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BRIEF COMMUNICATION

THE EFFECT OF SWIRL ON THE LIQUID DISTRIBUTION IN ANNULAR TWO-PHASE FLOW

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1. INTRODUCTION

In annular gas–liquid two-phase flow the liquid flows partly as a film along the channel walls, and partly as entrained droplets within the gas core. Droplet entrainment and deposition between the liquid film and the core are important factors in the flow. To maximise the wall film flow rate, and consequently the critical heat flux, it is therefore required to minimise the amount of entrainment. In the present work, the film flow rate was increased by inserting a length of twisted metal tape to swirl the flow so that some entrained droplets were centrifuged onto the tube walls. The film flow rate at varying distances downstream of the tape was then measured.

The increase of critical heat flux with swirl is discussed by Bergles (1978) in a general review of heat transfer enhancement, and is described by Whalley (1979) who also presents a simple method for calculating the length of tube over which the effect of the swirl persists. Continuous lengths of twisted tape within tubes can increase the critical heat flux by more than 100%, see for example Gambill *et al.* (1961). Whalley (1979) analysed some results from a tube with a short length (0.05 m) of twisted tape which led to increases in the critical heat flux of up to 25%. The present work examines the variation in film flow rate with distance downstream of a swirl section for various combinations of air and water flowrates.

2. APPARATUS

The experiments were carried out in a vertical perspex tube, 0.032 m internal diameter. Metered air and water were supplied to the base of the tube, the water being introduced through a short length of porous wall made of sintered metal. Annular flow was produced with the air flowing up the tube and a surface film of water travelling up the tube walls. The water film had large disturbance waves on its surface.

The water film flow rate was measured by allowing the film to flow through another sinter section 5.2 m above the first. The pressure at this point was maintained at 1.5 bar. The air and water takeoff rates through the sinter could be measured after the two phases had been separated in a cyclone; the air flow rate by a gas meter, the water flow rate by timed collection of the flow. The water flow rate is almost independent of air flow rate except at very low air flow rates, and results derived on the basis of assuming the constant value of water flow rate at the higher air flow rates to be the water film flow rate have been shown to be consistent with other methods, see Hewitt (1978). Swirl was imparted to the flow by a 0.3 mm thick nickel tape, 0.144 m in length and 0.032 m in width, twisted through 180° and inserted into a section of the tube. Each corner of the tape was attached to the tube with the minimum amount of silicone rubber glue to minimise turbulence from the mounting. A check was made to ensure that the

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results obtained were independent of the mounting. The tube sections could be rearranged so that the tape section was at varying distances from the outlet sinter. Only this one swirl inducing section was tested in this work, and no measurements of pressure drop were taken.

In a separate test, high speed cine photographs (4000 frames per second) were taken of the flow using the axial view technique described by Arnold & Hewitt (1967). In this technique the camera is mounted at the top of the tube and the flow is photographed as it approaches a window. The window is kept dry by a number of powerful air jets. The camera was focussed on the top of the twisted tape which was approximately 0.2 m below the top of the tube. The flow rates used for the photographic runs was 53.5 g/s of air and 25.2 g/s of water. The pressure at the top of the tube was close to 1 bar.

3. RESULTS

Film flow rate measurements were taken for eight combinations of air and water flow rates, and for eight positions of the tape within the tube. The results are given in detail by Fryer & Whalley (1980) and are plotted in figures 1 and 2. The points marked at zero distance represent the values of the film flow rate with no swirl in the tube, i.e. the asymptotic value of the curve. These values are consistent with the results of Whalley & Azzopardi (1980). The distances given in figures 1 and 2 correspond to the distance between the top of the tape and the bottom of the sinter where the film flow is measured.

To the naked eye the tape seemed to produce two effects. The flow lines of the water on the tube walls were helical downstream of the tape for up to about a metre, and the disturbance waves on the liquid film could not be seen immediately above the tape, but reformed further up the tube.

The following points can be seen from figures 1 and 2:

(i) In general, a rapid rise in film flow rate is followed by a gradual decline. The peak values do not correspond to 100% of liquid flow. Closest approach comes for low water flow rates, see figure 2. This can also be seen in table 1 where the film flow rate without swirl and the peak film flow rate are given as a fraction of the total water flow rate. The ratio of peak film flow rate to total water flow rate is remarkably independent of air flow rate at constant water flow rate.

