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International Journal of Multiphase Flow 32 (2006) 926–934
International Journal of Multiphase Flow
www.elsevier.com/locate/ijmulflow

Effect of drag reducing polymer on air–water annular flow in an inclined pipe

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Received 12 February 2006; received in revised form 7 March 2006

Abstract

Drag reduction (DR) for air and water flowing in an inclined 0.0127 m diameter pipe was investigated experimentally. The fluids had an annular configuration and the pipe is inclined upward. The injection of drag reducing polymer (DRP) solution produced drag reductions as high as 71% with concentration of 100 ppm in the pipeline. A maximum drag reduction that is accompanied (in most cases) by a change to a stratified or annular-stratified pattern. The drag reduction is sensitive to the gas and liquid superficial velocities and the pipe inclination. Maximum drag reduction was achieved in the case of pipe inclination of 1.28° at the lowest superficial gas velocity and the highest superficial liquid velocity. For the first time in literature, the drag reduction variations with the square root of the superficial velocities ration for flows with the same final flow patterns have self-similar behaviors.

Keywords: Inclined pipeline; Annular gas–liquid flow; Drag reducing polymers

1. Introduction

The injection of small amounts of high molecular weight long-chain polymers into a single-phase liquid flow can cause large decreases in the frictional resistance at the wall; this interesting finding was first published by Toms (1948). Recent studies with laser doppler velocimetry (Harder and Tiederman, 1991, Wei and Willmarth, 1992 and Warholic et al., 1999) have revealed how the turbulence properties differ from those of the solvent.

Warholic et al. (1999) in their studies of drag reduction in single-phase flows 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 wppm. The principal effect of the polymer is to reduce Reynolds shear

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0301-9322/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijmultiphaseflow.2006.03.001

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 wppm and 50 wppm.

Two phase gas liquid flow in pipes is regularly encountered and is of great commercial importance in the natural gas and petroleum industries. This paper presents results of experiments in which drag-reducing polymers were added to the flow of water and air in an inclined pipe, with a diameter of 0.0127 m. The gas velocity was large 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 in the core of the pipe.

At low gas and liquid rates the liquid flows along the wall in a stratified manner. At low superficial gas velocities, 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 atomization 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 called disturbance waves. An annular flow has been defined as a situation in which the film on the top wall is turbulent (Lin and Hanratty, 1987).

The only similar 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 polyethylene 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 m/s 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.

Sylvester et al. (1980) studied the effect of liquid flow rate and gas flow rate on drag reduction in horizontal natural gas–hexane pipe flow in three different diameter (1, 2 and 3 in.). Drag reduction of 34% were obtained. It was found that drag reduction increased with decreasing gas rate.

Al-Sarkhi and Hanratty (2001a) found that the injection of a concentrated drag reducing polymers into an air–water in a 9.53 cm pipe changed an annular pattern to a stratified by destroying the disturbance waves in the liquid film. Drag reduction of 48% were realized. In a following study in a 2.54 cm pipe, Al-Sarkhi and Hanratty (2001b) observed similar results and obtained drag reduction as high as 63%.

Soleimani et al. (2002) studied experimentally the effect of drag reducing polymers on pseudo-slugs-interfacial drag and transition to slug flow. They revealed that the transition to slug flow is delayed by drag reducing polymers and the pressure drop can increase or decrease when polymers are added.

Al-Sarkhi and Soleimani (2004) conducted a series of experiments to investigate the effect of drag reducing polymer on two phase flow pattern in a horizontal 2.54 cm pipe. The characteristics of two phase flow with and without drag reducing polymers were described. It is noted that the interfacial shear stress decreases sharply by adding polymers and flow pattern map is changed.

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.

Al-Sarkhi and Abu-Nada (2005) have investigated the effect of drag reducing polymer on annular flow pattern in 0.0127 pipeline. The maximum drag reduction of 47% with concentration of only 40 wppm in the pipeline was observed. The result showed a maximum drag reduction that is accompanied (in most cases) by a change to a stratified pattern for which the concentration of drops in the gas phase is zero or close to zero.

