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Brief communication

Effects of a drag reducing polymer on stratified gas–liquid flow in a large diameter horizontal pipe

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1. Introduction

Considerable work has been done on the influence of high molecular weight polymers on drag in single phase flow. The effect of such additives on gas–liquid systems has received relatively little attention. A summary of work in this area is presented in a review by Manfield et al. (1999). Recent studies from this laboratory (Al-Sarkhi and Hanratty, 2001a,b) show that the injection of a partially hydrolyzed solution of polyacrylamide (HPAM) into a horizontal flow of air and water causes a change from an annular flow to a stratified flow by destroying the disturbance waves on the liquid film. Drag reductions of 48% were realized for a 9.53 cm pipe and 63%, for a 2.54 cm pipe.

In subsequent studies Soleimani et al. (2002) injected an HPAM solution into a stratified flow of air and water in a horizontal 2.54 cm pipe. A damping of waves and an increase in the liquid holdup were observed. These changes, in turn, cause an increase in the gas velocity and a decrease of the interfacial drag, which have counterbalancing effects. Consequently, increases or decreases in the pressure drop could be realized. Transition to slug flow was found to occur at larger liquid flows because the damping of turbulence in the slugs causes an increase in the shedding rate of slugs and, therefore, a decrease in their stability.

The stratified flow and the transition to slug flow in a 2.54 cm pipe is more complicated than that observed for flow in pipes with larger diameters. The interface is covered with large amplitude waves which appear to touch the top wall momentarily. Lin and Hanratty (1986) called these disturbances pseudo-slugs and pointed out that they are less prevalent in larger diameter pipes. This motivated experiments in a 9.53 cm pipe which are described in this paper.

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Studies of stratified flows by Andritsos and Hanratty (1987) show, at low gas velocities, the existence of regular waves which can develop into slugs through wave growth. At superficial gas velocities greater than about 4 m/s, irregular waves with a large range of wavelengths were generated by a Kelvin–Helmholtz mechanism. Slugs form by wave coalescence. Fan et al. (1993) investigated, in more detail, how waves evolve over the length of a 9.53 cm pipe at low gas velocities. They observed that waves with a frequency of about 10 cps form near the inlet. These grow as they propagate downstream and spawn waves with a frequency of about 5 cps through a nonlinear resonance mechanism. These waves can grow until they either tumble or evolve into slugs.

This paper shows how the addition of polymers to a stratified flow can influence wave structure. Of particular interest is the finding that the bifurcation process, described above, is inhibited. This can be associated with appreciable drag-reduction and a delay of the transition from a stratified to a slug flow.

The authors are not aware of previous studies of the influence of polymers on gas–liquid stratified flow in a large diameter pipe.

2. Description of the experiments

The experiments were conducted in a horizontal Plexiglas pipe that had a diameter of 9.53 cm and a length of 23 m. The air and water were combined in a tee-section at the entry. The water flowed along the run of the tee. Conductance probes at three locations were used to measure liquid heights, and differential pressure sensors were used to measure pressure drop. A detailed description of the flow loop and of the measurement techniques is given in a thesis by Williams (1990).

The partially hydrolyzed polyacrylamide (HPAM, Magnafloc 1011) was mixed with water using a method described by Al-Sarkhi and Hanratty (2001a). The concentration of the master polymer solution was 1000 ppm (weight basis). It was injected into the flow loop through a hole with a diameter of 10 mm that was located at the bottom of the pipe, 2.9 m downstream of the tee-section. The mixed concentration in the flow loop was 50 ppm (weight basis).