(ii) The peak liquid film flowrate occurs at between 4 and 30 diameters downstream of the tape. The distance of the peak downstream of the tape increases with increasing air flow rate

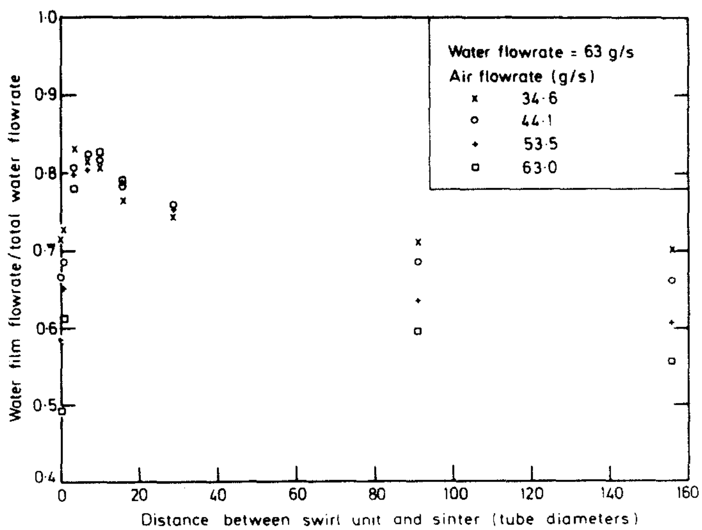

Figure 1. Variation of film flowrate with distance at constant water flowrate.

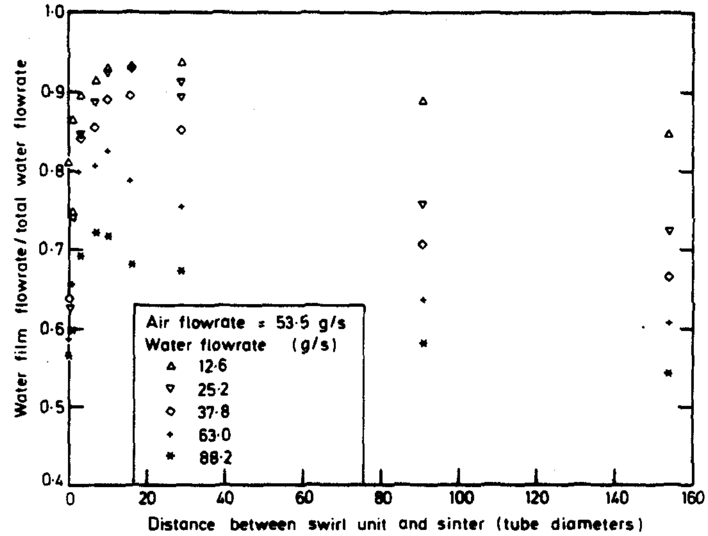

Figure 2. Variation of film flowrate with distance at constant air flowrate.

Table 1. Effect of swirl on film flowrate

Tube Flow Rates (g/s)		Film Flow Rate (No Swirl) W_{LF} (g/s)	Peak Film Flow Rate with Swirl W_{PLF} (g/s)	$\frac{W_{LF}}{W_L}$	$\frac{W_{LFP}}{W_L}$
Air	Water (W_L)				
34.6	63.0	45.1	52.3	0.712	0.830
44.1	63.0	42.0	52.0	0.667	0.825
53.5	12.6	10.2	11.8	0.810	0.937
53.5	25.2	15.8	23.4	0.627	0.929
53.5	37.8	24.1	33.8	0.638	0.894
53.5	63.0	37.0	52.1	0.587	0.827
53.5	88.2	52.3	63.5	0.593	0.720
63.0	63.0	31.0	52.0	0.492	0.825

and decreases with increasing water flow rate. Commonly the peak is found about 10 diameters downstream of the tape.

(iii) The return to the equilibrium value is approximately exponential with a characteristic length of between 30 and 90 diameters. The characteristic length is lower at high water flowrates, see figure 2.

