on these flows. Here one specific fitting, the sudden expansion is examined. This is the joint between larger and smaller diameter pipes. This geometry has been studied by a number of researchers. Initially measurements were made of the pressure profile along the pipe, both upstream and downstream of the contraction [1, 2]. Subsequent work examined the variation of cross-sectionally averaged void fraction using pairs of electrodes in the form of rings mounted flush in the channel wall. The liquid employed was water and the void fraction was determined by measurement of the conductance of the gas liquid mixture [3]. The same approach was also used to examine the effect of an orifice [4]. These studies were carried out with the pipes mounted in a horizontal plane. More recent studies were carried out on sudden contractions in vertical pipes [5-7]. Of those, the work of Ijioma et al. [7] is most similar to the present work. Here, we examine the effect of inclination with the pipe mounted with a small upward inclination.

2. EXPERIMENT

2.1 Flow facility

The experiments were carried out on a gas/liquid facility at Nottingham. It had previously been used for experiments on straight pipes on a single diameter [8]. Metered air and a silicone oil (density = 900 kg/m^3; viscosity = 5.25 mPa s; surface tension = 0.02 N/m) were introduced at the start of the test pipe which was inclined at 5° upwards from the horizontal. The first section of length of 5 m was of 67 mm diameter. The second section was of 38 mm diameter and 1 m long. The test pipe was equipped with 4 Electrical Capacitance Tomography (ECT) probes each consisting of eight electrodes each. Two were mounted at 0.489 and 0.4 m upstream of the construction with the remaining two 0.22 and 0.52 m downstream.

2.2 ECT

The Electrical Capacitance Tomography (ECT) is a non-intrusive technique which can be used for imaging and velocity measurement in flows of mixtures of 2 non-conducting materials. Developments over the last 15 years have made fast, accurate measurement systems available for laboratory research. Using ECT can offer measurements unobtainable with other measurement technologies, but the interpretation of quantitative flow data requires a good physical model of the interaction of the materials with the electric field in the sensor and appropriate reconstruction and analysis algorithms. Arrays of electrodes were arranged around the outside of the non-conducting pipe wall and all unique capacitance pairs were measured using a Tomoflow R5000 flow imaging and analysis system. The instrument contains 16 identical measurement channels and 16 identical driven guard circuits and in the tests reported here was operated with a twin-plane sensor.

Data can be captured at rates up to 5000 image frames per second with typical measurement noise level at 500 fps of 0.02fF rms. The typical average value between two opposite electrodes is 10fF. In the experiments reported here the frame rate was 1000 fps.

Measurements were made between all pairs of electrodes within each plane around the sensor using a charge/discharge capacitance technique. An excitation signal was used in the form of a 15V peak to peak square wave with a frequency of 5 MHz. The sensor included a full set of driven guard electrodes running axially before, between and after the measurement planes giving a total of 5 axial sets of 8 azimuthal electrodes ensuring that an axially-uniform electric field was maintained over the capacitance sensor cross-section and the two sensor 'planes' (actually short cylindrical sections). Inversion of the 28 capacitance pairs to a 812 pixel image on a 32x32 square grid was undertaken as described below, and component information (void fraction etc.) was extracted from these images.

Cross-correlation between the image planes gives the velocity distribution across the flow. The resolution of ECT images is limited so cross-correlation is not carried out for all pixels, but for a set of larger 'zones' containing the average of a number of pixels.

Each probe consisted of an array of 8 azimuthal electrodes 35 mm long in the axial direction with guard electrodes before and after. The centres of the electrode rings on the 67 mm diameter pipe were 89 mm apart axially. Those on the 38 mm diameter pipe were 300 mm apart.