3. Effect of the polymer on waves

3.1. Low superficial gas velocity

Fig. 1 shows wave patterns measured for a superficial gas velocity of 1.5 m/s at $L/D = 214$, where L is the distance from the entry and D is the pipe diameter. The pattern for air–water flow with a superficial liquid velocity, U_{sl}, of 0.15 m/s and an average liquid height of $h/D \cong 0.54$ shows large amplitude waves with a frequency, f, approximately equal to 5 cps (the dark line). Slugs are observed at liquid flows slightly larger than this. As shown in Fig. 2a, frequency spectra measured at different locations along the pipe are similar to what has been observed by Fan et al. (1993). A mixture of waves with $f \cong 5$ and 10 cps is observed at $L/D = 102$. There is a large exchange of energy between the 10 and 5 cps waves between $L/D = 102$ and 173, so that only waves with $f \cong 5$

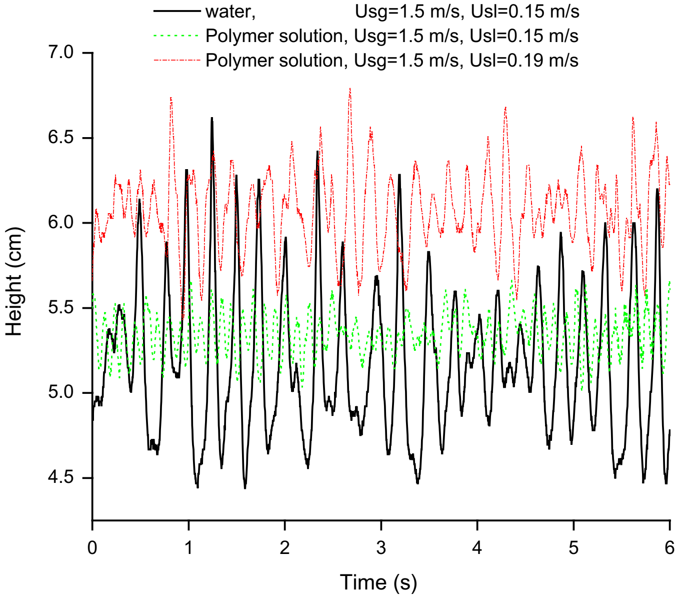


Fig. 1. Wave patterns measured at 20.4 m ($L/D = 214$) for $U_{sg} = 1.5$ m/s.

cps exist at $L/D = 173$. A rapid increase in the power (and, perhaps, a slight decrease in the frequency) of these low frequency waves occurs between $L/D = 173$ and 214.

As shown in Fig. 1, the wave amplitude decreased dramatically when a 50 ppm polymer solution was used at $U_{sl} = 0.15$ m/s. However, the average liquid height, $h/D \cong 0.55$, was about the same as for a water flow. We estimate that a reduction of the drag of the liquid on the wall of about 42% was realized (see Section 5). Spectral density functions characterizing this experiment are shown in Fig. 2b. A peak at $f \cong 10$ cps is noted. The bifurcation observed for water does not occur.

The addition of polymers also delayed the transition to slug flow. The tracing in Fig. 1 for $U_{sl} = 0.19$ m/s ($h/D \cong 0.63$) represents a condition just before the transition to slug flow. Slugs would be observed if water were used at this superficial liquid velocity. Fig. 3 presents the spectral density functions for this experiment. The wave growth that accompanies the bifurcation process could not be completely suppressed at this increased U_{sl} (or increased h/D). A peak appears at $f \cong 10$ cps at $L/D = 102$. The spectral density function at $L/D = 173$ indicates the initiation of a bifurcation. There is a rapid transfer of energy from $f \cong 10$ cps waves to $f \cong 5$ cps waves between $L/D = 173$ and 214. The spectrum at $L/D = 214$ shows a single peak at $f \cong 5$ cps.

3.2. High superficial gas velocity

At high gas velocities the presence of polymers can cause a small decrease in the mean-square displacement of the interface, as shown in Fig. 4 for $U_{sg} = 5$ m/s. The appearance of the waves and the spectral density functions for these waves are the same as described by Fan et al. (1993) for

