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Effect of drag-reducing polymers on pseudo-slugs—interfacial drag and transition to slug flow

Arash Soleimani, Abdel Al-Sarkhi, Thomas J. Hanratty *

Department of Chemical Engineering, University of Illinois at Urban-Champaign, 205 Roger Adams Laboratory, Box C-3 600 South Mathews Avenue, Urbana, IL 61801, USA

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Abstract

Drag-reducing polymers were added to air and water flowing in a stratified configuration in a horizontal 2.54 cm pipe. The interface was covered with large amplitude roll waves, that have been called pseudo-slugs, over a range of flow conditions. The damping of small wavelength waves causes a large decrease in the interfacial stress and, therefore, an increase in the liquid holdup. At superficial gas velocities greater than 4 m/s the transition to slug flow is delayed in that it occurs at larger liquid holdups. This observation is interpreted by assuming that turbulence in slugs is damped. This increases the shedding rate of a slug and, therefore, its stability. The pressure drop can increase or decrease when polymers are added. The increase in holdup is accompanied by an increase in gas velocity, which causes an increase in the pressure drop. The decrease in the interfacial stress has the opposite effect.

1. Introduction

The addition of very small amounts of a high molecular weight polymer (of the order of 1 ppm) to a turbulently flowing liquid causes dramatic changes in the turbulence, which result in the reduction of the drag on a solid surface. This remarkable finding has prompted a number of studies of the influence of polymers on gas–liquid flows. Drag-reductions have been noted but the most interesting aspect of these works is the finding that the configuration of the phases can be changed. For example, Al-Sarkhi and Hanratty (2001a) found that the injection of a concentrated solution of a co-polymer of polyacrylamide and sodium acrylate into an air–water flow in a

* Corresponding author. Tel.: +1-217-333-1318; fax: +1-217-333-5052.
E-mail address: hanratty@scs.uiuc.edu (T.J. Hanratty).

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9.53 cm pipe changed an annular pattern to a stratified pattern by destroying the disturbance waves in the liquid film. This occurred with mixed mean concentrations of 10–15 ppm. Drag reductions of 48% were realized. In a subsequent study in a 2.54 cm pipe, Al-Sarkhi and Hanratty (2001b) obtained similar results and observed drag-reductions as large as 63%.

This paper looks at the influence of a drag reducing polymer on the transition to slug flow and on interfacial drag. The studies were carried out for air and water flowing in a horizontal pipe with a diameter of 2.54 cm. At a fixed gas velocity, roll waves appear on the interface of an air–water flow at a sufficiently large liquid flow. This transition is described by viscous long wavelength theory (Lin and Hanratty, 1986). At low gas velocities, slugs appear at liquid flows slightly above this critical condition, so that viscous long wavelength theory predicts the transition to a slug flow pattern. At high gas velocities the instability of the stratified flow occurs at too low a layer height for a stable slug to exist. The critical liquid hold-up for the appearance of slugs is, then, predicted by considering the stability of a slug.

The choice of a pipe diameter of 2.54 cm for this study was made so that direct comparisons could be made with results recently obtained for air and water flowing in a horizontal pipe (Soleimani and Hanratty, in press). This has the disadvantage that the transition to slug flow is more complicated than what is observed in larger diameter pipes. At a fixed gas velocity, roll waves exist over a large range of liquid flows. These waves can touch the top of the pipe, so visual observations suggest the existence of slugs. This pattern has been characterized by Lin and Hanratty (1986) as pseudo-slugs. They can be differentiated from slugs by examining the sizes of the pressure pulsations and the velocities of the disturbances, as suggested by Lin and Hanratty (1986).

2. Description of the experiment

The 2.54 cm pipeline had a length of 18.3 m. The liquid and gas were mixed in a tee-section at the inlet. The thickness of the liquid layer was determined by measuring the conductance between two parallel wires located at 15.5 and 16 m from the entrance. The conductance method is described in several previous papers from this laboratory (Lin and Hanratty, 1987a,b; Fan et al., 1993; Woods and Hanratty, 1996). The probes are calibrated by measuring the conductance when the pipe is filled to different levels. A plot of h/D, where h is the height at the center of the stratified layer and D the pipe diameter, versus conductance gives a linear relation (Williams, 1990) so that the time-averaged conductance gives the time-averaged h when the liquid level is varying. The frequency response of the probes might not be satisfactory for capillary waves because of the unknown response of the meniscus on the wires.

Pressure gradients were measured with a capacitance differential pressure transducer that was situated between 15 and 16.5 m from the entrance Transducers with pressure ranges of 25 and 5000 Pa were used. Pressure fluctuations were determined with a pressure transducer that was located 13.3 m from the outlet of the pipe. Pressure and height measurements were made every 3 milliseconds.

The additive was a co-polymer of polyacrylamide and sodium acrylate. On the day before the experiment was performed, the powder was gently mixed with water, to form a master solution of

1000 ppm, by a method described by Warholic et al. (1999). This was injected 1.25 m from the inlet through three holes located at the bottom of the pipe.

Mixed mean concentrations, C_H, of the polymer solution in the pipe of 10, 50 and 100 ppm were studied. Most of the discussion focuses on the results obtained with $C_H = 100$ ppm because these showed the largest effect on holdup and on interfacial stress.

3. Results

3.1. Measurement of holdup for $C_H = 100$ ppm

Measurements of the time variation of h/D at a superficial gas velocity, U_{SG}, of 6 m/s are presented in Fig. 1 for different superficial liquid velocities, U_{SL}. Those on the left side are for air–water flows. Those on the right side are for situations in which polymer solution was added. The transition to slugging occurs at $U_{SL} = 0.22$ m/s for a water flow. The injection rate was such that the mixed average concentration was 100 ppm.

These tracings are compressed considerably so the waves are distorted. The wave velocity is 1–3.5 m/s, depending on the liquid flow, both for the water and for the polymer solutions. The diameter of the pipe is 0.0254 m, so $h/D = 0.8$ corresponds to a distance of about 0.02 m. For a wave velocity of 2.2 m/s the abscissas of these plots should be stretched by a factor of about 13,000 to obtain a true geometric representation of the waves. We characterize the large scale structure of the h/D tracings as roll waves which have very long wavelengths, a steep rise in h at their front and a more gradual decrease in h at the rear. This behavior is clearly seen in the tracings for polymer solutions. It can also be seen in the tracing for water if the tracings are given over a much shorter time interval than used in Fig. 1. Larger U_{SL} are required to initiate roll waves when polymers are added. Visual observation indicates that the surfaces of the roll waves and of the stratified flow between roll waves are smoother for the polymer solutions than for water. This is reflected in the tracings.

