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Brief communication

# The influence of a bend on drop sizes in horizontal annular two-phase flow

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## 1. Introduction

Annular flow is just one of the various flow patterns appearing in gas–liquid two-phase flow in pipes, and occurs for high gas to liquid mass flow ratios. In this regime, the gas phase occupies the central part of the pipe. The liquid travels as entrained drops in the gas core, and also as a film that completely wets the inner surface of the tube.

For horizontal flow, however, gravity causes the liquid to drain downwards, so that the film is thickest at the bottom of the tube. With increasing gas velocity, this asymmetry in the film becomes less pronounced, as demonstrated in the work of Dallman (1978), Jayanti (1990) and Sekoguchi et al. (1982).

The drops present in the system are linked to the appearance of large amplitude waves in the liquid film, that are formed due to the shearing action of the gas at the gas–liquid interface. Liquid is torn from the surface of these waves giving rise to drop entertainment in the gas core; at the same time the liquid film is replenished by drop deposition.

An important requirement in the study of annular two-phase flow is the determination of the drop size distribution, since drop size affects heat, momentum, and mass transfer. Previous studies were mainly carried out for vertical flows, and have examined the influence of gas and liquid flow rates, gas density, liquid viscosity, surface tension and tube diameter on drop size (Azzopardi et al., 1978; Ueda, 1979; Gibbons, 1985; Jepson, 1992). For horizontal flow, the results published so far, are limited and have been obtained in rectangular channels (Namie and Ueda, 1972; Russell and Rogers, 1972; Chang, 1973; Tatterson, 1975 and Akagawa et al., 1980).

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The study of the flow characteristics in bends was initiated by Eustice (1911), who visualised the laminar flow of water in a curved pipe using dye injection experiments. For a 90° bend, it was noticed that a dye filament at the axis of the tube moved away, towards the outside of the bend, while the fluid near the wall flowed towards the centre. These experiments demonstrated the existence of a transverse motion superimposed on the primary flow, the so-called "secondary flow". Since that time several researchers have investigated single-phase flow in curved pipes.

For two-phase flow, the presence of a bend can modify drastically the flow conditions, because it introduces a changing condition in the flow pattern, whereby the relative positions and local velocities of the two-phases, are redistributed. Banerjee et al. (1967) studied stratified air–water flows in helical coils, and observed a displacement in the maximum film thickness from the bottom of the tube. At low air and water flow rates, the maximum film thickness was located mainly on the outside of the bend, while for high gas velocities and low liquid loadings, the maximum film thickness was seen on the inside of the bend. These phenomena are explained on the basis that the gas phase momentum is higher than that of the liquid phase, and identified as "film inversion".

For vertical flow, the influence of a bend on annular flow has been studied by Anderson and Hills (1974) and Maddock et al. (1974). Chakrabarti (1976) and Balfour and Pearce (1978) investigated horizontal flow and noticed a thickening in the liquid film towards the inside of the horizontal bends due to film inversion. For some flow conditions, a local maximum in the film thickness profile was also found towards the outside of the bend. The appearance of this thick film on the outside of the bend is due to the deposition of entrained drops under the influence of centrifugal forces.

The deposition of particles present in a flow stream on the outer wall of a curved pipe was also observed in the work of Wang and Mayinger (1995), who studied the effect of a 90° vertical bend in post-dryout dispersed flow. Gupta et al. (1997) investigated the flow distribution of a heterogeneous slurry around a horizontal bend and noticed the migration of larger particles towards the outer wall of the bend due to centrifugal forces. Bends also affect the drop size distribution of entrained drops in annular flow.

The work reported in this paper includes a new set of experimental data on drop size for air–water horizontal annular flow, for different gas and liquid flow rates, and the effect of a 90° horizontal bend on the drop size distribution.

## 2. Experimental method

Filtered air from the main air supply was metred and introduced into a horizontal 0.032 m ID Perspex tube. The air passed along a 1 m calming section, before being combined, through a porous wall section, with metered demineralised water. The air–water mixture annular flow characteristics were established over a distance of 5 m, before encountering a 90° horizontal bend with the same internal diameter as the straight tube, and a radius of curvature of 0.166 m. The pressure in the test section was maintained at 1.3 or 1.4 bar, and the average temperature was 15°C.

A Malvern 2600 Particle Sizer was used to measure the drop size distribution, which requires unimpeded access to the gas core by its laser beam. In order to achieve this requirement, the liquid film flowing on the tube surface, was completely removed through a porous wall immediately before the optical section. In horizontal flow, it was considered that there would be a vertical concentration gradient in the pipe. To overcome this experimental difficulty, the Malvern laser was vertically mounted.