The present study differs from the previous work on annular flows in that a smaller pipe diameter was used, inclined angle (θ) effect was studied, 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. Detail description of the flow configuration with and without drag reducing polymer is explained.

The finding that the annular flow regime is changed to a stratified pattern at maximum drag reductions or an annular-stratified or even remained an annular could, in some applications, be very important.

2. Experimental setup

The 0.0127 m pipeline used in this study has a length of 7 m. The pipe sections were constructed from Plexiglas to allow visual observations. The pipe is inclined upward. 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 (0.15×10^5 Pa). A detailed description of the loop is shown in Fig. 1.

The master drag reducing polymer (DRP) solution was prepared the day before an experiment was performed. MAGNAFLOC 110L is a high molecular weight anionic polyacrylamide flocculant as a liquid dispersion grade (produced by Ciba) was mixed gently with water in a 150-l tank with a concentration of 1000 wppm (weight basis). The master solution was transferred by gravity to a smaller tank, which was pressurized with air at 3×10^5 Pa (see Fig. 1). 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 by introducing of the master solution into the liquid through a hole with a diameter of 2 mm that was located at the bottom of the pipe, 1.0 m downstream of the tee where the air and water were mixed. This method involved injection at a location where the annular pattern was developed, i.e., 1.0 m from the mixing tee. In this way the polymer was rapidly mixed with liquid

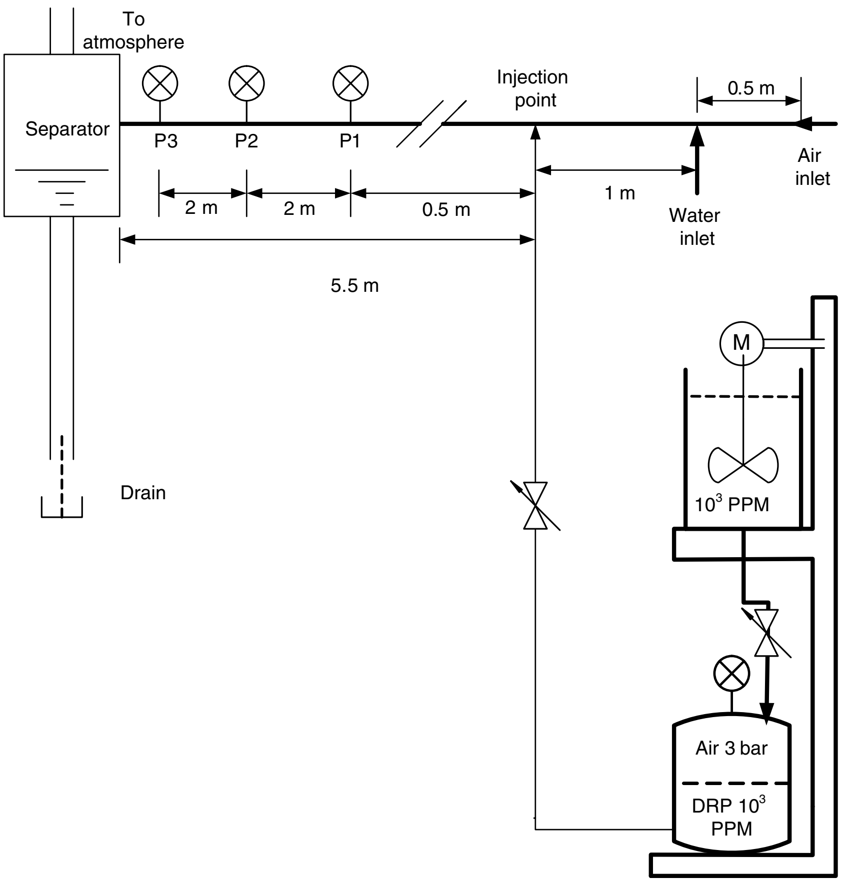

Fig. 1. Experimental setup.

flowing along the wall. A polymer concentration in the liquid in the pipeline of 100 ppm was used. A U-tube manometer was used to measure the pressure drop over a 2 m length of pipeline. The first pressure tap was located 0.5 m from the downstream injection point.