The frequency of the roll waves, f, was determined simply by counting the number of waves in tracings such as shown in Fig. 1. It is clearly seen that f is smaller for the polymer solution. The height of the roll waves are about the same. However, the lengths (or the holdups) of the roll waves are larger for the polymer solutions. The height of the stratified flow between the roll waves is about the same so that the total liquid carried by the roll waves is about the same for water and polymer solutions at a given U_{SL}.

Measurements of h/D are presented as a function of U_{SL} for $U_{SG} = 6$, 10 m/s in Fig. 2. For $U_{SG} = 3$ m/s the transition to slugging occurs at a U_{SL} close to that observed for the transition to roll waves. The addition of polymers only slightly affects the critical h/D. For the air–water system at $U_{SG} \geqslant 4$ m/s, the h/D at which slugs appear is larger than the h/D at which roll waves appear. The critical h/D for the initiation of slugs is described by considering the stability of a slug. The prediction of the critical U_{SL} is much more difficult. This can be understood by examining Fig. 2. There is a large range of liquid flows, before the initiation of slugs, over which h/D is relatively constant and approximately equal to the critical, so the critical h/D roughly corresponds to a range of U_{SL}. This remarkable result indicates a very complicated pattern for which increases in liquid flow are accommodated mainly by increases in the velocities of the roll waves. We have called this regime "incipient slugging".

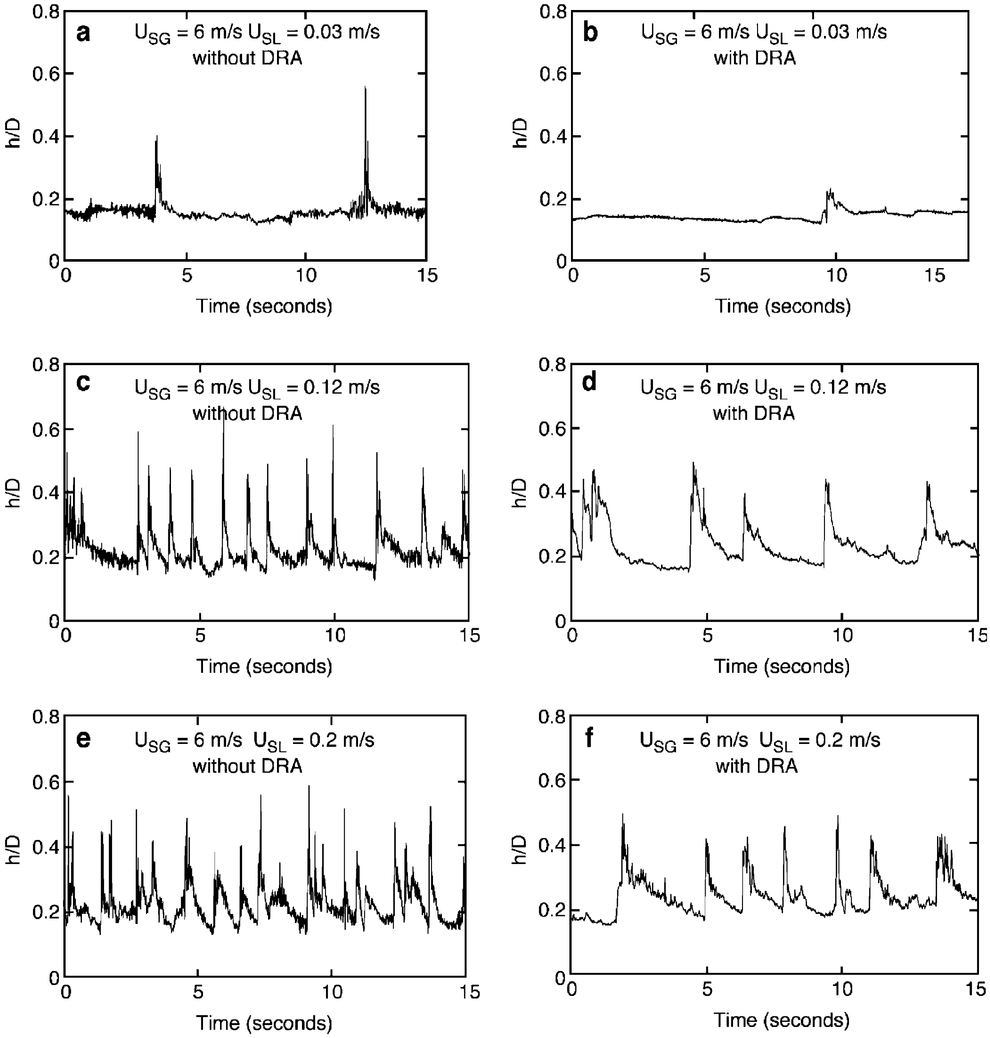

Fig. 1. Liquid holdup measurements at a gas superficial velocity of 6 m/s for flow with ($C_H = 100$ ppm) and without polymer additive.

The addition of polymers causes the h/D or liquid hold-up to increase significantly. Results for $U_{SG} = 6$ and 10 m/s, given in Fig. 2, show that the influence of U_{SL} on h/D at a given U_{SG} for the polymer solution is qualitatively the same as found for water. However the region of incipient slugging extends over a much larger range of liquid flows so that both the critical h/D and U_{SL} increase.