Two optical sections were used in the experiments, fabricated from Perspex with flat glass windows positioned on opposite sides of the unit. Air jets were used to prevent splattering of drops on the windows.

The data obtained with the laser diffraction technique, were treated using a model independent analysis. The reason for this was the fact that some drop size histograms obtained for measurements before the bend presented a multimodal behaviour, while after the bend all histograms were multimodal.

## 3. Results and discussion

### 3.1. Drop sizes before the bend

The drop size measurements before the bend were made for gas mass flux ($G_G$) between 40 and 70 kg/m$^2$ s, and liquid mass fluxes between 20 and 110 kg/m$^2$ s. Figs. 1 and 2 show the influence of liquid mass flux on the Sauter mean diameter of the drops ($D_{32}$) for a working pressure of 1.3 and 1.4 bar, respectively. In Fig. 1 and for the lower gas mass flux ($G_G = 40$ kg/m$^2$ s), $D_{32}$ decreases as

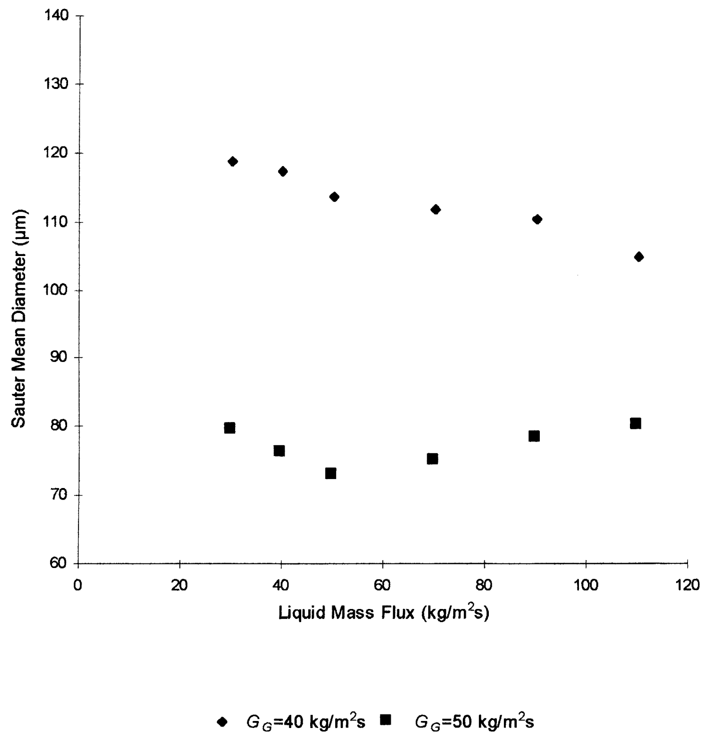

Fig. 1. Effect of liquid mass flux on drop size before the bend, at a pressure of 1.3 bar.

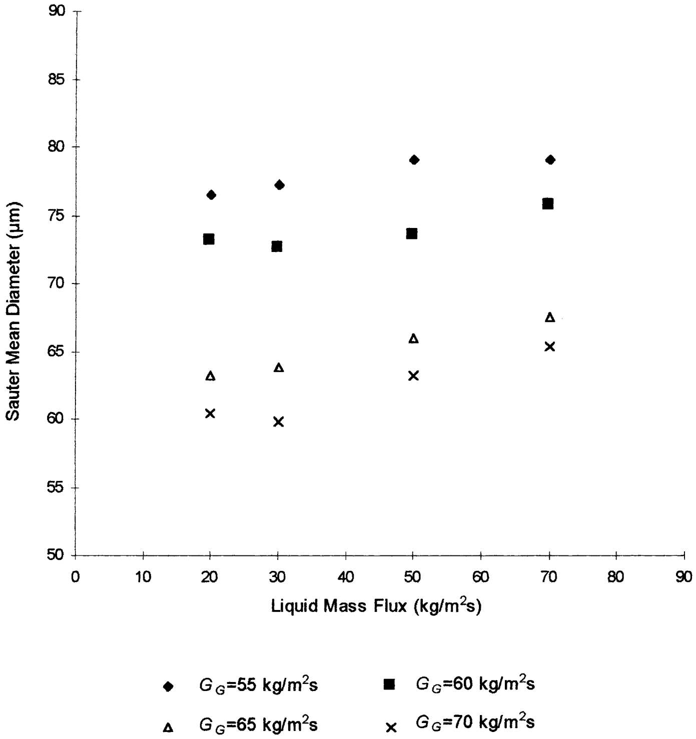

Fig. 2. Effect of liquid mass flux on drop size before the bend, at a pressure of 1.4 bar.

liquid flow rate increases. For $G_G = 50$ kg/m$^2$ s, the drop size passes through a minimum. Similar behaviour was found for drop size measurements in vertical annular flow. Azzopardi (1983) suggested that these trends can be linked to the different mechanisms responsible for drop entrainment. One of them, termed "bag break-up", occurs when a roll wave is undercut by the gas to form an open-ended bubble with a thick filament rim. The gas pressure inside the bubble builds up until eventually the bubble bursts forming large drops from the rim and smaller drops from the bubble skin. At higher flows, a second mechanism, termed "ligament break-up", predominates. Here, the top of the wave is pulled forward in the form of a ligament. This ligament is torn from the surface and broken-up in the gas stream.