3. Results

3.1. Visual observations of flow pattern

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).

Detail explanation of the effect of the addition of polymer to the flow on the flow pattern is listed in Table 1. The air and water without DRP has an annular configuration with liquid film wetting the whole pipe circumference and the presence of a large-scale disturbance wave. The forth, fifth and sixth column represent the flow of air and water with 100 ppm of polymer added to the liquid for horizontal, and 1.28° and 2.4° of pipe inclination. The flow pattern at lowest gas and liquid superficial velocities ($U_{SG} = 19$, 24 m/s and $U_{SL} = 0.04$, 0.05 and 0.07 m/s) shows a stratified flow with a relatively smooth surface and a negligible amount of entrained drops in the gas phase.

These results can be interpreted by noting 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.

At the lowest superficial gas velocities ($U_{SG} = 19$ and 24 m/s) and highest superficial liquid velocity ($U_{SL} = 0.1$). Considering the horizontal case; the flow pattern with 100 ppm of polymer injected to the liquid film, the new flow pattern characterized by a thin liquid film at the top of the pipe and a thick film at the lower half of the pipe with no disturbance waves shown in the pipe. This flow configuration is called annular-stratified

Table 1
Flow patterns with and without 100 ppm polymers

U_{SG} (m/s)	U_{SL} (m/s)	Without DRP all angles	With 100 ppm ($\theta = 0°$)	With 100 ppm ($\theta = 1.28°$)	With 100 ppm ($\theta = 2.4°$)
38	0.10	Annular	Annular-clear	Annular-clear	Annular-clear
38	0.08	Annular	Annular-clear	Annular-clear	Annular-clear
38	0.07	Annular	Annular-stratified	Annular-clear	Annular-clear
38	0.05	Annular	Annual-stratified	Annular-clear	Annular-clear
38	0.04	Annular	Annular-stratified	Annular-clear	Annular-clear
33	0.10	Annular	Annular-stratified	Annular-stratified	Annular-clear
33	0.08	Annular	Annular-stratified	Annular-stratified	Annular-clear
33	0.07	Annular	Annular-stratified	Annular-stratified	Annular-clear
33	0.05	Annular	Annular-stratified	Annular-stratified	Annular-clear
33	0.04	Annular	Annular-stratified	Stratified	Annular-clear
28	0.10	Annular	Annular-stratified	Stratified	Annular-clear
28	0.08	Annular	Annular-stratified	Stratified	Annular-stratified
28	0.07	Annular	Stratified	Stratified	Annular-stratified
28	0.05	Annular	Stratified	Stratified	Stratified
28	0.04	Annular	Stratified	Stratified	Stratified
24	0.10	Annular	Annular-stratified	Stratified	Annular-pseudo slug
24	0.08	Annular	Annular-stratified	Stratified	Annular-stratified
24	0.07	Annular	Stratified	Stratified	Stratified
24	0.05	Annular	Stratified	Stratified	Stratified
24	0.04	Annular	Stratified	Stratified	Stratified
19	0.10	Annular	Annular-stratified	Stratified	Annular-pseudo slug
19	0.08	Annular	Annular-stratified	Stratified	Annular-mist
19	0.07	Annular	Stratified	Stratified	Stratified
19	0.05	Annular	Stratified	Stratified	Smooth-stratified
19	0.04	Annular	Stratified	Stratified	Smooth-stratified

as in Al-Sarkhi and Hanratty (2001b). The case for the angle 1.28° the final configuration with DRP was stratified but for the angle 2.4°, the final pattern was pseudo slug.

At the highest U_{SL} and U_{SG} the annular air and water flow contains many of the high amplitude disturbance waves. The pressure gradient is very high. Adding small amount of polymers to the flow causes the pressure gradient to start to drop down and the disturbance waves to start to disappear. With adding enough polymers (reaching 100 ppm) maximum drag reduction is achieved and beyond that amount there was no more drag reduction with adding more polymers, this situation is described as an annular with out disturbance waves (annular-clear). Annular-clear pattern id defined in the present work as annular flow pattern without disturbance waves and the concentration of drops in the gas phase is zero or close to zero. At lower superficial gas velocity (33 m/s) and same $U_{SL} = 0.1$ m/s the same sequences happened but the final pattern was stratified-annular instead of an annular for the horizontal and 1.28° angles and annular with out disturbance waves (annular-clear) for the 2.4° angle.