3.2. Measurements of the pressure gradient and calculated stresses

Measurements of the pressure gradient are given in Figs. 3 and 4 for $C_H = 100$ ppm. Little effect of the polymer is observed at very low U_{SL}. As mentioned earlier, initiation of slug flow, for

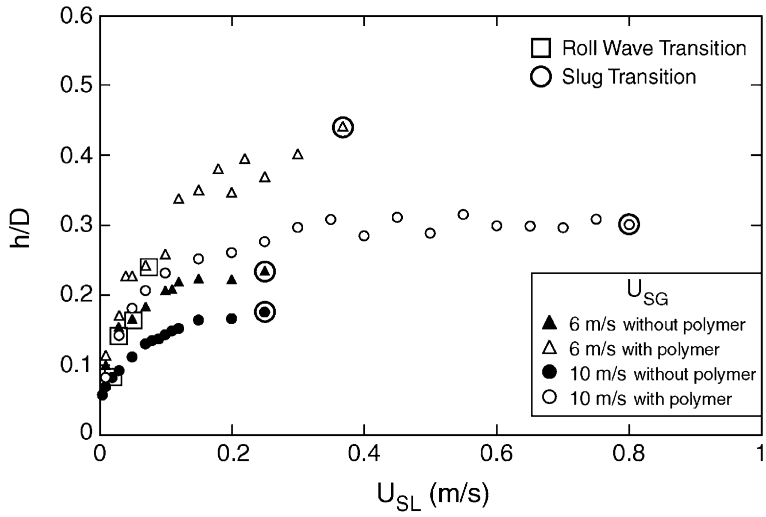

Fig. 2. Holdup at $U_{SG} = 6$, 10 m/s for a range of superficial liquid velocities with ($C_H = 100$ ppm) and without polymer additive.

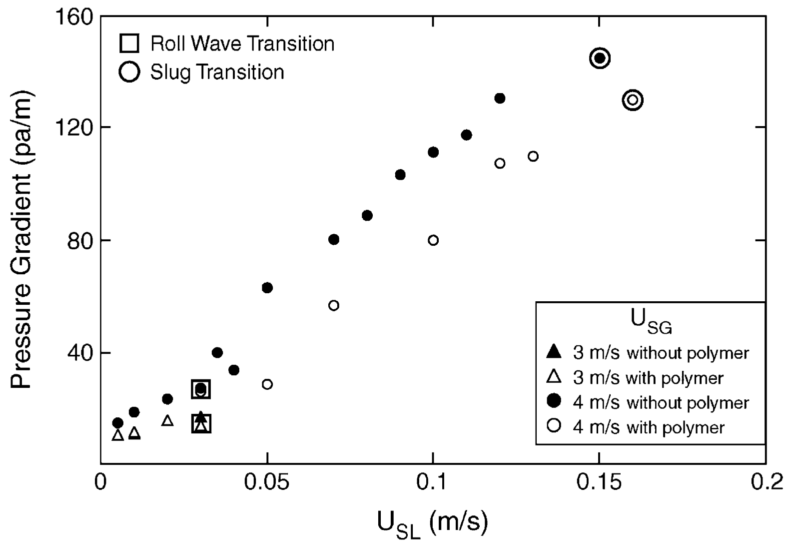

Fig. 3. Measurements of the effect of U_{SL} on the pressure gradient for $U_{SG} = 3$, 4 m/s with ($C_H = 100$ ppm) and without polymer additives.

$U_{SG} = 3$ m/s, almost coincides with the appearance of roll waves. After the initiation of roll waves the pressure gradient shows large increases with increasing U_{SL}. For $U_{SG} = 4$, 6 m/s, dP/dx is observed to decrease with the addition of polymer. The polymers have counterbalancing influences. The increase in holdup causes an increase in the gas velocity, which causes an increase in the resisting stresses at the wall, τ_{WG}, and at the interface τ_i. However, the large decrease in the

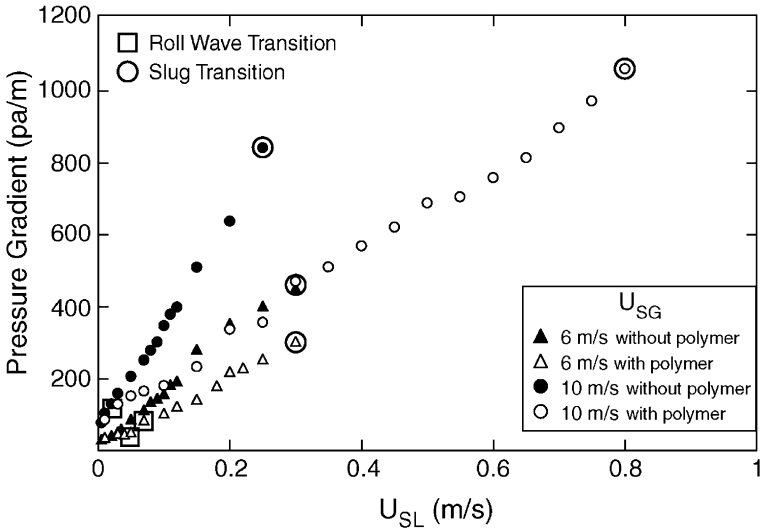

Fig. 4. Measurement of the effect of U_{SL} on the pressure gradient for $U_{SG} = 6$, 10 m/s with ($C_H = 100$ ppm) and without polymer additive.

roughness of the interface causes a decrease in τ_i. Thus, an increase or decrease in dP/dx could be expected.

For $U_{SG} = 10$ m/s (Fig. 4) two effects are noted. For $U_{SL} \leqslant 0.25$ m/s the addition of polymers is seen to cause a decrease in the pressure gradient, when comparisons are made at the same U_{SL}. For 0.25 m/s $< U_{SL} <$ 0.8 m/s slugging is observed for the air–water. This is not the case for the system with $C_H = 100$ ppm. Thus, over this range of U_{SL}, one can expect significantly smaller pressure gradients for the polymer solution since comparisons are being made for flows with and without slugs.

The interfacial stress, τ_i, and the stress on the part of the wall in contact with the stratified layer, τ_{WL}, can be estimated by using an idealized model, which pictures the interface to be flat (Andritsos and Hanratty, 1987) and by using a friction factor relation to calculate the drag of the gas in the wall, τ_{WG}. Thus

$$\tau_{WG} = \frac{f_G \rho_G U_G^2}{2} \tag{1}$$

where U_G is the gas velocity, ρ_G the gas density and f_G the friction factor for the gas flow:

$$f_G = 0.046 \left(\frac{\rho_G U_G D_{HG}}{\mu_G} \right)^{-0.2} \tag{2}$$

where μ_G is the viscosity of the gas, D_{HG} the hydraulic diameter,

$$D_{HG} = 4 \frac{A_G}{S_G + S_i} \tag{3}$$

and A_G, A_L are the areas of the cross sections occupied by the gas and the liquid. The lengths of the portions of the pipe wall touched by the gas and the liquid are S_G and S_L. The length of the interface is S_i. Parameters A_G, A_L, S_G, S_i, S_L can be calculated from measurements of h/D (Govier and Aziz, 1972).