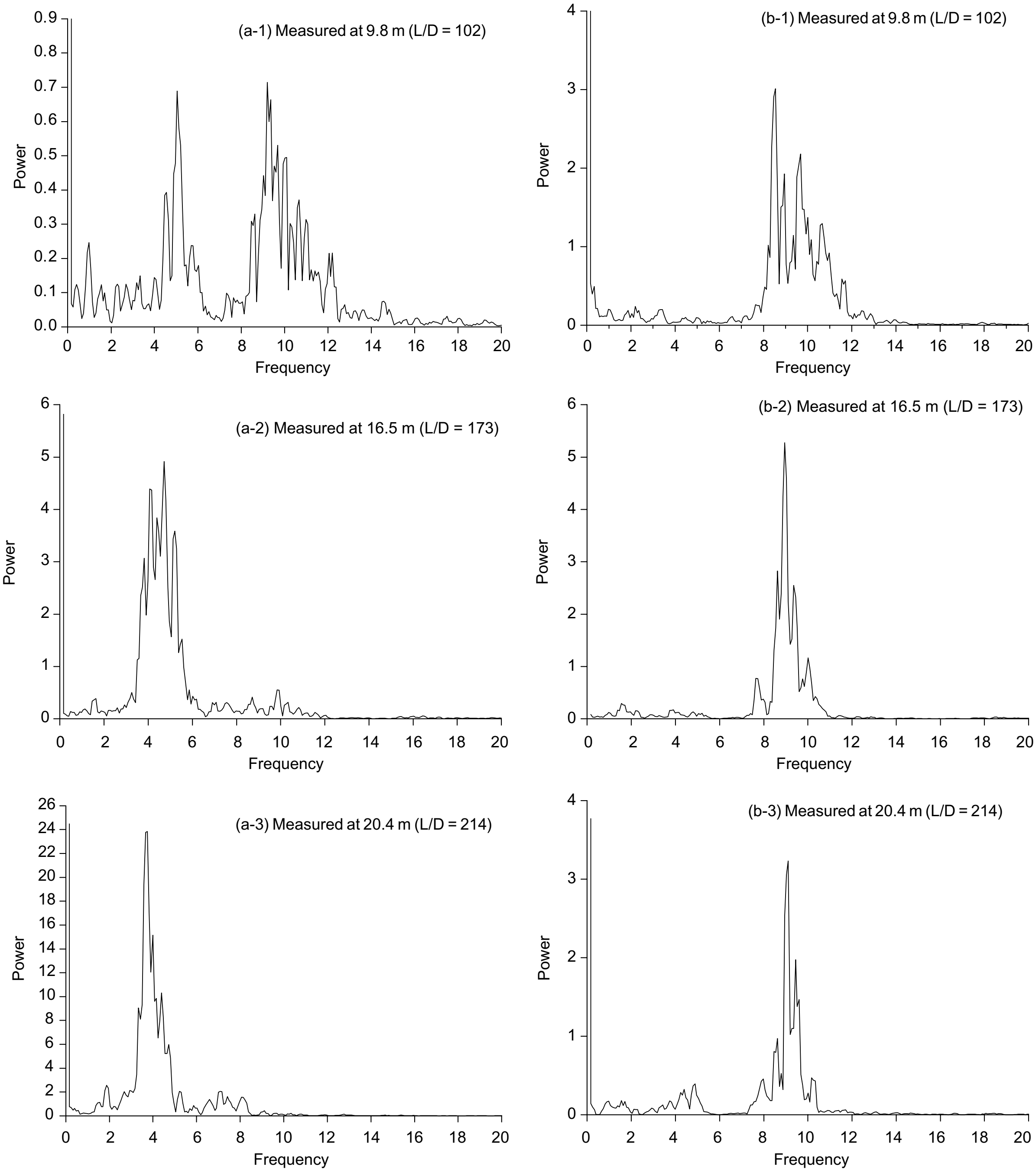
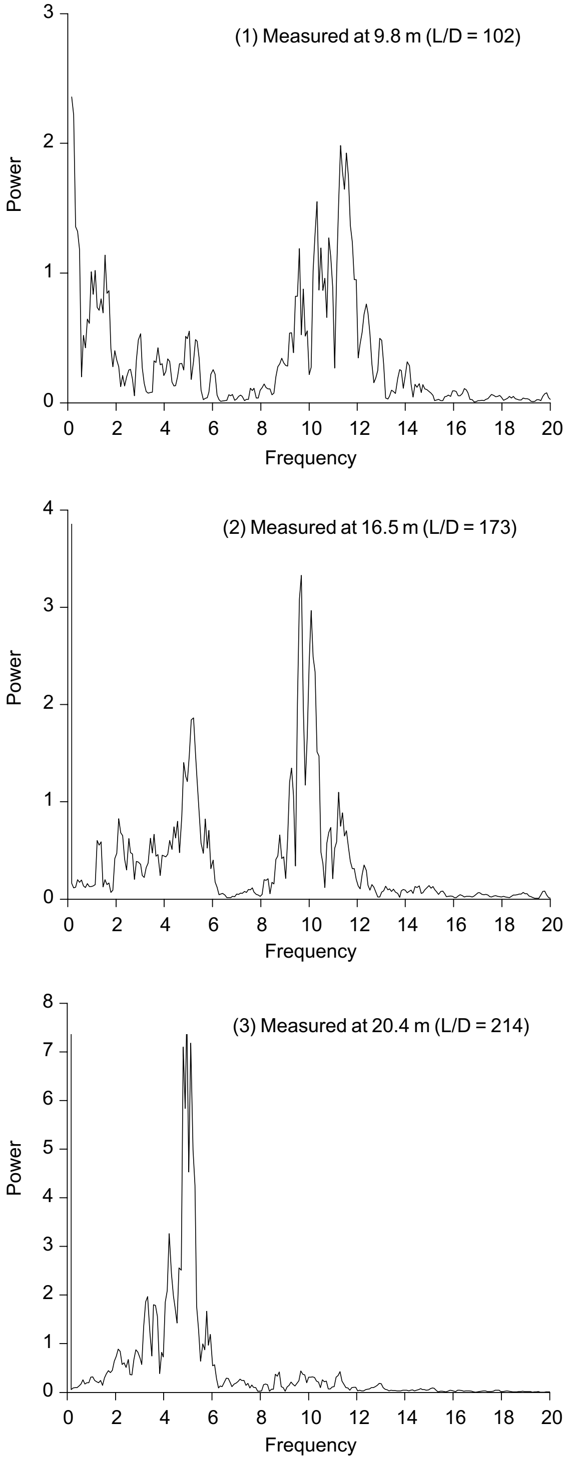


