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Effect of drag-reducing polymers on annular gas–liquid flow in a horizontal pipe

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Abstract

Measurements of drag-reduction are presented for air and water flowing in a horizontal 0.0953 m pipe. The fluids had an annular configuration. The injection of polymer solution produced drag-reductions of about 48% with concentrations of only 10–15 ppm in the liquid. The effectiveness of the drag-reducing polymer is sensitive to the method of injection and the concentration of the polymer solution that is injected. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Horizontal gas–liquid flow; Drag-reducing agent; Annular flow

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1. Introduction

One of the more intriguing advances in single-phase turbulence is the finding that the introduction of small amounts of long-chain polymers into a liquid flow can cause large decreases in the frictional resistance at the wall (Toms, 1948). Recent studies with laser doppler velocimetry (Harder and Tiederman, 1991; Wei and Willmarth, 1992; Warholic et al., 1999) have revealed how the turbulence properties differ from those of the solvent.

Warholic and Hanratty used a solution of a co-polymer of polyacrylamide and sodium-acrylate (Percol 727) in water. They realized significant drag-reduction with a concentration as low as 0.25 ppm. The principal effect of the polymer is to reduce Reynolds shear stresses and velocity fluctuations in a direction normal to the wall. Maximum drag-reductions, for which the Reynolds stresses are approximately zero, were observed for polymer concentrations of 13 and 50 ppm.

This paper presents results of experiments in which drag-reducing polymers were added to the flow of water and air in a horizontal pipe, with a diameter of 9.53 cm. The gas velocity was large

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enough that an annular flow existed. This pattern commonly occurs in natural gas/condensate pipelines. It is characterized by a situation in which a part of the liquid flows along the wall as a liquid layer and part as drops entrained in the gas.

At low gas and liquid rates the liquid flows along the wall in a stratified manner. At superficial gas velocities, U_{sg}, of the order of 10 m/s, waves are ripped off the liquid surface to form drops. These drops mix in the gas and, eventually, redeposit. At high enough gas flows some of these drops hit the top wall where (depending on the surface properties of the wall) they can form an extremely thin film, which is covered by capillary ripples. At still larger U_{sg} drop mixing and deposition is such that the film on the side walls becomes thick enough for groups of large amplitude irregular waves to form intermittently. These disturbances are sites for atomizations and the fluid in them has characteristics similar to turbulence. They greatly enhance the ability of liquid to climb up the wall in opposition to the gravitational force and they increase interfacial drag. An annular flow has been defined as a situation in which the film on the top wall is turbulent (Lin and Hanratty, 1987). For air–water flows at atmospheric pressure, this is usually realized at $U_{sg} > 25$ m/s for a 9.53 cm pipe diameter.

The only previous study of the effect of drag-reducing polymers on annular gas–liquid flow was carried out by Sylvester and Brill (1976) for air–water in a horizontal pipe with a diameter of 1.27 cm and a length of 6.1 m. A polymer solution with 100 ppm of polyethlene oxide, contained in a holding tank, was pumped to a tee where it was mixed with the gas. The data are plotted as pressure gradient versus liquid flow rate for superficial gas velocities 86 and 111 m/s. The percent change in the pressure gradient from what was observed in the absence of polymer varied from zero to about 37. No explanation for these changes was given.

Studies of the effect of the drag-reducing polymer on frictional losses have been made by Rosehart et al. (1972) and by Otten and Fayed (1976) for bubbly and plug flows. Kang et al. (1997) studied the influence of an additive (which is not identified) on three-phase flow (oil, water and carbon dioxide). They found a drag-reduction of 35% at the two highest superficial gas velocities that were studied, $U_{sg} = 13, 14$ m/s. A review of work on this area by Manfield et al. (1999) concludes that understanding of the influence of drag-reducing polymers on multiphase flows is not satisfactory.

The present study used technology developed by Warholic et al. (1999) in their studies of drag-reduction in single-phase flows. It differs from all of the studies listed above in that a concentrated polymer solution (master solution) was injected at the wall without using a pump. The concentration in the liquid in the pipeline was controlled by varying the flowrate of the master solution. Gas and liquid superficial velocities of 30–43 m/s and 0.03–0.09 m/s were used. Drag-reductions from zero to a maximum were observed.