A force balance on the gas phase is given as

$$-A_G\left(\frac{dP}{dx}\right) = \tau_{WG}S_G + \tau_i S_i \tag{4}$$

From measured dP/dx and Eq. (1), the above equation is used to calculate the drag on the interface, τ_i. A friction factor, f_i, is defined as

$$\tau_i = \frac{f_i \rho_G U_G^2}{2} \tag{5}$$

Values of f_i are plotted in Figs. 5 and 6, as the ratio f_i/f_G. For the air–water flow just before the transition to roll waves $f_i/f_G = 1, 3, 4, 5$ for $U_{SG} = 3, 4, 6, 10$. After transition, f_i/f_G increases dramatically with increasing U_{SL}. It reaches values of 2, 19, 30, 35 just before the transition to slug flow for $U_{SG} = 3, 4, 6, 10$ m/s. The very large values of interfacial friction factor are associated with the presence of large amplitude roll waves (pseudo-slugs). The addition of polymers causes a decrease in f_i/f_G, of the order of 1/2–1/4, from what is observed for air–water. At the transition to roll waves $f_i/f_G = 1, 1, 2, 2$ for $U_{SG} = 3, 4, 6, 10$ m/s.

Values of the resisting stress of the wall on the liquid, τ_{WL}, are calculated from measured dP/dX and h/D by using a force balance over the entire pipe cross section,

$$-A\left(\frac{dP}{dx}\right) = \tau_{WG}S_G + \tau_{WL}S_L. \tag{6}$$

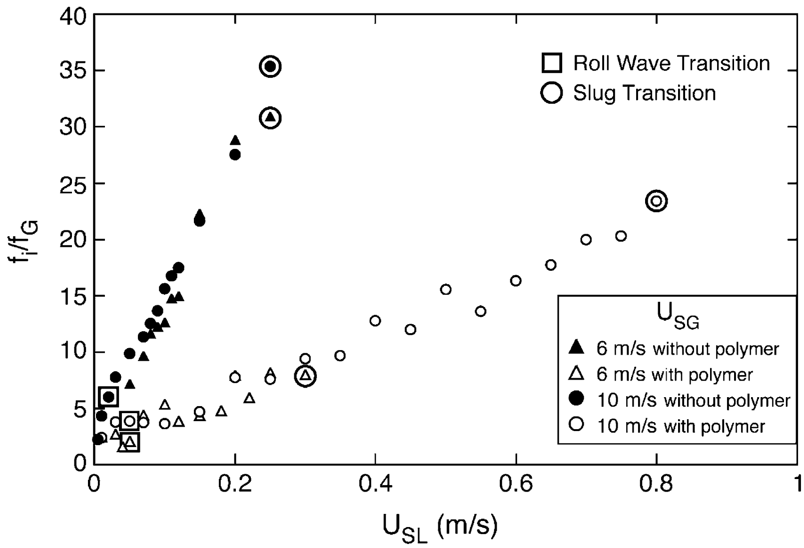

Fig. 5. Interfacial friction factors at $U_{SG} = 6$, 10 m/s for a range of superficial liquid velocities with ($C_H = 100$ ppm) and without polymer additive.

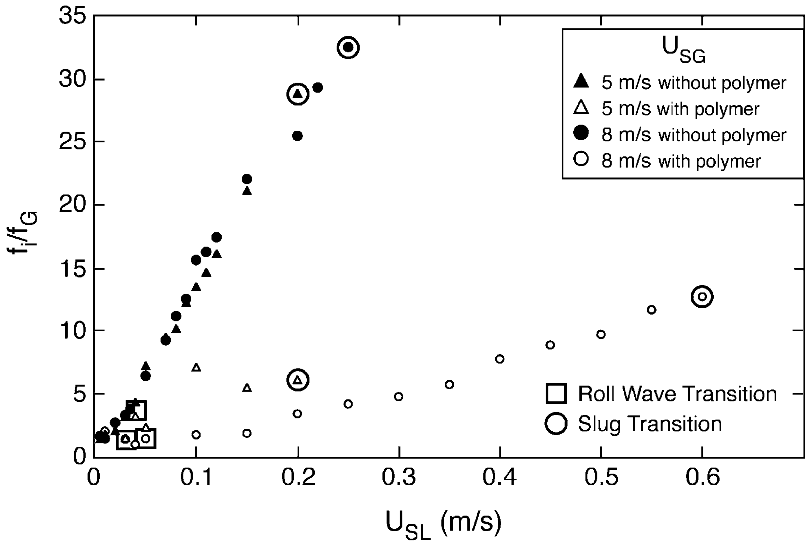

Fig. 6. Interfacial friction factors for $U_{SG} = 5$, 8 m/s for a range of superficial liquid velocities with ($C_H = 100$ ppm) and without polymer additive.

These are plotted in Fig. 7 for $U_{SG} = 6$, 10 m/s. Increases are noted in the region of incipient slugging where h/D is approximately independent of U_{SL}. The addition of polymers is seen to decrease the wall stress. This occurs both because of the decrease of the liquid velocity associated with the increase in h and because of the damping of the turbulence in the liquid.

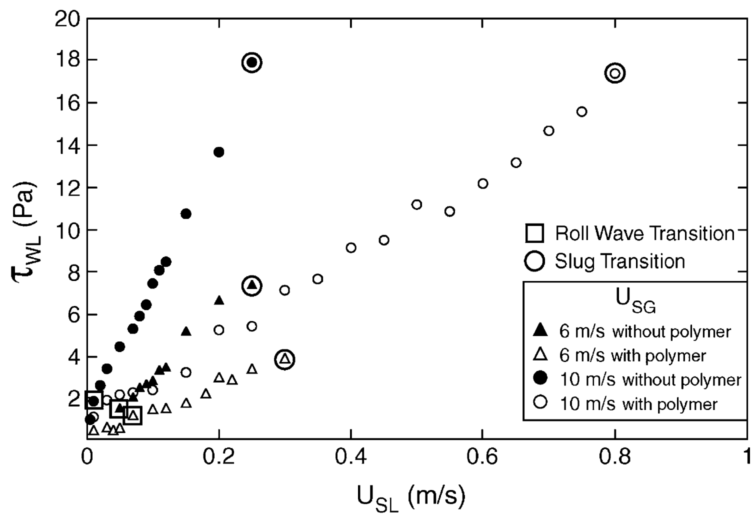

Fig. 7. Measurements of the effect of U_{SL} on the resisting stress on the liquid for $U_{SG} = 6$, 10 m/s with ($C_H = 100$ ppm) and without polymer additive.

