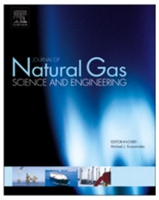
Journal of Natural Gas Science and Engineering 2 (2010) 41–48

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse



Review article

Drag reduction with polymers in gas-liquid/liquid-liquid flows in pipes: A literature review

Abdelsalam Al-Sarkhi*

Department of Mechanical Engineering, King Fahd University of Petroleum & Minerals, P.O. Box 1604, Dhahran 31261, Saudi Arabia

ARTICLE INFO

Article history:
Received 16 December 2009
Accepted 6 January 2010
Available online 24 February 2010

Keywords:
Two-phase flow
Drag reduction
Drag reducing polymers

ABSTRACT

A literature survey of the published work on drag reduction by Drag Reducing Agent (DRA) in two-phase flow is reviewed. Characteristics of the two-phase flow with drag reducing additives are described and the research approaches and methodology concerning drag reduction with additives in multiphase flow is introduced. Suggested mechanisms for drag reduction phenomena and procedure in two-phase flow are discussed. Some of the industrial application of the use of drag reducing additives in two-phase flow is explained. Finally, Recommendations, new suggested approaches for future research needs and potential areas that need further research is highlighted.

© 2010 Elsevier B.V. All rights reserved.

1. Introduction

One of the most fascinating 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). Several 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 ppm and 50 ppm.

Oil–water–gas mixtures flow in pipelines is a common occurrence in the petroleum production. Enhanced oil recovery (EOR) techniques may involve injecting gas into the well tubing to reduce static pressure losses. It is often not practical and very expensive to separate the outlet flow of oil–water–gas mixture at the well site so the multiphase mixture is pumped through a pipeline to a separation or processing station. The traveling distances of which the multiphase mixture must be transported are often many kilometers and the pressure drop in these pipelines can be very significant and high cost effective item.

The oil and gas producing industries have conventionally used drag reducing agents (DRA) to assist in lowering the pressure loss for the transport of single-phase liquids over long distances. One of the most impressive successes in polymer applications for drag reduction in advanced production systems was the use of 10 ppm oil-soluble polymers in the 1300 km trans-Alaska pipeline system which increased pipeline flow rates significantly (Burger et al., 1982).

DRA has been very beneficial in reducing frictional pressure losses, allowing a greater production flow rate at an economical cost. DRA has not been specially designed for use in multiphase systems where oil–water–gas mixtures are transported. Current production facility design requires the transportation of fluids from wellhead to processing facilities, at ever increasing distances, to remain economically feasible especially for sub-sea plants. The use of DRA in this application is a unique and novel method, while it has been tried in existing systems without conclusive published results. Both the effects of DRA on flow regime and concentration requirements at industrial level are almost unknown, thus making an economic benefit analysis is not practical at this time.

The benefits of DRA use in existing systems are increased production, reduction of operating costs such as pumping power, reduction of pipeline pressure while maintaining throughput, and to facilitate refinery loading and unloading operations. The design benefits of DRA in new systems are a reduction in pipeline diameter and pumping station capital costs.

For the purpose of this review Drag Reduction (DR) term is used to describe the frictional pressure drop of a flowing fluid(s) establishing in a system when it is deliberately reduced. Drag Reducing Polymers (DRP) term is used to describe a high-molecular weight polymer (MW > 10^6 kg/kmol) that is added (mixed or injected) into the flowing liquid in the pipe at low concentration. The low

---

* Fax: +966 3 8602949.
E-mail address: alsarkhi@kfupm.edu.sa

1875-5100/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jngse.2010.01.001

concentration means the concentration of the polymers in the flowing liquid which is usually less than 100 ppm by mass at which drag reduction can be noticed clearly. PDRA means a polymer drag reducing agent.

This review paper aims to present to the reader the current status and advances in the subject of drag reduction in multiphase flow. Special emphasis on the research methodology, approaches, applications, shortcomings as well as potential areas that need further research.