Fig. 2. Spectral density functions at $U_{sg} = 1.5$ m/s and $U_{sl} = 0.15$ m/s. (a) Water flow, (b) 50 ppm polymer solution flow.

air–water flows. No effect of polymers on the critical U_{sl} for the transition to slugging was observed for $U_{sg} = 5$ m/s.



(1) Measured at 9.8 m (L/D = 102)

(2) Measured at 16.5 m (L/D = 173)

(3) Measured at 20.4 m (L/D = 214)

Fig. 3. Spectral density function of a 50 ppm polymer solution flow ($U_{sg} = 1.5$ m/s, $U_{sl} = 0.19$ m/s).

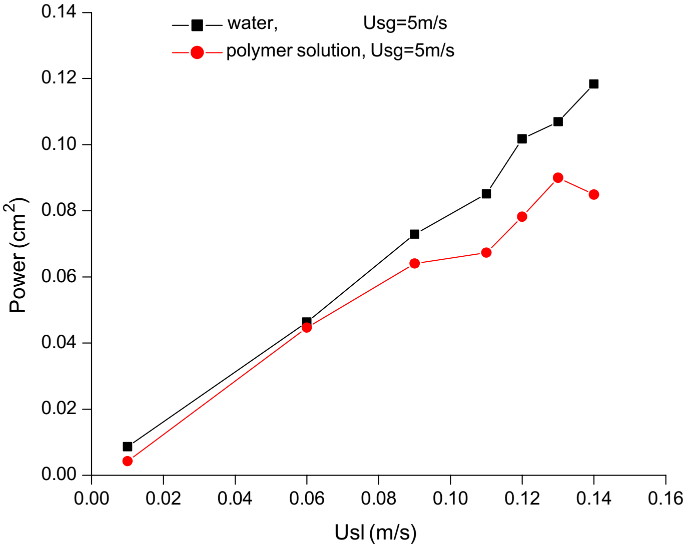


Fig. 4. Total power of the wave spectra, $\overline{(h - \bar{h}^2)}$, averaged over three locations.