3.3. Critical condition for the initiation of the roll waves and slugs

The critical h/D for the transition to roll waves are, respectively, given by the squares and $\times$'s in Fig. 8 for water and for a polymer solution with $C_H = 100$ ppm. It is noted that the critical height decreases with increasing U_{SG}. The addition of polymers increases the critical h/D, slightly, at large U_{SG}.

Critical h/D for the initiation of slugs are, respectively, represented by circles and diamonds, for flow of water and of polymer solutions with $C_H = 100$ ppm, in Fig. 8. The polymers are seen to have no effect at low U_{SL}, but they cause large increases in the critical h/D for $U_{SG} > 5$ m/s.

3.4. Wave properties

Measurements of the effect of polymers on the frequency of roll waves are given in Fig. 9 for $U_{SG} = 10$ m/s. These were obtained by simply counting the number that passed a certain location over a period of time. As already noted in Fig. 1, the addition of polymers causes a decrease in the frequency.

Measurements of the cross-correlation coefficients of height variations were obtained with two probes separated by a distance of 0.91 m. Average wave velocities, calculated as the ratio of separation distance and the time characterizing the first maximum in the cross-correlation, are shown in Fig. 10 for $U_{SG} = 10$ m/s and $C_H = 0, 25, 50, 100$ ppm. Polymers cause a decrease in the wave velocity. Of particular interest is the large increase in wave velocity with increasing U_{SL}. In the region of "incipient slugging", where h/D is roughly constant, the increase in U_{SL}, at

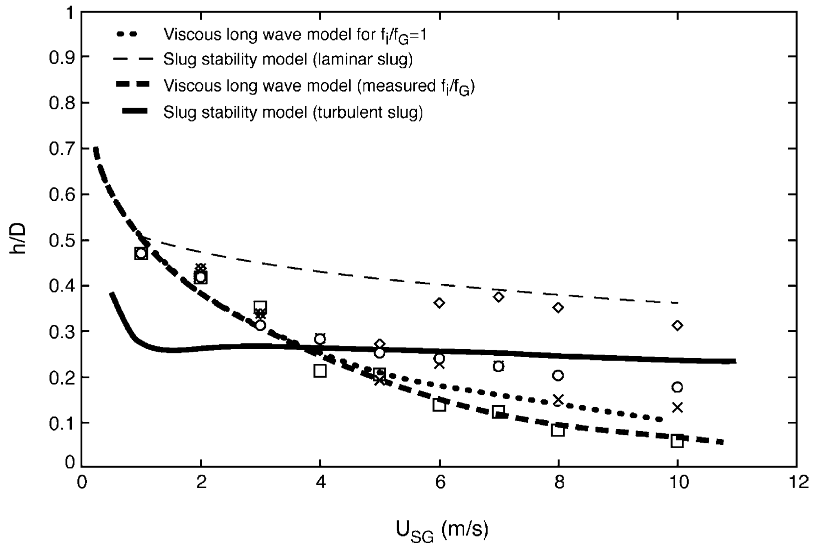

Fig. 8. Critical heights for air–water flows in a horizontal pipe with ($C_H = 100$ ppm) and without polymer additive; $\times$ roll wave transition for polymer solution, $\square$ roll wave transition for water, $\diamondsuit$ slug transition for polymer solution, $\circ$ slug transition for water.

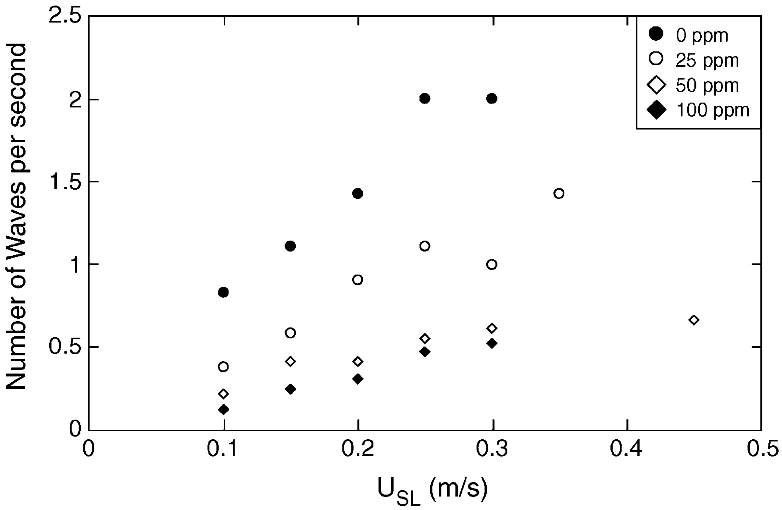

Fig. 9. The influence of U_{SL} and polymer concentration on roll wave frequency for $U_{SG} = 10$ m/s.

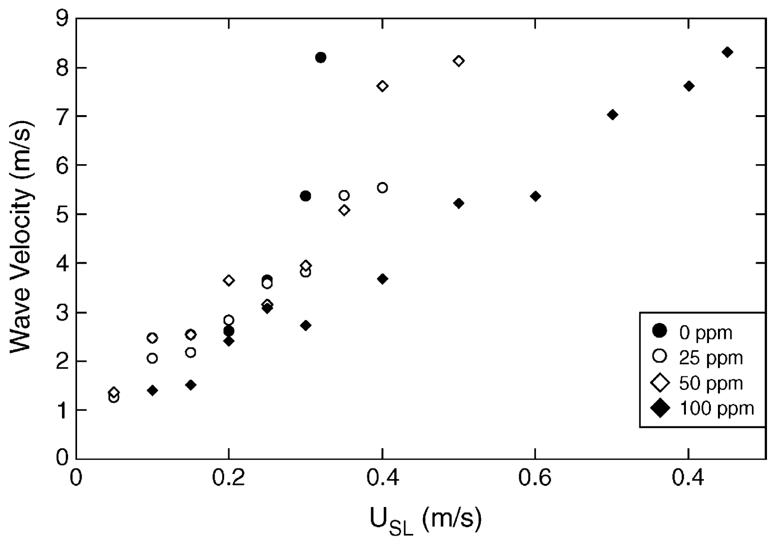

Fig. 10. The influence of U_{SL} on wave velocity for different polymer concentrations at $U_{SG} = 10$ m/s.

a constant U_{SG}, appears to be accommodated by increases in the velocities and the sizes of the roll waves.