2. Drag reduction additives in two-phase flow

2.1. Gas–liquid flow

One of the earliest experiments on drag reduction in gas–liquid flows were reported by (Oliver and Young Hoon, 1968) who used 1.3% polyethylene oxide (PEO) aqueous solution and air. They found that in slug flow the liquid showed considerably less circulation while in annular flow wave formation was damped resulting in a smoother liquid film. Greskovich and Shrier (1971) first used the term DRP in multiphase systems and found drag reduction that could reach 40% during slug air–water flow. Since then drag reduction has been documented by a number of investigators in a variety of systems with differing results (Otten and Fayed, 1976; Thwaites et al., 1976).

Scott and Rhodes (1972) investigated Polyhall295, a polyacrylamide polymer drag reducer in co-current, two-phase, gas-liquid slug flow. Water and air flowing in 2.5 cm ID pipelines was considered. The liquid Reynolds number was held constant at 13,000 and the gas Reynolds number was varied from 1500 to 6100. it was concluded that two phase drag reduction exceeded that of single phase flows for the same superficial liquid velocities. The measured drag reductions were in the range of 29 - 33% in single phase flow for Reynolds numbers between 7000 and 30,000. The contribution of the pressure gradient was separated into liquid wall friction and slug inertial effects. The acceleration energy term in slug flow exceeded the frictional component of the axial pressure gradient in their experiments. In all cases, the pressure gradient due to acceleration was greater than the frictional pressure gradient in the slug flow regime. It was found a maximum of 33% drag reduction to occur at a polymer concentration of 68 ppm by weight and concluded that the polymer was shear degradable, losing its effectiveness after six residence times.

Studies of the effect of the drag-reducing polymer on frictional losses have been made by (Rosehart et al., 1972). It was found higher drag reduction in a slug flow than in a single phase.

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 m/s and 111 m/s. The percent change in the pressure gradient from what was observed in the absence of polymer varied from 0 to about 37. No explanation for these changes was given.

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.

During slug flow Rosehart et al. (1972), for example, found higher drag reduction than in single phase while Saether et al. (1989) found lower drag reduction.

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 Hanratty (2001) studied the effect of drag reducing polymers on annular air-water flow in a horizontal pipe with a diameter of 0.0953 m and 23 m of length. Their polymer solution was a co-polymer of polyacrylamide and sodium-acrylate (Percol 727) in water. The injection of polymer solution (without using a pump) produced drag reduction of 48% with concentrations of only 10–15 wppm in water. Also, they found that annular flow regime is changed to a stratified pattern at large drag reductions. In addition, they reported that transference of the DRP to the liquid in the pipe should not involve the use of high shear pump.

Al-Sarkhi and Hanratty (2002) studied the effect of pipe diameter on the performance of drag-reducing polymers in annular air-water flows by varying the diameter of the pipe from 0.0953 m to 0.0254 m. Drag reductions up to 63% were observed in the 0.0254 m pipe compared with 48 % previously achieved in the 0.0953 m pipe. At maximum DR the ratio of the friction factor to the friction factor that would be measured if the gas were flowing alone in the pipe, f/fg, is 1.2–1.9 for a 9.53 cm pipe and 1.2–2.0 for a 2.54 cm pipe.

Soleimani et al. (2002) injected a co-polymer of polyacrylamide and sodium acrylate solution into a stratified flow of air and water in a horizontal 0.0254 m pipe. A damping of waves and an increase in the liquid holdup were observed. Those changes, in turn, caused an increase in the gas velocity and a decrease of the interfacial drag. Transition to slug flow was found to occur at larger liquid flows.