3.2. Effectiveness of drag reducing polymer (DRP)

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

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

where $\Delta P_{\text{with DRP}}$ is the pressure drop when drag-reducing polymer was present and $\Delta P_{\text{without DRP}}$ is the pressure drop in the absence of drag-reducing polymer. Results show that DR is very sensitive to U_{SG} and U_{SL}. The DR increases with increasing U_{SL}. Drag reduction increases with increasing U_{SG} at lower U_{SG} values and then decreases with increasing U_{SG} at higher U_{SG} values. Maximum and minimum DR for the 100 ppm of 100 ppm of DRP added to the liquid in the pipeline is listed in Table 2. Effect of pipe inclination can be appeared on two things; the first is the changes on the flow pattern with addition of the DRP and the second on the DR. in general all angles have the same trend of DR with U_{SL} and U_{SG}. The case of 1.28° inclination has the highest DR and the case of 2.4° has the lowest DR. The maximum DR among all experiments occurs at 1.28° inclination and lowest U_{SL} and highest U_{SG} as shown in Table 2. The effect of pipe inclination also appears on the changes of the flow pattern with adding DRP. At the lowest two superficial gas velocities (19 and 24 m/s) and the highest U_{SL} (0.1 m/s) the final pattern for air and water with 100 ppm DRP at inclination of 2.4° was pseudo slug while at 1.28° was stratified and at zero inclination was an annular-stratified. Noting that the maximum DR occurs for the case of 1.24° inclination in which the flow pattern changes from the annular to stratified. This behavior agrees with all previous studies, which indicated that the maximum DR accompanied always with change in the flow pattern from annular to stratified (Al-Sarkhi and Hanratty, 2001a,b and Al-Sarkhi and Soleimani, 2004).

Fig. 2 shows the variation of the drag reduction (DR) for all angles of inclination with the dimensionless superficial velocities $(U_{SG}/U_{SL})^{0.5}$. All angles of inclinations have the same behavior with increasing the dimensionless superficial velocities. The DR decreases with increasing the normalized superficial velocities. Fig. 3 shows the variation of DR with normalized superficial velocities for all angles having the same final pattern (after adding the 100-ppm of DRP) which is an annular. As mentioned above for different gas and liquid flow rate, the flow pattern after the addition of DRP changes to a new pattern. In Figs. 3–5 collections of those flows for which the final patterns after adding the 100-ppm DRP are the same. Surprisingly and the first time in literature, these results show that the behavior of DR with the normalized superficial velocities are nearly self-similar for similar final flow pattern (after adding the polymers) for all angle of inclinations in the present study.

Table 2
Maximum and minimum drag reduction for air and water with 100 ppm of DRP

Pipe inclination	Maximum DR (%)	U_{SG} (m/s)	U_{SL} (m/s)	Minimum DR (%)	U_{SG} (m/s)	U_{SL} (m/s)
0°	64.4	24	0.1	20	38	0.04
1.8°	71	19	0.1	16.8	38	0.04
2.4°	66	24	0.08	10	38	0.04

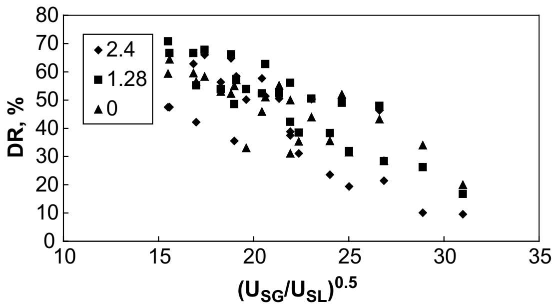

Fig. 2. Drag reduction for various angles versus normalized superficial velocities.