Autocorrelations of the height fluctuations are defined as

$$\rho(\Delta t) = \frac{\overline{h'(t)h'(t+\Delta t)}}{\overline{h'^2}} \tag{7}$$

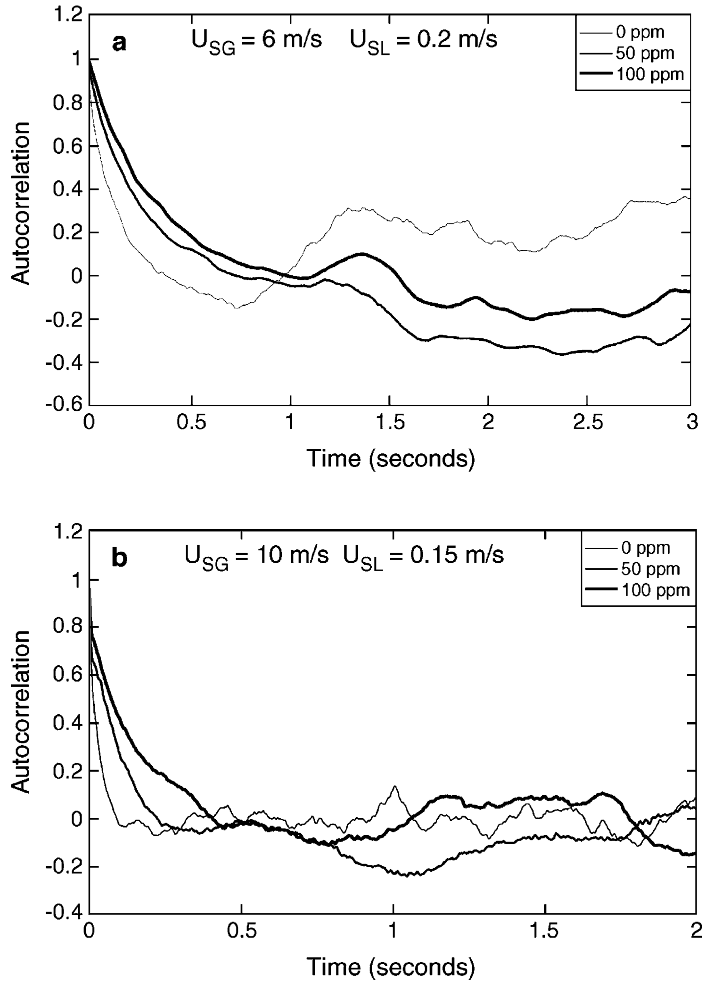

Fig. 11. Autocorrelation of the height fluctuations at $U_{SG} = 6$, 10 m/s for different polymer concentrations.

where $h' = h - \bar{h}$. Examples are presented in Fig. 11. Of particular interest is the behavior at small times, where the addition of polymers is seen to cause an increase in the autocorrelation coefficient. This indicates a damping of small wavelength waves, already noted in Fig. 1.

3.5. *Effect of polymer concentration, C_H*

The effects of polymer concentration, C_H, on roll wave frequency, roll wave velocity and on the autocorrelation of the height fluctuations are shown in Figs. 9–11. These show progressive decreases in the frequency, the velocity and the importance of small wavelength waves with increasing polymer concentration. This suggests that further changes could be realized for $C_H > 100$ ppm.

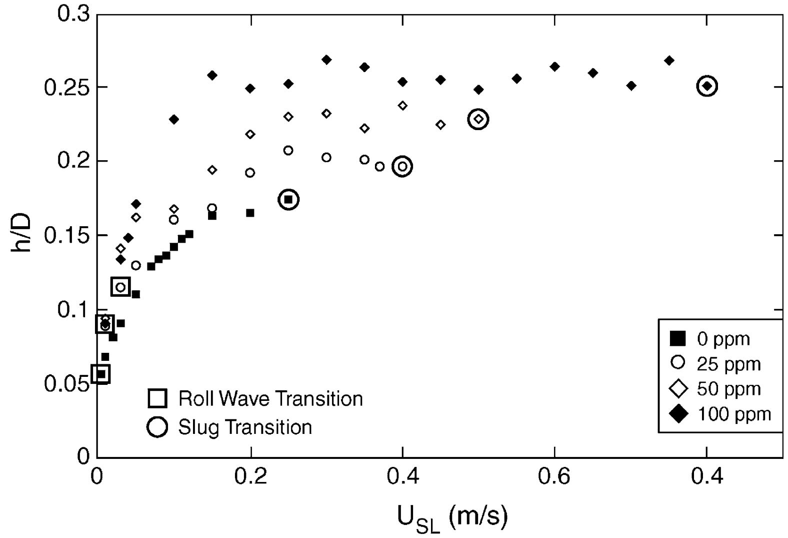

Fig. 12. Holdup at $U_{SG} = 10$ m/s for a range of superficial liquid velocities and for different concentrations of polymer.

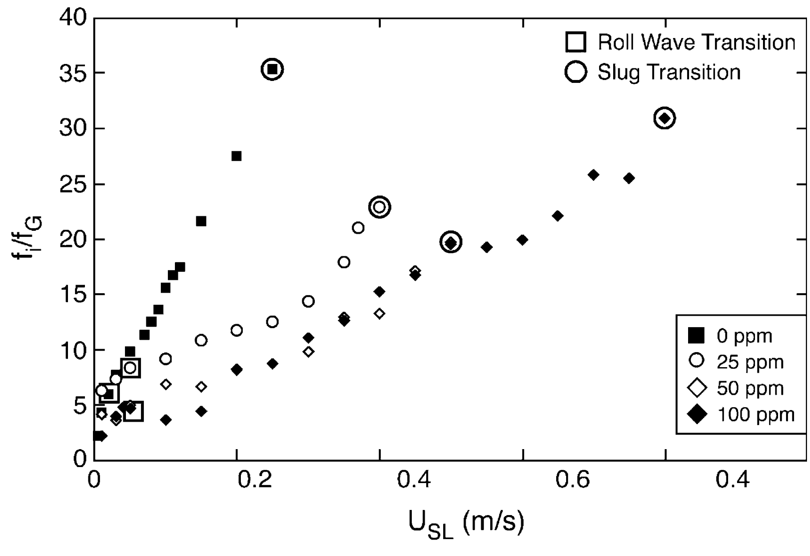

Fig. 13. Interfacial friction factors at $U_{SG} = 10$ m/s for a range of superficial liquid velocities and polymer concentrations.