The results were found to be consistent: two sets of results given for a distance of 29 diameters were taken on different days, and for all but 1 flowrate the points are co-incident on the figures. Care was taken to ensure that liquid sampling only took place on the constant water output region of the output curve (see section 2).

The cine photographs showed that a large amount of liquid was collected by the twisted tape by direct impingement of drops. The resulting liquid film was re-entrained at the top (downstream) edge of the tape. These drops could be seen to be moving in a helical path and some deposited onto the liquid film on the tube walls.

4. DISCUSSION

There are three distinct phenomena which a complete analysis of the flow situation should explain. These are the amount by which the film flow is increased by deposition due to the swirl, the length over which this deposition takes place, and the rate at which the normal undisturbed flow is re-established. Here the second and the third points are discussed: the analysis of the extra deposition is a difficult problem.

Whalley (1979) obtains a simple formula for calculating the length of persistence of swirl, z_0, given by

$$z_0 = \frac{R}{2c_f^{TP}} \quad [1]$$

where R = tube radius, c_f^{TP} = two-phase Fanning friction factor. This friction factor is obtained from c_f^{ST}, the smooth tube friction factor

$$c_f^{ST} = 0.079\,\mathrm{Re}_G^{-1/4} \quad [2]$$

where Re_G = gas phase Reynolds number, using the expression of Wallis (1970), derived for air water systems

$$c_f^{TP} = c_f^{ST}\left(1 + 360\frac{m}{D}\right) \quad [3]$$

where m = wall film thickness, D = tube diameter.

Table 2 shows values of z_0 for the present work, together with experimental peak distances. The wall film thickness in [3] was obtained from the annular flow model of Whalley *et al.* (1978). The values used in [3] are given in table 2, and are the calculated values of the film thickness at hydrodynamic equilibrium, when the entrainment rate is equal to the rate of droplet deposition. It can be seen that the two sets of values have similar trends: the distances both increase with increasing air flow rate, and decrease with increasing water flow rate. It should be realised that close numerical agreement would not be expected, as [1] was derived with very crude assumptions, and was intended only to give a rough estimate of z_0. It does, however, as noted above, correctly reproduce the trends in the experimental date.

The annular flow model of Whalley *et al.* (1978) can be used to study the rate at which the equilibrium undisturbed flow is re-established after the swirl has decayed. When this is done it is found that the film flow is predicted a die away towards its equilibrium value approximately exponentially with a characteristic length of 30 ± 6 tube diameters. The actual flows decay with a characteristic length between 30 and 90 diameters as noted earlier. This discrepancy is not unexpected as Hutchinson *et al.* (1974) found similarly that the annular flow model predicted a too rapid attainment of equilibrium. The experiments demonstrate that droplet deposition by the effects of the swirl is neither instantaneous nor total. In addition, the effects of the swirl persist for a considerable distance downstream, because the re-establishment of equilibrium is

Table 2. Calculated and experimental distances

Tube Flow Rates (g/s)		Calculated Liquid Film Thickness m (mm)	Calculated Swirl Length z_o (m) from [1]	Experimental Peak Distance (m)
Air	Water			
34.6	63.0	0.324	0.36	0.15
44.1	63.0	0.256	0.46	0.2
53.5	12.6	0.129	0.75	0.8
53.5	25.2	0.165	0.66	0.5
53.5	37.8	0.195	0.59	0.4
53.5	63.0	0.210	0.56	0.3
53.5	88.2	0.222	0.54	0.3
63.0	63.0	0.176	0.66	0.3

slow. This agrees with the conclusions of Brown *et al.* (1975) who found that it could take several hundred tube diameters to attain equilibrium.

5. CONCLUSIONS

Water film flow rates have been measured in annular air–water flow in a vertical tube at various distances downstream of a swirl section, for various combinations of gas and liquid flow rates. The experimental results demonstrate that the swirl does not deposit 100% of the entrained water droplets, and that the return to the equilibrium state is very gradual. The formula of Whalley (1979) for the distance between the swirl section and the position of maximum film flow rate has been tested and found to predict the trend of experimental results, and the order of magnitude.

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