Baik and Hanratty (2003) studied how the addition of polymers to a stratified flow can influence wave structure. Their experiments of air-water system were conducted in a horizontal Plexiglas pipe that had a diameter of 0.0953 m and a length of 23 m. Magnafloc 1011 was mixed with water. The concentration of the master polymer solution was 1000 wppm. 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 wppm. They found that the wave amplitude decreased dramatically when a 50 wppm polymer solution was used (superficial liquid velocity (U_{SL}) = 0.15 m/s) at low superficial gas velocity (U_{SG}) and the addition of polymers also delayed the transition to slug flow. However, no effect of polymers on the critical U_{SL} for the transition to slugging was observed for $U_{SG} = 5$ m/s (high superficial gas velocity).

Al-Sarkhi and Soleimani (2004) studied the effect of the addition of drag reducing polymers on air–water flow patterns in a horizontal pipe of 0.0254 m diameter and 17 m long. The additive was a copolymer of polyacrylamide and sodium acrylate (formally sold under the trade named Percol 727 but now called Magnafloc 1011). They used the same mixing technique that was first used by Warholic et al. (1999). They described the characteristics of two phase flow with and without drag reducing polymers. They reported that the addition of drag-reducing polymers is accompanied by changes in the flow pattern map and pressure drop reduction occurs in almost all flow pattern configurations. Their study indicated that maximum drag reduction usually occurs when a slug, pseudoslug or annular flow changes to stratified flow by adding drag reducing polymers.

Fernandes et al. (2004) conducted experimental measurements of drag reduction in a horizontal annular two phase flow. The experiments were conducted in a high-pressure (10 bar) two-phase flow of methane (CH_4) and a condensate sample with thermophysical properties close to that of decane ($C_{10}H_{22}$) in 0.019 m inside diameter pipe. The drag reducers were high molecular weight poly-alpha-olefin polymers. They argued that the reduction of frictional drag in an annular flow is primarily due to the modification of the flow regime or flow pattern. Also, they noticed that, in the annular flow regime, for a fixed superficial gas velocity, the magnitude of drag reduction increases with increasing superficial liquid velocity. Beyond a threshold U_{SL} (approximately $U_{SL} = 0.2$ m/s) the drag reduction reached a maximum and remained constant for increasing U_{SL} for all the U_{SL} examined (up to 0.7 m/s). However, for superficial gas velocities which result in an annular flow, the maximum drag reduction decreased with increasing U_{SG} (as the U_{SG} increased from 10.4 to 21.3 m/s the maximum drag reduction decreased from 62% to 44%). Finally, they concluded that for low superficial liquid velocities, the overall drag reduction is generally dominated by the reduction of interfacial friction.

Al-Sarkhi and Abu-Nada (2005) studied the effect of drag reducing polymers on an annular air–water flow in a small horizontal pipe. Pipe with inside diameter of 0.0127 m and a length of 7 m was used. Magnafloc 1011 (polyacrylamide) was mixed with water in a 150-l tank with a concentration of 1000 wppm. The injection of polymer solution (without using a pump) produced drag reduction of 47% with concentrations of only 40 wppm in water. Also, they found that annular flow pattern was changed to a stratified pattern at large drag reductions and the effectiveness of the drag-reducing polymer is sensitive to the gas and liquid flow rates.

Mowla and Naderi (2006) studied the effect of the presence of a polymer drag reducing agent (PDRA) on the pressure drop in co-current horizontal pipes carrying slug two phase flow of air and crude oil. The test section of the experimental set-up is consisted of: a smooth pipe of polycarbonate with 10.3 m long and 0.0254 m ID (inside diameter), a rough pipe of galvanized iron with 8.8 m long and 0.0254 m ID and a rough pipe of galvanized iron with 8.8 m long and 0.0127 m ID. The employed PDRA was a Polyalpha olefin (Polyisobutylene). Their results showed that the addition of PDRA could be effective up to some doses of PDRA after which the pressure drop was kept constant. A drag reduction percentage of about 40 was obtained for some experimental conditions. Also, they reported that PDRA are more effective in rough pipe than in smooth pipe and the drag reduction in 0.0127 m ID pipe is higher than that in 0.0254 m ID pipe.