The influences of polymer concentration on the critical h/D and U_{SL} needed for generating roll waves and slugs are shown in Fig. 12 for $U_{GG} = 10$ m/s. The critical condition and the region of incipient slugging are seen to increase progressively with increasing C_H. Fig. 13 shows decreases in the interfacial friction factor, normalized with the value obtained from Eqs. (1) and (2), with increasing polymer concentration. Measurements of the pressure gradient for different polymer concentrations are presented in Fig. 14. All of the runs with polymer solutions show a smaller

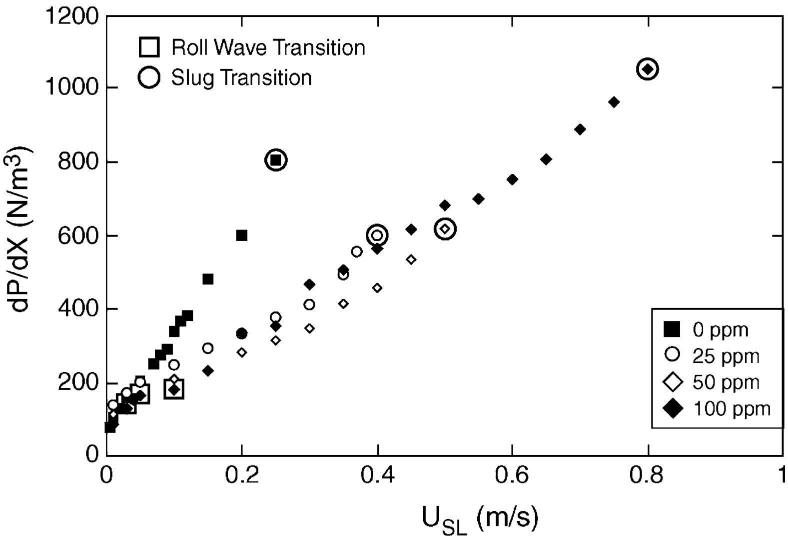

Fig. 14. Pressure gradients at $U_{SG} = 10$ m/s for a range of superficial liquid velocities and polymer concentrations.

pressure gradient than is observed for water. However, it is interesting to note that the decrease is not monotonic with increasing C_H. The pressure gradients for 25 and 50 ppm are seen to be lower than what was observed for 100 ppm. This reflects on the observation made earlier that the changes of holdup and interfacial drag, caused by the addition of polymers, have different effects on the pressure gradient.

4. Discussion

4.1. Transition to slug flow

The result of particular interest is the increase in the h/D needed to initiate slugging when polymers are added. This change is not enormous, but it translates into large increases in the critical U_{SL}. We explore an interpretation of this behavior, which presumes that the polymers damp the turbulence in a slug. An upper limit for the critical h/D is obtained by assuming a laminar flow in the slug.

Slugs are stable when the rate at which they pick up liquid is greater than the rate at which liquid is shed. The pickup is obtained by applying conservation of mass at the front of the slug. The back of the slug is pictured as a bubble, which has a velocity C_B. The following equation is derived for a neutrally stable slug:

$$\left(\frac{A_{L1}}{A}\right)_{Crit} = \frac{(C_B - u_3)(1 - \varepsilon)}{C_B - u_1} \tag{8}$$

where A_{L1} is the average area of the stratified liquid and u_1 the liquid velocity in the stratified flow in front of the slug. The void fraction of the slug is designated by ε and u_3 is the liquid velocity in the slug, given by

$$u_3 = \frac{U_{\text{mix}}}{(1 + (s - 1)\varepsilon)} \tag{9}$$

$$U_{\text{mix}} = (U_{\text{SL}} + U_{\text{SG}}) \tag{10}$$

Term s is the slip, equal to the ratio of the velocity of the bubbles in the slug to the velocity of the liquid in the slug.

For Newtonian fluids with viscosities close to that for water the flow in the slug is turbulent. The slip ratio varies from 1 at $U_{\text{mix}} < 2$ m/s to about 1.5 at $U_{\text{mix}} > 8$ m/s. Experiments by Bendiksen (1984) and by Woods and Hanratty (1996) give

$$C_{\text{B}} = 1.2U_{\text{mix}} \quad \text{for } U_{\text{mix}} > 3.5\sqrt{gD} \tag{11}$$

$$C_{\text{B}} = 1.1U_{\text{mix}} + 0.542\sqrt{gD} \quad \text{for } 2\sqrt{gD} < U_{\text{mix}} < 3.5\sqrt{gD} \tag{12}$$

$$C_{\text{B}} = U_{\text{mix}} + 0.542\sqrt{gD} \quad \text{for } U_{\text{mix}} < 2\sqrt{gD} \tag{13}$$

For the situation considered in the paper, Eq. (11) is applicable. This relation has been interpreted as being the ratio of the centerline velocity to bulk-average velocity in the slug (Hurlburt and Hanratty, 2002).

For (A_{L1}/A) greater than the critical, the slug will grow and for (A_{L1}/A) less than the critical the slug will decay. Under neutrally stable conditions the stratified flows in front and behind the slugs will have the same A_{L}, which can be calculated from Eq. (8) and is designated by A_{L0}. It is not possible to generate stable slugs from a stratified flow with $A_{\text{L}} < A_{\text{L0}}$. From geometric relations that assume a flat horizontal interface one can calculate a critical h_0/D that corresponds to A_{L0}/A.