Cine films made prior to these experiments and described elsewhere (Ribeiro, 1993), have demonstrated that for the flow conditions analysed, both the bag and ligament break-up mechanisms are present in horizontal flow. As such, the decreasing drop diameter with increasing liquid mass flux shown in Fig. 1 may be due to the increasing predominance of ligament break-up over bag break-up. Here, ligament break-up is assumed to produce smaller drops. For $G_G = 50$ kg/m$^2$ s, the subsequent rise in $D_{32}$ with liquid flow rate is probably due to drop coalescence. For the flow conditions in Fig. 2, the trend is for increasing drop size with liquid mass flux. Under these circumstances, the concentration of drops has a predominant effect, leading to drop coalescence and a consequent increase in drop size. The presence of drop coalescence has also been observed from cine films.

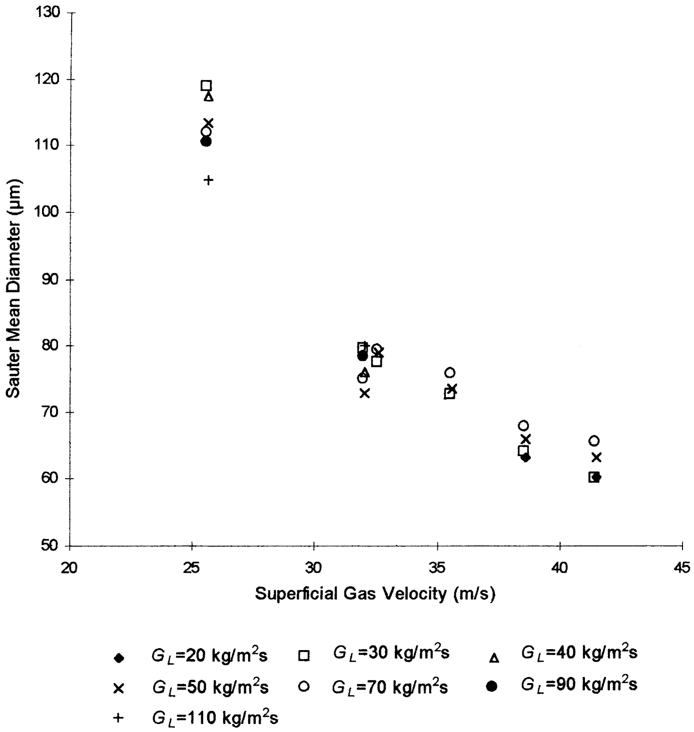

Fig. 3. Effect of superficial gas velocity on drop size before the bend.

Fig. 3 shows the strong effect of the superficial gas velocity on $D_{32}$, which decreases with increasing gas velocity. This is expected because the higher the gas flow, the greater the shearing force imposed on the liquid, leading to more intense surface deformation and break-up into smaller drops. For the flow conditions under study, $D_{32}$ was found to be proportional to the superficial gas velocity raised to the power of $-1.0$.

### 3.2. Drop size measurements after the bend

A set of drop size measurements was carried out after the bend for gas mass flux between 40 and 70 kg/m$^2$ s and liquid mass flux in the range of 30–90 kg/m$^2$ s. In Fig. 4, drop size is plotted against liquid mass flux. For the lower gas mass fluxes ($G_G = 40$ and 50 kg/m$^2$ s), drop size is almost independent of liquid flow rate. For the higher gas flow rates, there is a tendency of the drop size to decrease with increasing liquid flow rate. The effect of gas velocity on the drop size after the bend, as before the bend, is that it decreases with increasing gas velocities. For the flow conditions analysed, $D_{32}$ is proportional to the superficial gas velocity raised to the power of $-1.5$.