The present study differs from the previous work on annular flows in that a larger pipe diameter was used, a more careful study of the effect of polymer mixing was carried out and the influence of the polymer on the characteristics of the flow was identified. The finding that the annular flow regime is changed to a stratified pattern at large drag-reductions could, in some applications, be of more importance than the finding of a large decrease in frictional pressure loss. For given gas and liquid flows the pressure drop was measured as a function of the concentration of the polymer in the liquid in the pipeline. A critical concentration was observed below which the frictional drag was the same as for water: Above this critical condition the frictional drag decreased with increasing polymer concentration in the liquid. Eventually, at high enough concentration there was no further decrease. Also, of interest is the occurrence of this maximum drag-reduction at concentrations as low as 10 ppm.

2. Description of the experiments

The 9.53 cm pipeline used in this study has a length of 23 m. The pipe sections were constructed from Plexiglas to allow visual observations. The air and water were combined in a tee-section at the entry. The water flowed along the run of the tee. The air discharged to the atmosphere so the pressure was slightly above the atmospheric (3×10^3 Pa). A detailed description of the loop is given in a thesis by William (1990).

The master polymer solution was prepared the day before an experiment was performed. Percol 727, in the form of a white powder was mixed with water by a method described in Warholic et al. (1999), in a 1-m^3 tank. Concentrations varied from 250 to 1500 ppm (weight basis). The master solution was transferred by gravity to a smaller tank, which was pressurized with air (see Fig. 1(a)). The flow rate out of the tank was measured by a rotameter. These methods for transferring the concentrated polymer solution (master solution) were used in order to avoid the degradation that would have occurred if a pump were used.

The polymer solution was injected into the flow loop in two ways, as indicated in Fig. 1(b). The first of these involved the introduction of the master solution into the liquid through a hole with a diameter of 18 mm that was located at the bottom of the pipe, 0.6 m upstream of the tee where the air and water were mixed. Experiments in which coloring was included in the master solution suggested that the polymer was completely mixed (in a gross sense) in the stratified liquid before it reached the air inlet. The second method involved injection at a location where the annular pattern was developed, i. e., 3.7 m from the mixing tee. The injection device involved the use of three holes with diameters of 3 mm that were oriented in the vertical and ±15° from the vertical. The vertical jet feeds the liquid at the very bottom of the pipe and the inclined jets feed the films on both sides of the pipe. The addition of dye to the master solution suggested that the polymer was rapidly mixed with liquid flowing along the wall in about 2 pipe diameters downstream of the injection point.

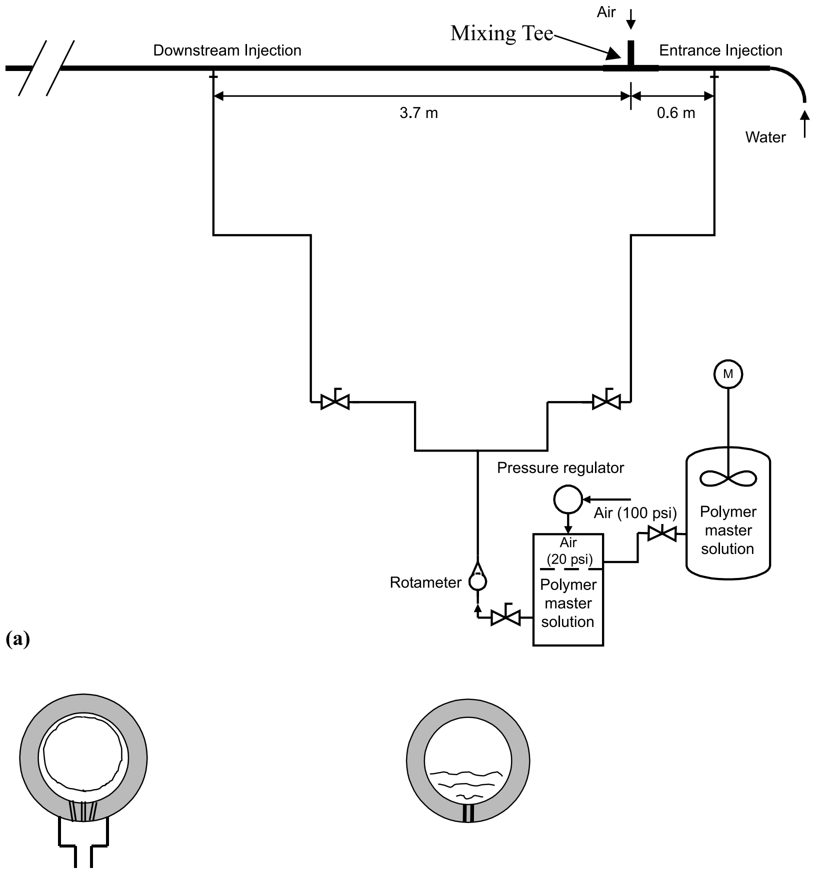
A U-tube manometer was used to measure the pressure drop over a 10.7 m length of pipeline. The first pressure tap was located 5.5 m from the downstream injection point.