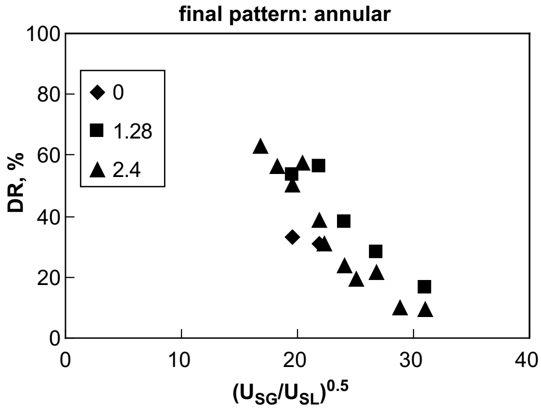

Fig. 3. Drag reduction versus normalized superficial velocities for flows with an annular final flow pattern.

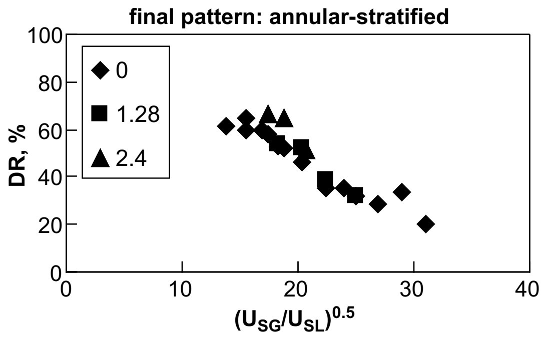

Fig. 4. Drag reduction versus normalized superficial velocities for flows with an annular-stratified final flow pattern.

Figs. 6 and 7 show the variations of the DR with U_{SL} at the highest and lowest U_{SG}, respectively. Figs. 8 and 9 show the variations of the DR with U_{SG} at the highest and lowest U_{SL}, respectively. The DR increases with U_{SL} and decreases with U_{SG} and the cases for the pipe inclination of 2.4° have the lowest drag reduction.

The uncertainty in the measurements of superficial velocities within ±4% and the uncertainty in the pressure measurements within ±4% to ±7%.

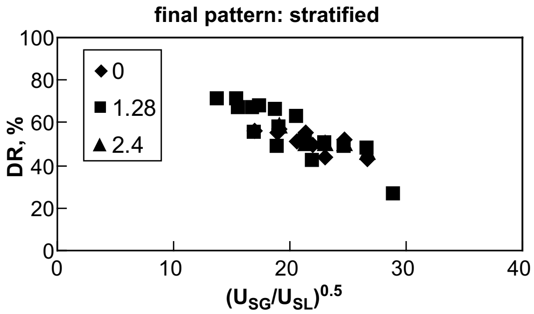

Fig. 5. Drag reduction versus normalized superficial velocities for flows with stratified final flow pattern.

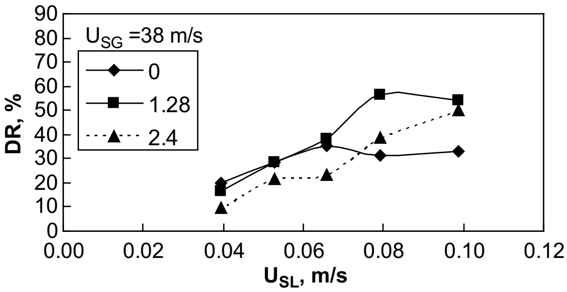

Fig. 6. Drag reduction versus superficial liquid velocity for different pipe inclinations and superficial gas velocity of 38 m/s.

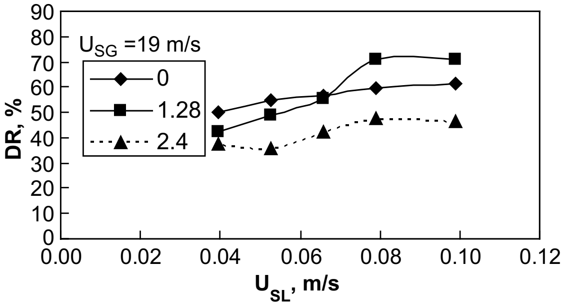

Fig. 7. Drag reduction versus superficial liquid velocity for different pipe inclinations and superficial gas velocity of 19 m/s.