Jubran et al. (2005) published a review research on drag reduction in single and multiphase flows with particular reference to the oil industry. It was reviewed research work related to theories of drag reduction, the influence of drag reduction types and hydrodynamic and heat transfer characteristics of the flows in the presence of a drag reducing agent. They reviewed the possible shortcomings as well as pin-pointing potential areas that need further research. Accordingly to them, more work is needed in the areas of shear degradation, and the effect of wax content, water cut, and pipe inclination on the performance of drag reduction with emphases on oil wells.

Dass and Bleyle (2006) conducted an experimental work in 0.1 m ID horizontal pipes utilizing carbon dioxide as the gas phase and two types of oil with different viscosities; namely 0.0025 Pa s (density = 800 kg/m^3) and 0.05 Pa s (density = 830 kg/m^3), as the liquid phase. They studied the influence of oil viscosity on the magnitude of total pressure drop and the effectiveness of a polymer drag reducing agent (PDRA) in decreasing the pressure in two-phase oil–gas slug flow. They concluded that the DRA was more effective in reducing the total pressure drop and its components in the 0.0025 Pa s oil, but the magnitude of drag reduction was higher in the 0.05 Pa s oil.

Al-Sarkhi et al. (2006) investigated experimentally the drag reduction by polymers of air and water flowing in an inclined 0.0127 m diameter pipe. 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. It was reported that for the first time in literature, the drag reduction variations with the square root of the superficial velocities ratio for flows with the same final flow patterns have self-similar behaviors.

Parimal et al. (2008) carried out experiments in a 36-m long, 10-cm diameter multiphase flow system to examine the effect of drag reducing agents (DRA) on average pressure drop and slug characteristics. Oil-soluble and water-soluble DRA were tested. Superficial liquid velocities between 0.5 and 1.5 m/s and superficial gas velocities between 4 and 10 m/s were investigated. Temperature and pressure were maintained at 30 °C and 0.45 MPa. The DRA concentrations of 0, 25 and 50 ppm were used in this study. It was concluded that the average pressure drop decreased significantly by the change of flow characteristics when DRA was injected into the pipeline. At certain conditions, it was seen that a transition in flow pattern occurred from slug to wavy stratified flow with DRA. In addition, DRA was able to decrease the degree of turbulence at the gas–liquid interface with the addition of DRA. Some negative performance with the use of DRA in multiphase flow pipeline was presented in this paper. When multiphase mixture has a condition of dispersion (or emulsion), the oil-soluble DRA showed negative effectiveness. The negative effectiveness was explained due to the fact that the apparent viscosity of the emulsion substantially increased when the oil-soluble DRA was added. The pressure drop increased substantially with addition of DRA. Although, it was mentioned that oil and water soluble DRA was used, the composition or the brand name was not identified and the molecular weight was not reported.

Fernandes et al. (2009) investigated experimentally the effect of drag reducing polymers on a vertical two-phase annular flow. The motivation was a test for applying PDRA in high production-rate gas-condensate wells where friction in the production tubing limits the production rate. The flow regime was the annular-entrained. The result showed a reduction in the frictional component of the pressure gradient by up to 74%. However, PDRA also resulted in a significant increase in the liquid holdup by up to 27%. This phenomenon is identified as “DRA-induced flooding.” Since the flow was vertical, the increase in the liquid holdup increased the hydrostatic component of the pressure gradient by up to 25%, offsetting some of reduction in the frictional component of the pressure gradient.

2.2. *Liquid–liquid flow*

Sifferman and Greenkorn (1981) studied drag reduction of three types of polymers (carboxymethyl cellulose, polyethylene oxide, and guar gum) in three different fluid flow systems: single-phase dilute polymer-water solutions, two-phase liquid–solid, and three-phase immiscible liquid–liquid–solid solutions. Drag reduction was clearly observed for all three flow systems studied. At Reynolds numbers exceeding 10^5 drag reduction of up to 80% was achieved for the dilute polymer system at concentrations of 0.3 wt% DRA. The liquid-solid system, drag reduction of 95–98% was achieved, indicating an additive drag reduction effect for polymer solutions with suspended solid particles.