3. Results

3.1. Visual observations

Visual observations of the air–water flow revealed a turbulent liquid film with intermittent disturbance waves around the whole pipe circumference. These were longer and more intense at the bottom, as would be expected, since the average height of the film is distributed asymmetrically (Williams et al., 1996).

The effect of the addition of polymer to the flow is illustrated in Figs. 2(a) and (b). The picture for air–water flow shows the liquid wetting the whole pipe circumference and the presence of a large-scale disturbance wave. A flow with the same rates of liquid flow and gas flow, but with



Downstream Injection Point (D.I.P) Entrance Injection Point (E. I. P)
(b)

Fig. 1. (a) Sketch of the flow facility; (b) Method of injection at the entrance position (EIP) and at a downstream position (DIP).

15 ppm of polymer added to the liquid, shows a stratified flow with a relatively smooth surface and a negligible amount of entrained drops in the gas phase, that is, an insufficient amount to create a film at the top of the pipe.

These results can be interpreted by arguing that the polymers damped the disturbance waves. This, in turns, reduces the rate of atomization and the ability of liquid to spread upward along the wall. A secondary effect is a damping of the waves on the stratified flow that finally results. If one looks upon disturbance waves as patches of turbulence, then their destruction could be looked upon as a decrease in turbulence activity.

3.2. *Effect of mixing*

A comparison of results obtained with the two methods of injection outlined in Section 2, is presented in Figs. 3(a)–(c). These were obtained with a master solution that had a concentration