4. Effect of polymer addition on liquid holdup and pressure drop

Measurements of the average height of the liquid, $\bar{h}$, and of the drag reduction are presented in Figs. 5 and 6. Almost no change in $\bar{h}$ was observed at $U_{sg} = 1.5$ m/s after the addition of polymers. However, small increases in liquid height were observed at $U_{sg} = 5$ m/s. The numbers next to the data points in Fig. 5 are the actual gas velocities. A Kelvin–Helmholtz instability is expected to occur at a critical relative velocity of about 6.6 m/s for air water flows at atmospheric pressure (Hurlburt and Hanratty, 2002). The liquid interface at the smallest U_{sl}, for $U_{sg} = 5$ m/s, was smooth. At $U_{sl} = 0.06$ m/s and larger, the interface was covered with irregular waves.

The percent drag reduction, given in Fig. 6, is defined as

$$\mathrm{DR}(\%) = \frac{(\Delta P)_{\mathrm{water}} - (\Delta P)_{\mathrm{polymer}}}{(\Delta P)_{\mathrm{water}}} \times 100 \tag{1}$$

For $U_{sg} = 1.5$ m/s very little effect on DR is observed at $U_{sl} \leqslant 0.13$ m/s. For $U_{sl} > 0.13$ m/s a bifurcation occurs for water flows, whereby there is a rapid exchange of energy from waves with $f \cong 10$ cps to waves with $f \cong 5$ cps. This is accompanied by a large increase in the wave energy and the interfacial drag. Since this bifurcation is inhibited by the addition of polymers the interfacial drag is much smaller than is observed for water. For $U_{sg} = 5$ m/s large amplitude irregular waves appear for $U_{sl} \geqslant 0.06$ m/s. As shown in Fig. 4, polymers decrease the amplitudes of these waves. This contributes to an increase in drag reduction with increasing U_{sl}. A maximum drag reduction of 19% was realized for $U_{sl} = 0.13$ m/s.

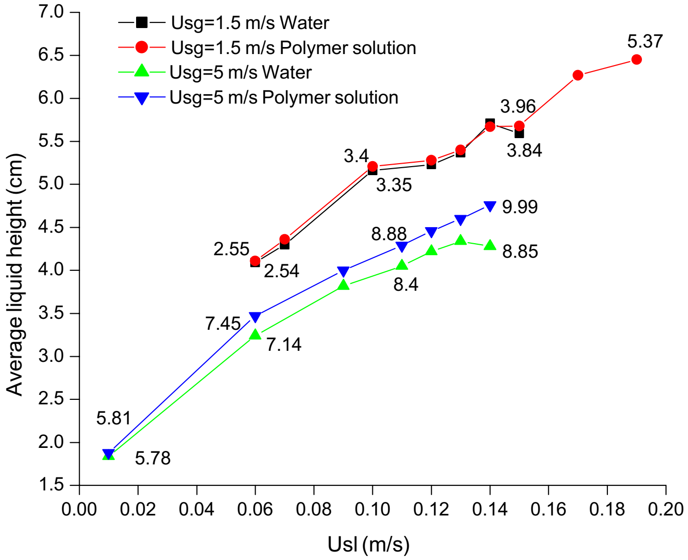


Fig. 5. Average liquid heights. Calculated gas velocities are also shown (in m/s) next to the symbols for selected cases.