The probes were calibrated by taking readings with the pipe empty (gas only) and full of liquid. Images of flows can be presented as circular maps on a grid of the 812 pixels in a circle inscribed onto a 32x32 square pixels using a colour scale. To investigate details of flow conditions it is more helpful to divide each image plane into a number of zones arranged appropriately for the flow conditions. For 8 electrode systems, dividing the flow into 13 zones containing approximately 62 pixels each and which have typical length scales of R axially and

R/2 within the cross section where R is the pipe radius. These zones are more consistent with the linear spatial resolution of ECT, which is sometimes quoted as $2R/n_e$ where n_e is the number of electrodes circumferentially around the pipe. Within each zone the pixel values are averaged to give one concentration value per zone for each frame of data.

To gain confidence in the ECT instrument, it has been run simultaneously with another instrument, i.e., a Wire Mesh Sensor system. The latter give good very detailed spatial and temporal information. The results of this comparison [9, 10] show that the mean void fractions (spatial and temporal average) agree very well with each other. Similar agreement can be seen in the time series, particularly when the traces are transposed in time to compensate for the different axial positions at which the probes were placed.

3. RESULTS AND DISCUSSION

3.1 Flow patterns

Measurements were made at gas superficial velocities of 0.3-3.3 m/s and liquid superficial velocities of 0.05-0.24 m/s, based on the upstream diameter. The ECT provides data from which cross-sectionally averaged time series can be produced. Examination showed that most of these consisted of alternating regions of high and low void fractions very characteristic of slug flow. Flow patterns could also be deduced from the Probability Density Functions (PDFs) of the time series. Runs with slug flow showed the characteristic signature of two peaks. The peak at low void fraction corresponds to that for the liquid slug whilst the peak at high void fraction represents the value for the large bubble part of the flow. At high gas rates, particularly in the smaller diameter pipe, there were runs exhibiting flows which were more akin to churn or annular. When compared with the predictions of the flow pattern map of Shoham [11] there was good agreement for the smaller diameter pipe but it was significantly poorer for the larger diameter upstream pipe. For both diameter pipes, the range of gas flow rates over which non-slug flow occurred became larger the lower the liquid flow rate.

Another primary parameter that can be examined is the mean void fraction. This is important in engineering calculations as it determines the gravitational component of pressure gradient. This parameter can be obtained by averaging the time series of cross-sectionally averaged void fraction. A selection of the values obtained is shown in Figure 1 and illustrates the effect of axial position about the sudden contraction. It shows that for lower gas superficial velocities, there is a small increase from upstream to downstream of the contraction but that this is less noticeable at higher gas flow rates. This increase can be up to 50 % at lower liquid flow rates.

When the measured void fractions are compared with the standard engineering correlations, it is seen that the predicted values tend to be higher than those measured. Because it only depends on gas mass fraction (which does not vary across the contraction) and the phase densities, the equation of Chisholm [12] does not show any difference between upstream and downstream. The more complex expression of Premoli et al. [13] does show an increase about the junction but the trend of the downstream/upstream ratio is opposite to that determined from the experiments. However the absolute values predicted are high: 14-100 % for the upstream case and 25-50 % for the downstream.

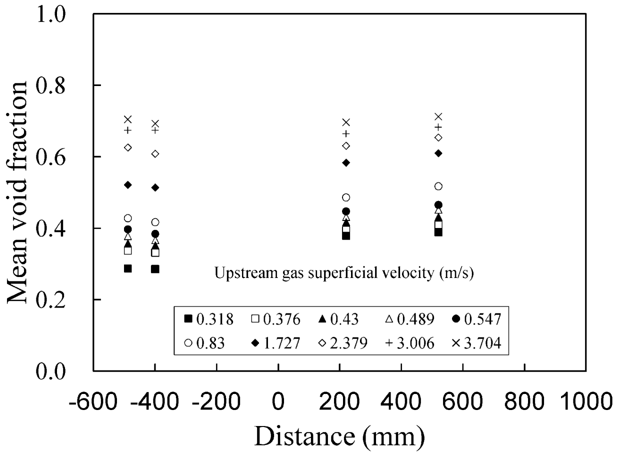

Figure 1 Variation of mean void fraction with axial position about sudden contraction. Upstream liquid superficial velocity = m/s.