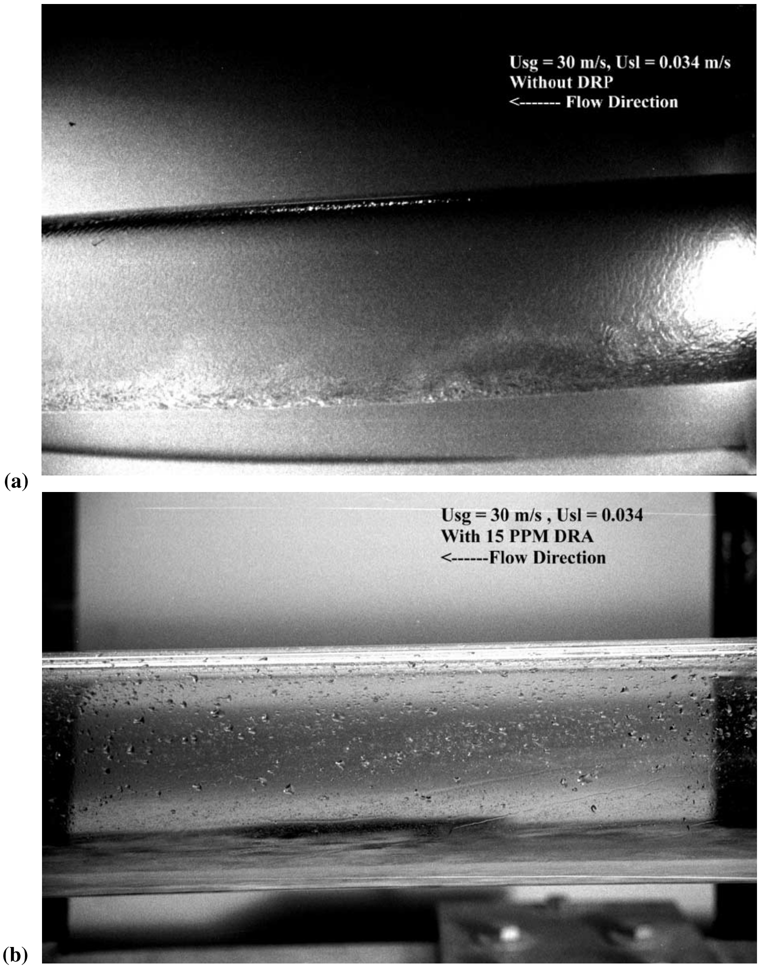


Fig. 2. (a) Annular flow without DRA ($U_{sg} = 30$ m/s, $U_{sl} = 0.034$ m/s); (b) Annular flow with 15 PPM DRA ($U_{sg} = 30$ m/s, $U_{sl} = 0.034$ m/s).

of 1000 ppm. The effectiveness of the polymer is expressed in terms of the drag-reduction (DR) defined as

$$\mathrm{DR} = \frac{\Delta P_{\text{without DRA}} - \Delta P_{\text{with DRA}}}{\Delta P_{\text{without DRA}}}, \tag{1}$$

where $\Delta P_{\text{with DRA}}$ is the pressure drop when the drag-reducing agent (DRA) was present and $\Delta P_{\text{without DRA}}$ is the pressure drop in the absence of the drag-reducing agent. Plots of DR versus the concentration of polymer in the flow loop are presented for three U_{sg}.

It is noted that all of the figures show that drag-reduction, DR, increases with increasing concentration and eventually reaches a plateau. The most important feature of these figures is that they demonstrate the advantage of injecting the polymer directly into the annular flow.