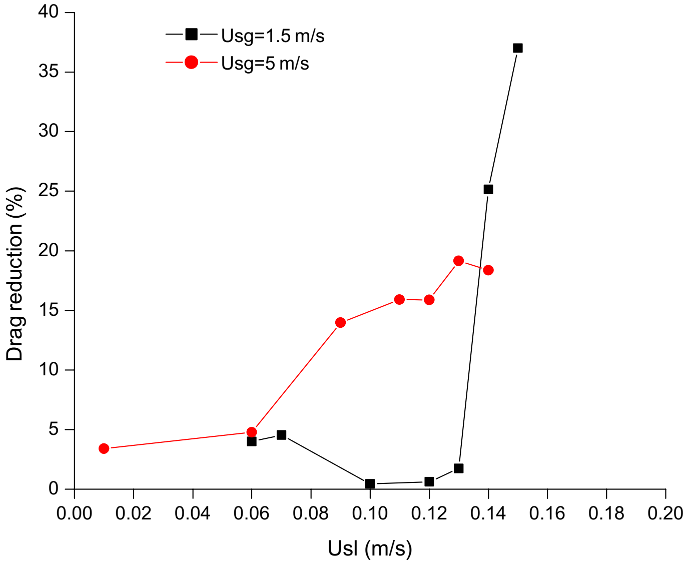


Fig. 6. Drag reduction.

5. Concluding remarks

The physical understanding of results on liquid holdup and on pressure drop can be helped by considering an idealized model of a stratified flow whereby the time-averaged interface is considered to be flat and to have a length of S_i. The liquid is defined to have a height, h, that is equal to the distance of the interface from the bottom of the pipe. The lengths of the portions of the wall in contact with the gas and the liquid are defined as S_g and S_l. These lengths as well as the area of the part of the cross section occupied by the gas, A_g, can be calculated from measurements of h/D by using geometric relations given by Govier and Aziz (1972). The following force balances for fully-developed flow in a horizontal pipe can be derived for the whole pipe and for the portion occupied by the gas:

$$A\frac{\mathrm{d}P}{\mathrm{d}L} = S_l\tau_{wl} + S_g\tau_{wg} \tag{2}$$

$$A_g\frac{\mathrm{d}P}{\mathrm{d}L} = S_i\tau_i + S_g\tau_{wg} \tag{3}$$

where τ_i, τ_{wl}, τ_{wg} are the stresses at the interface, on the portion of the pipe wall in contact with the liquid and on the portion of the pipe wall in contact with the gas. Andritsos and Hanratty (1987) have shown that τ_{wg} can be calculated with the Blasiuss equation by using an hydraulic diameter defined as $4\,A_g/(S_i + S_g)$.

From measurements of h/D, $S_g\tau_{wg}$ can be calculated. For $U_{sg} = 1.5$ m/s, h/D is the same for flows of water and polymer solutions (Fig. 5). Therefore, from Eqs. (2) and (3), decreases in $\mathrm{d}P/\mathrm{d}L$ caused by the addition of polymers are accompanied by decreases both in τ_i and in τ_{wl}. Similar results are obtained for $U_{sg} = 5$ m/s. A reduction of the drag of the liquid on the wall is defined as

$$\mathrm{DR}(\%) = \frac{(\tau_{wl})_{\text{water}} - (\tau_{wl})_{\text{polymer}}}{(\tau_{wl})_{\text{water}}} \times 100 \tag{4}$$

Wall drag reductions of 42% were realized for $U_{sg} = 1.5$ m/s, $U_{sl} = 0.15$ m/s and 30%, for $U_{sg} = 5$ m/s, $U_{sl} = 0.14$ m/s. For $U_{sg} = 1.5$ m/s the liquid velocity is the same with and without polymers, so the reduction in drag can be interpreted as a decrease in the friction factor. Reynolds numbers based on the hydraulic diameter ($4A_l/S_l$) were on the order of 25,000 for these conditions. These results are reasonable since maximum drag reduction could be realized for a 50 ppm HPAM solution that is flowing in a rectangular channel with a width of 61 cm and a height of 5.1 cm at a Reynolds number of about 20,000. From these considerations we conclude that polymer additions affect the flow both by damping interfacial waves and by reducing the turbulence in the liquid.

An explanation of how polymers affect interfacial waves and, in particular, the bifurcation process is not available. It emerges as a central problem in understanding how drag reducing polymers affect gas–liquid stratified flows. The chief rheological property of the dilute polymer solution, associated with drag reduction in single phase flow, is that it exhibits large elongational viscosities. However, wave growth could also be affected by shear thinning (Khomami, 1990) and by the injection process which creates coherent polymer threads.

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