Fourier transform techniques were employed to provide data of the most probably frequency of the periodic structures which clarify the flows. Cross-correlation techniques were used to obtain the velocities of these structures. The results of this analysis were compared with mean values determined from time delay between the times traces from adjacent probes. The effect of the mixture velocity on the structures is illustrated in Figure 2 for an upstream liquid superficial velocity of 0.24 m/s. The data for both upstream and downstream can be seen to follow the equation suggested by Bendiksen [14] for those runs in the slug flow region. At higher gas flow rates the measured velocities deviate from the equation and have a much lower dependence on gas flow rate. This has been observed previously in other studies at difference pipe orientation.

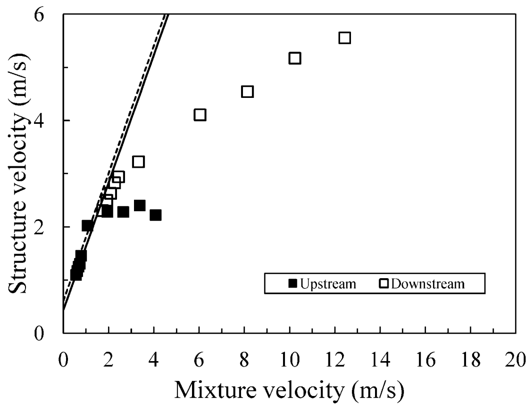

Figure 2 Dependence of structure velocity on mixture velocity (sum of gas and liquid superficial velocities). Upstream liquid superficial velocity = 0.24 m/s.

From a mass balance over a slug unit (liquid slug plus adjoining large bubble), Khatib and Richardson [15] obtained an expression for the fraction off the slug unit length that was the liquid slug. This can be expressed as

$$\frac{L_s}{L_u} = \frac{<\varepsilon_g> - \varepsilon_{gB}}{\varepsilon_{gs} - \varepsilon_{gB}} \quad (1)$$

where,

L_s is liquid slug length, L_u is the length of the unit slug, $<\varepsilon_g>$ is the overall averaged void fraction, ε_{gs} is the void fraction in the liquid slug and ε_{gB} is the void fraction in the large bubble region.

Now, L_u can be determined of the slug velocity and its frequency. The void fractions for the two part of the slug unit can be extracted from the PDF of the time series. Obviously, the length of the large bubble is given by difference, $L_B = L_u - L_s$. This approach has been applied to all the runs which featured slug flow. The lengths of both the liquid slugs and of the large bubbles were seen to increase with increasing gas flow rate. Part of this is illustrated in Figure 3 which shows the lengths of the large bubbles made dimensionless by the local diameter.

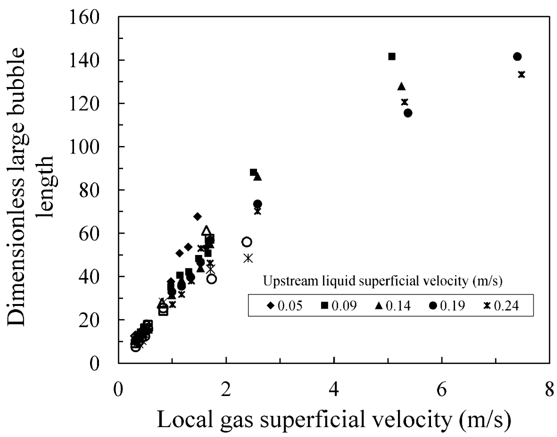

Figure 3 Lengths of large bubbles made dimensionless by the local pipe diameter. Full symbols are for the downstream pipe whilst the open symbols are for the larger diameter

More detailed information on the three dimensional structure of the flow about the sudden expansion have been extracted from the ECT output.

4. CONCLUSIONS

From the output of ECT probes it is seen that the behaviour of a gas/liquid flow about a sudden expansion essentailly show only the effect expected by the increases in superficial velocity of the two phases caused by the change in diameter.

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