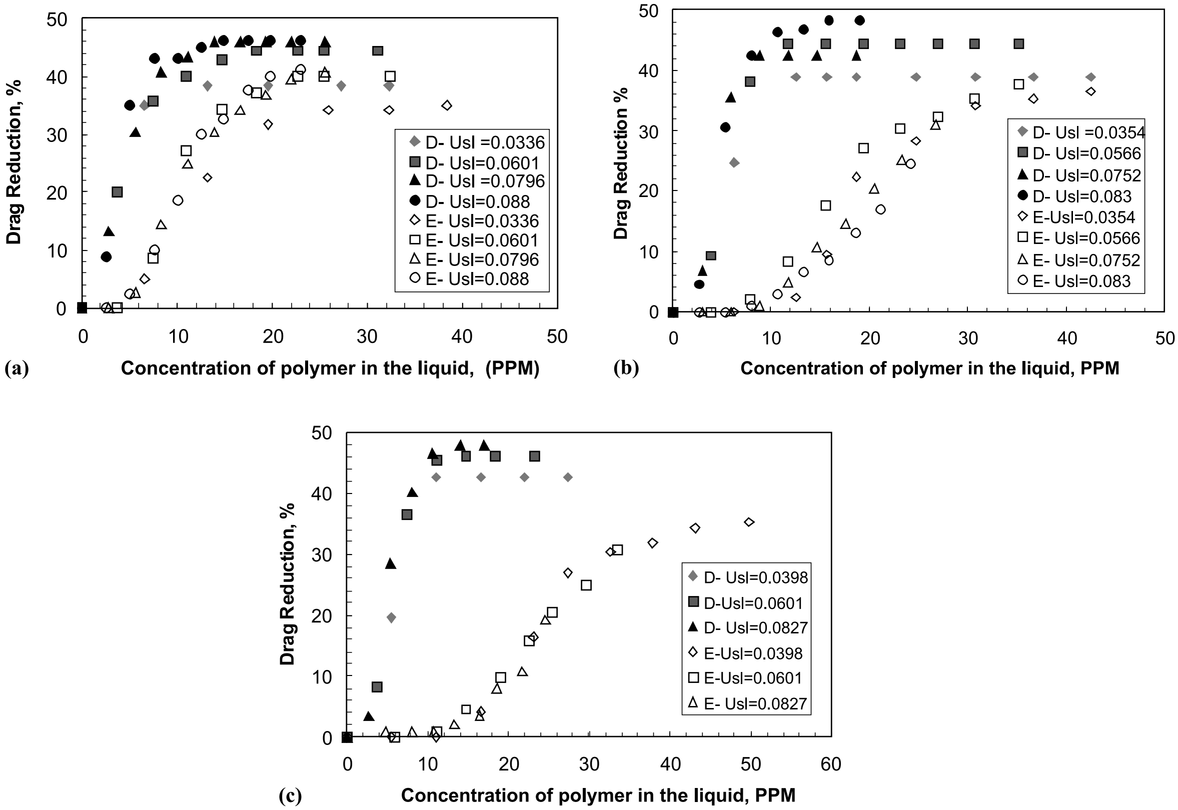


Fig. 3. (a) Effectiveness of DRA at $U_{sg} = 30$ m/s and 1000 ppm master solution. (D: downstream, E: Entrance injection); (b) Effectiveness of DRA at $U_{sg} = 36$ m/s and 1000 ppm master solution (D: downstream, E: Upstream Entrance injection); (c) Effectiveness of DRA at $U_{sg} = 43$ m/s and 1000 ppm master solution.

Lower concentrations are needed to initiate drag-reduction and to reach maximum effectiveness. The value of the maximum drag-reduction appears to be slightly larger when injection is done downstream. Both types of experiments eventually result in a stratified flow, so this seems to suggest that waves on the stratified flow that is eventually realized are affected by the manner in which the polymers are introduced.

The influence of the method of injection is considered in a different way in Figs. 4(a) and (b). These show that the effectiveness of polymers injected downstream is not affected by gas velocity. The opposite is the case when polymers are injected upstream, in that the effectiveness of the polymers decreases with increasing gas velocity.

3.3. Effect of the concentration of the master solution

Warholic et al. (1999) found, for drag-reduction in single-phase flows, that the concentration of the polymers in the solution injected into the flow had a large effect. For situations in

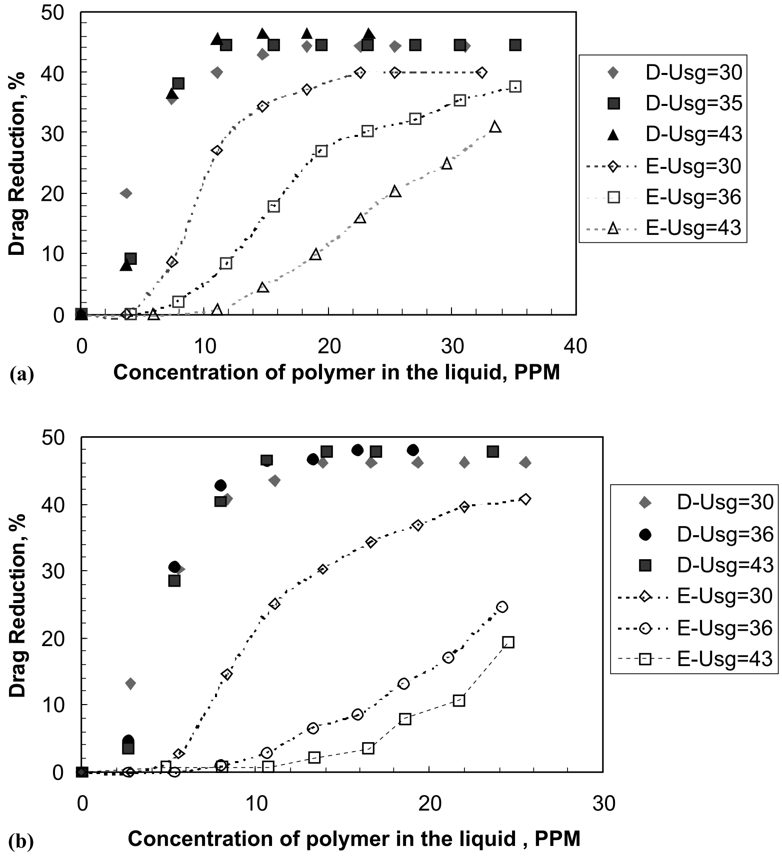
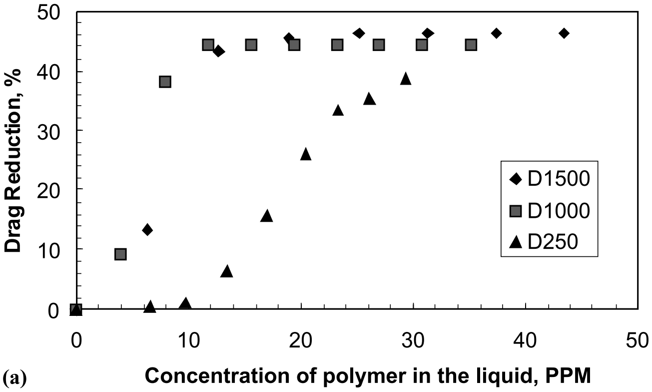