A comparison between the drop size data before and after the bend, shows that in general, $D_{32}$ increases after the bend. Several phenomena may contribute to the increase in drop size at the bend. It is believed that an important factor is the coalescence of drops. Separate photographic studies have revealed coalescence of drops. The secondary flow pattern existing in the gas phase at the bend, may also enhance this increase in drop size. During the present experiments it was

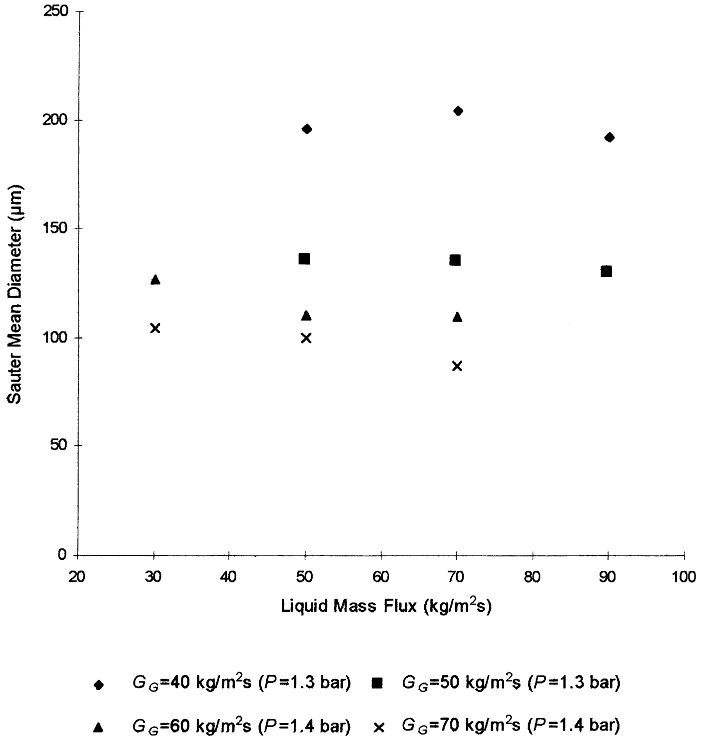

Fig. 4. Effect of liquid mass flux on drop size after the bend.

observed that in the upper half of the tube, the liquid was drawn from the outer wall of the bend to the top of the tube in an anti-clockwise, cork-screw fashion. In the lower half, the liquid was drawn from the outer wall towards the bottom of the tube, in a clockwise motion. This movement of the liquid film, which is caused by the secondary flow in the gas phase, results in an accumulation of liquid on the inner wall of the bend. From this thick film, drops may be re-entrained into the gas. These are expected to be large, because the local gas velocity has a minimum value towards the inside of the bend. Previous studies of the gas velocity at the exit of a bend (Anderson and Hills, 1974; Chakrabarti, 1976) showed that the velocity profile was distorted, with the maximum towards the outside of the bend.

At high gas velocities and low liquid loadings, film inversion may occur at the bend. This may also cause a thickening of the liquid film on the inside of the bend, and a consequent appearance of large drops created by re-entrainment. Film inversion could explain why in Fig. 4, for the higher gas flow rates ($G_G = 60$ and 70 kg/m$^2$ s), the drop size decreases with increasing liquid flow rate.

Farwagi (1983) also found an increase in drop size after a bend for water drops transported in an air stream, although as the author pointed out, his results were not statistically valid. No other publications have been found in the open literature for comparison purposes, concerning the study of the effect of a bend on the drop size distribution.

It is not possible from the data obtained in these experiments, to establish which mechanism is responsible for increased drop size at a bend, or whether or not it is a combination of phenomena.

## 4. Conclusions

From the above discussion, the following conclusions can be drawn concerning the drop size measurements before the bend:

- For the flow conditions analysed, $D_{32}$ varied between 60–119 μm.
- The gas velocity had a strong effect on drop size, $D_{32}$ being proportional to the superficial gas velocity raised to the power of $-1.0$.
- The influence of liquid flow rate is somewhat more complex. For the lower gas mass flux ($G_G = 40$ kg/m$^2$ s), $D_{32}$ decreased with increasing liquid flow rate. For $G_G = 50$ kg/m$^2$ s, the curve passed through a minimum. For the higher gas flows ($G_G = 55$–$70$ kg/m$^2$ s), drop diameter increased with liquid flow rate. These trends are linked to different mechanisms of entrainment.

The drop size measurements carried out after the bend can be summarised as follows:

- Measured $D_{32}$ ranged between 87–204 μm.
- For the lower gas mass fluxes ($G_G = 40$ and 50 kg/m$^2$ s), the drop size was almost independent of liquid flow rate. For $G_G = 60$ and 70 kg/m$^2$ s the drop size decreased slightly with increasing liquid flow rate.
- The drop size decreased with increasing gas velocity. $D_{32}$ was found to be proportional to the superficial gas velocity raised to the power of $-1.5$.
- The effect of the 90° horizontal bend on the drop size distribution was to increase the diameter of drops. Several processes taking place at the bend, such as drop coalescence may be responsible for the coarsening of the distribution. In addition, the secondary flow pattern existing in the gas phase at the bend, and film inversion are also thought to have some effect.

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