Values of h_0/D have been obtained for air–water flow with Eq. (8) by using an equation for ε given by Andreussi and Bendiksen (1986). These are presented in Fig. 8 as the solid curve. Rough agreement with the measurements for gas–water is observed. For laminar flow we have presumed that

$$\frac{C_{\text{B}}}{u_3} = \frac{\text{centerline velocity}}{\text{bulk velocity}} = \frac{3}{2} \tag{14}$$

The dashed curve in Fig. 8 was calculated with Eq. (8) by using Eq. (14) to represent C_{B}. Approximate agreement with the critical h/D measured for a polymer solution is obtained. This suggests that the increase in the critical h/D caused by the addition of polymers is the result of a suppression of turbulence in the slugs.

4.2. Transition to roll waves

Viscometric studies show that solutions of the polymer in tap water at 100 ppm have shear viscosities close to that of water. Furthermore, it is believed that the injected polymer solution remains intact and is mixed as a thread as it moves downstream, so the wall sees a much more dilute solution than would be expected for a completely mixed solution of 100 ppm. We do not feel that the influence of the polymer on the transition to roll waves can be explained as being due to a change in shear viscosity.

A striking observation is that the interface appears to be much smoother when polymers are present. The polymers tend to damp small wavelength waves. Thus, the stratified flow that exists prior to the appearance of roll waves has a glassy appearance. This is manifested by a decrease in f_i. Thus $f_i/f_G \cong 3$ characterizes water interface of the stratified flow at the transition to roll waves, while $f_i/f_G \cong 1$ characterizes the interface at transition after the addition of polymers. We, therefore, have explored the possibility that the small influence of polymers on the initiation of roll waves, shown in Fig. 8, can be explained as being due to this decrease in f_i/f_G.

Hanratty and Hershman (1961) have explained the appearance of roll waves by carrying out an analysis of the stability of a stratified flow in a rectangular channel by using viscous long wavelength theory. Lin and Hanratty (1986) adapted this analysis to the stratified flow that exists in a horizontal circular pipe in order to relate the instability to the appearance of slugs at low gas velocities. Soleimani and Hanratty (in press) have recently used the analysis to describe the appearance of roll waves in a pipeline flow. The solid curve in Fig. 8 represents the calculations for air–water flow, using $f_i/f_G = 3$. Good agreement with the results for water is noted. The second curve in Fig. 8 was calculated with viscous long wavelength theory using $f_i/f_G = 1$. Good agreement is also noted between the calculations and the measurements of the critical h/D for polymer solutions.

4.3. Measurements of f_i/f_G

The large decrease of f_i/f_G observed with addition of polymer can be ascribed to a change of wave properties. Miya et al. (1971) and Miya (1970) have considered the influence of roll waves on interfacial drag. They have shown that the form drag, associated with the flow over a protrusion with the average shape of a roll wave, is making a smaller contribution to the interfacial drag than the small wavelength waves that populate the interface of the roll wave. We use their observation to interpret the results presented in this paper. That is, we argue that the decrease in drag observed with the addition of polymers results from a damping of small wavelength waves rather than from a damping of the roll waves.

4.4. Wave properties

As shown in Figs. 1 and 9 the frequency of roll waves decreases and their holdup increases with the addition of polymer. Average velocities of roll waves are presented as a function of U_{SL} in Fig. 10. It is noted that the wave velocity increases with U_{SL} and decreases with the addition of polymers. It eventually approaches the velocity of a slug close to the transition to slug flow. In Section 4.1 an argument has been presented that the addition of polymers damps turbulence in the slugs and that a consideration of the stability of a laminar slug provides an upper bound for the height of an unstable stratified flow. Eqs. (11) and (14) suggest that, for a fixed U_{SG}, the slug velocity increases as the slug approaches a laminar condition. This indicates that there will be an increase in the range of U_{SL} defining incipient slugging, as is seen in Figs. 2 and 7.

4.5. Effect of concentration

As shown in Fig. 12, the roll wave and slug transitions change with polymer concentration. By increasing the polymer concentration, f_i/f_G is decreased. This causes a delay in roll wave transition. In the case of the transition to slugging, the ratio of the centerline velocity to the bulk velocity could increase with increasing polymer concentration. We postulate that this causes an increase in the shedding rate at the slug tail, which make the slug more unstable.

Increasing the polymer concentration causes a reduction in f_i/f_G because of damping of high frequency waves on the interface. This interpretation is supported by the measurements of the autocorrelation coefficient given in Fig. 11.

Increasing polymer concentration does not result in a monotonic decrease in the pressure gradient (Fig. 14) because the polymers increase the holdup and decrease the interfacial friction. These two changes have opposite effects on the pressure drop.

5. Concluding remarks

The influence of the addition of polymers on the transition to slugging, on the transition to roll waves, on the liquid holdup and on the interfacial drag is examined. The concentration of the injected polymer was large enough that it did not mix readily on a small scale, but kept a filamental configuration. The system considered was air and water flowing in a 2.54 cm pipe. This system presents a more complicated stratified flow than observed in a pipe with a larger diameter, because of the existence of a pseudo-slug (roll wave) pattern over a large range of flow variables.

The addition of polymers is found to increase the critical h/D and the critical U_{SL} for the initiation of slugs and roll waves and to increase the range of U_{SL} over which pseudo-slugs exist. The addition also causes a decrease in the interfacial friction coefficient, which can be particularly large in the pseudo-slug regime. Because of this decrease in f_i, a pronounced increase in h/D, the liquid hold up, is observed. The decrease in f_i also causes a decrease in the frictional pressure drop. However, this is counterbalanced because of an increase in the gas velocity that is associated with an increase in liquid holdup.

We interpret these results by arguing that the polymers destroy the turbulence in the slugs and damp waves at the interface. We suggest that laminarization of the slug is associated with an increase in the velocity of the bubble behind a slug. This causes an increase in the shedding rate and, therefore, a destabilization of the slugs. If one argues that the pseudo-slug regime is terminated when the roll wave velocity is approximately equal to the slug velocity, then the increase is slug velocity, caused by the addition of polymer, could also be associated with a lengthening of the range of U_{SL} over which pseudo-slugs exist.

The addition of polymers does not diminish the importance of roll waves. On the contrary, the liquid holdup of these waves increases. We suggest that the decrease in f_i is associated, mainly, with damping of small wavelength waves on the roll waves and on the stratified flow between the roll waves.

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