Fig. 4. (a) Effectiveness of DRA at $U_{sl} = 0.0601$ m/s (D: downstream, E: Entrance injection, U_{sg} in m/s); (b) Effectiveness of DRA at $U_{sl} = 0.082$ m/s (U_{sg} in m/s).

which the mixed concentration (in the pipeline) was the same, the drag-reduction increased with an increasing concentration of the master solution. They interpreted this behavior as resulting from larger entanglements of polymer chains in more concentrated solutions and suggested that much of the observed loss of effectiveness (or degradation) of drag-reducing polymers resulted from an irreversible breakup of these aggregates.

These results prompted experiments in which studies were made with master solutions with different concentrations. Some of these are presented in Fig. 5(a) for a situation in which the polymer was injected downstream and in Fig. 5(b) for injection upstream of the inlet. Results obtained with other superficial gas velocity, U_{sg}, and superficial liquid velocity, U_{sl}, show similar behaviors. An optimum concentration of 1000 ppm is suggested. The effectiveness appears to be greatly diminished if master solutions of 250 ppm are used, since no drag-reduction was observed for situations in which the polymer was introduced upstream for the



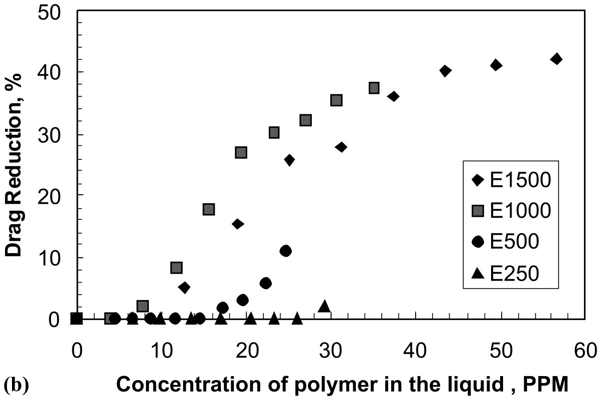


Fig. 5. (a) Effectiveness of DRA at different master solution concentrations using downstream injection ($U_{sg} = 36$ m/s, $U_{sl} = 0.0566$ m/s); (b) Effectiveness of DRA at different master solution concentrations using entrance injection ($U_{sg} = 36$ m/s, $U_{sl} = 0.0566$ m/s).

range of ppm used in Fig. 5(b). The use of smaller concentrations required larger injection velocities so degradation in the injection system could be a factor.

4. Interpretation

An important result emerging from this study is that drag-reductions of 48% can be realized by adding drag-reducing polymers to the flow. This finding can be interpreted by considering friction factors defined as

$$f = \frac{D}{2\rho_G U_{sg}^2}\frac{dP}{dx}, \tag{2}$$

where D is the pipe diameter, ρ_G is the gas density and dP/dx is the measured pressure gradient.

For a pipe with smooth walls,

$$f_s = 0.0791 Re_G^{-0.25}, \tag{3}$$

where Re_G is the gas Reynolds number based on the actual gas velocity, U_G, ($Re_G = \rho_G U_G D/\mu_G$).