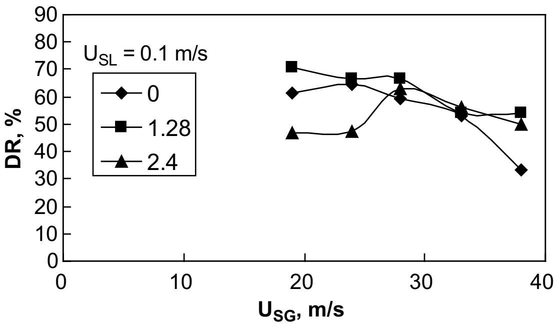

Fig. 8. Drag reduction versus superficial gas velocity for different pipe inclinations and superficial liquid velocity of 0.1 m/s.

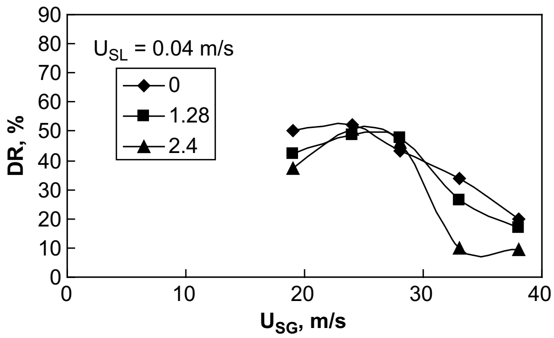

Fig. 9. Drag reduction versus superficial gas velocity for different pipe inclinations and superficial liquid velocity of 0.04 m/s.

4. Discussion and conclusions

The injection of polymer solution into an air–water flow that has an annular configuration in an inclined 1.28° pipe can produce drag reductions of about 71%. 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.

Visual observation of the pattern changes due to injection of polymers to an annular flow revealed that an annular flow pattern changes to stratified pattern at low superficial liquid and gas velocities. An annular flow pattern changes to an annular-stratified at higher gas and liquid velocities and finally, at highest superficial liquid and gas velocities an annular flow remains an annular but without disturbance waves. At lowest gas velocities, highest liquid velocity, and highest pipe inclination (2.4°) an annular flow changes to pseudo slug in the presence of DRP which expectable due to the tendency of accumulation of the liquid at the inlet of pipe with increasing the pipe inclination. A number of studies of air and water show that lower liquid flow rates are required to produce slugs in upflows and upward inclinations support transition to slug flows such as Grolman et al. (1996) and Simmons and Hanratty, (2001).

The pressure gradient of annular patterns of air and water in the absence of polymers are higher than that of air and water at same liquid and gas rates in the presence of polymers. The maximum drag reduction was achieved in the case of pipe inclination of 1.28° at the lowest superficial gas velocity and the highest superficial liquid velocity. The minimum drag reduction was achieved in the case of pipe inclination of 2.4° and at highest superficial gas velocity and lowest superficial liquid velocity. In general the higher the angle of inclination, the less drag reduction. However, the drag reduction is also highly dependant on the final flow pattern after adding the DRP. The present work and all previous research revealed that a maximum drag reduction that is accompanied (in most cases) by a change to a stratified flow for which the concentration of drops in the gas phase is zero or close to zero (Al-Sarkhi and Hanratty, 2001a,b and Al-Sarkhi and Soleimani, 2004). A plot of drag reduction versus the squared root of the ratio of the superficial velocities $(U_{SG}/U_{SL})^{0.5}$ shows that all angles have the same trend. As the ratio increases the drag reduction decreases. A plot of all angles of inclinations but for the same final (after adding the DRP) pattern shows that all graphs are nearly having self-similar behavior.

Acknowledgements

This work was supported by the Deanship of Research at Hashemite University under Grant 29/15/425. The authors are also would like to acknowledge the help of Munir Sukhtian Group Co. Ltd. for providing the drag reducing agent.

I thank Prof. T.J. Hanratty for all his support in the past, whose studies on gas–liquid flow have been an inspiration for many of us.

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