Measurements of the pressure drop with only gas flowing in the pipe give f_G/f_s of 1.16, 1.13 and 1.10 for $U_{sg} = 30$, 36 and 43 m/s, where f_G is the friction factor measured when only gas was flowing in the pipe. These results would correspond to a pipe wall characterized by a Nikuradse sand roughness (Schlichting, 1960) of about 0.04 mm.

Measurements of f for the annular flows studied in this research are plotted as f/f_s versus U_{sl} in Fig. 6. These would be characterized by sand roughness of 0.96–1.16 mm. These large values of f/f_s could result, because the actual gas velocity is larger than the superficial gas velocity, and because liquid interface is roughened with waves.

Visual observations suggest that maximum drag-reduction is reached when all of the liquid is flowing along the bottom of the pipe as a stratified flow with an approximately smooth interface. This would suggest that $f/f_{G\approx}$ 1 at maximum drag-reduction. Actually, one should expect larger values of f/f_G than unity, since the liquid in the stratified flow occupies a part of the cross-section and the interface is never completely smooth. Estimates of the area of the liquid have been made by assuming a horizontal interface. These give maximum values of $(U_G/U_{sg})^2 \approx 1.21$.

Values of f/f_G obtained from experiments in which polymer was injected downstream in the annular flow are shown in Fig. 7(a)–(c). At zero concentration a variation of f/f_G with U_{sl} is observed, as would be expected from the results presented in Fig. 6. At maximum drag-reduction $f/f_G \approx 1.2$–1.3. This value would be closer to what was measured for a single-phase flow if the actual gas velocity, rather than the superficial velocity, were used in Eq. (2).

Fig. 7 shows that f/f_G is weakly affected by U_{sl}, as would be expected from Fig. 3(a)–(c). The concentration of entrained drops increases with increasing U_{sl} in experiments without polymers. The small change in f/f_G with U_{sl}, shown in Fig. 6, suggests that the gas density, not the mixture density, should be used in Eq. (2). The large values of f/f_G observed for annular gas–liquid flows, therefore, seem to be associated primarily with roughness of the gas–liquid interface. The large change of the waves after adding polymer is the main factor responsible for the decrease in drag.

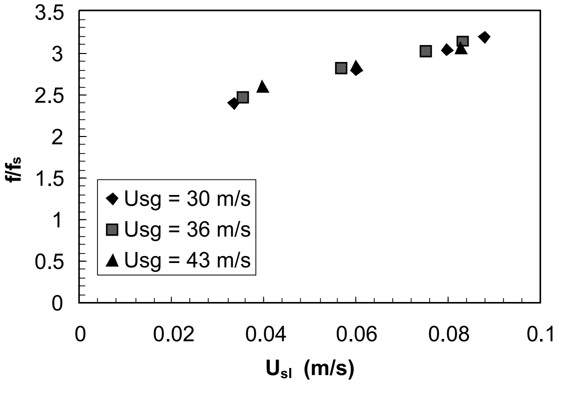


Fig. 6. Measurements of frication factor for annular flow (without polymer).

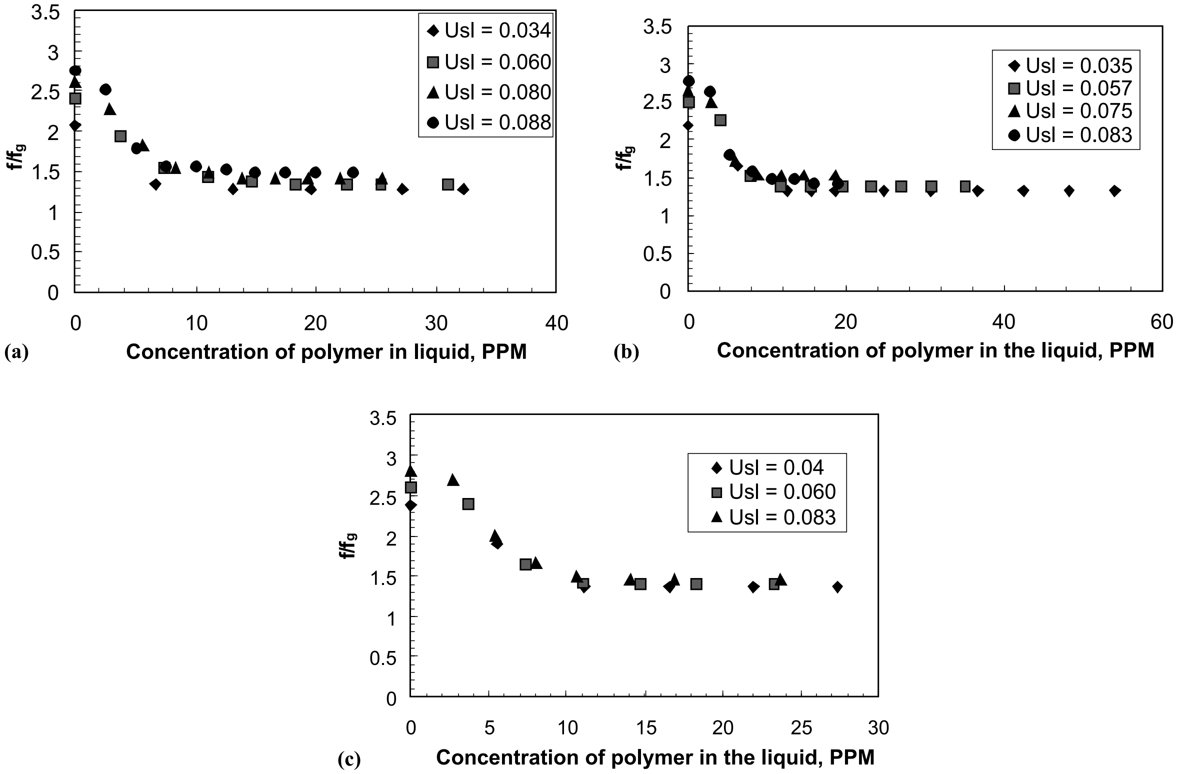


Fig. 7. (a) Friction factor variation at $U_{sg} = 30$ m/s, and 1000 ppm master solution; (b) Friction factor variation at $U_{sg} = 36$, and 1000 ppm master solution; (c) Friction factor variation at $U_{sg} = 43$, and 1000 ppm master solution.

5. Discussion

The injection of polymer solution into an air–water flow that has an annular configuration in a horizontal pipe can produce drag-reductions of about 48%. The polymer destroys the turbulent disturbance waves, which are the cause of drop formation and which help the water film to spread upward around the pipe circumference. At maximum drag-reduction almost all of the liquid flows along the bottom wall. The interface is relatively smooth and the friction factor is roughly equal to that which would characterize gas flowing alone in the pipe. A DR of 48% is thus obtained, as shown in Fig. 3, since the annular flow without polymer is characterized by a value of f/f_G slightly larger than 2.5. This interpretation suggests that larger drag-reduction might be realized for air–water annular flows which have larger f/f_G.

The effectiveness of a drag-reducing polymer is sensitive to the technology used to introduce polymer into the flow. The master solution needs to be prepared by a gentle mixing and should be injected into the wall film in a manner which distributes it along the circumference. Transference to the pipe should not involve the use of pumps. Effectiveness depends on the concentration of polymer in the master solution so an optimum needs to be determined.

The mixing of the polymer in the liquid prior to contacting the water solution with the air reduces the effectiveness, in that larger amounts of polymer are needed and the maximum drag-reduction could be reduced. These disadvantages are emphasized if dilute master solutions are used. Our interpretation of these results is influenced by the work of Warholic et al. (1999). Degradation could occur in two ways. One involves the breakup of aggregates of polymers. The other, which requires more severe hydrodynamic forces, is the mechanical breakup of high molecular weight molecules in the solutions. Our viewpoint is that concentrated master solutions contain more entanglements and that the impingement of the gas on the polymer solution could be breaking up the aggregates. This explanation is consistent with the observed strong effect of gas flow on DR, shown in Fig. 4, when polymers are injected upstream.

However, the advantage of injecting the polymer solution into the wall film of an annular flow could also result from a type of preconditioning that has been identified by Vissman and Bewersdorff (1989). The injection of the polymers through a narrow passage in the wall could cause them to elongate. The strong shearing action in the wall film would keep them in this desired configuration.

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