Al-Wahaibi et al. (2007) studied the effect of a drag-reducing polymer on oil–water flow in a relatively small 14 mm ID acrylic pipe. Oil (5.5 mPa s, 828 kg/m^3) and a co-polymer (Magnafloc 1011) of polyacrylamide and sodium acrylate were used. The results showed a strong effect of DRP on flow patterns. The presence of DRP extended the region of stratified flow and delayed transition to slug flow. The addition of the polymer clearly damped interfacial waves. The DRP caused a decrease in pressure gradient and a maximum drag reduction of about 50% was found when the polymer was introduced into annular flow. The height of the interface and the water holdup increased with DRP.

Al-Yaari et al. (2009) conducted Measurements of drag-reduction for oil–water flowing in a horizontal 0.0254 m pipe. Different oil–water configurations were observed. The injection of water soluble polymer solution (PDRA) in some cases produced drag reduction of about 65% with concentration of only 10–15 ppm. The results showed a significant reduction in pressure loss due to PDRA especially at high mixture velocity which was accompanied by a clear change in the flow pattern. Phase inversion point in dispersed flow regime occurred at a water fraction range of (0.33–0.35) indicated by its pressure drop peak which was disappeared by injecting only 5 ppm (weight basis) of PDRA. Effect of PDRA concentration and molecular weight on flow patterns and pressure drops were presented in this study. Two different polymers were examined (Magnafloc 1011 and polyethylene oxide). As the injected PDRA molecular weight increases, oil–water flow pattern is affected in the direction of stratification and the transition to the dispersed flow pattern is delayed at higher water fraction. At the phase inversion from water continuous to oil continuous, a greater reduction in pressure gradient is achieved as PDRA molecular weight increases.

Influence of salt content in the water phase on the performance of PDRA was also examined in this work. Effect of salt content in water on the performance of PDRA was examined at mixture velocity of 1.5 m/s, and 3 m/s. a negative salt effect on the PDRA effectiveness was observed. A possible explanation of the negative effect of the salt on the PDRA effectiveness was explained as by arguing that, in saline water, the electrolytes in the solution cause the ionic polymer molecules to coil (Carcoana, 1992) due to the electrostatic interaction between different parts of the same polymer. As a result, the polymer ability to expand and the formation of aggregates, which plays a major role in the drag reduction phenomenon, were reduced.

3. Approaches in drag reducing additives in multiphase flow studies

3.1. Experimental approach

The experimental investigation of the effect of PDRA in multiphase flow has been done in two different techniques regarding to the way of introducing the PDRA into the flow which is one of the most important factor for drag reduction success. The first is preparing the total patch of liquid at the desired concentration of the PDRA then mixing this liquid with gas. The second way which is the more effective way is to inject a master solution of PDRA at high concentration into the liquid in the pipeline. Fig. 1 shows the experimental setup and the method of injection of Al-sarkhi and Hanratty (Al-Sarkhi and Hanratty, 2001) for an annular flow of air and water.

The polymer solution was injected into the flow loop in two ways, as indicated in Fig. 1b. 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. 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 second method results in much greater drag reduction than the first method.

The effectiveness of a drag-reducing polymer is sensitive to the technology used to introduce polymer into the flow and the concentration of the injected master polymer solution. 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. Transferrence to the pipe should not involve the use of high shear pumps. Effectiveness depends on the concentration of polymer in the master solution (to be injected into the liquid in the pipe) so an optimum needs to be determined (1000 ppm was found optimum in (Al-Sarkhi and Hanratty, 2001) experiments).

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. The 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. the concentrated master solutions contain more entanglements.

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 (Al-Sarkhi and Hanratty, 2001). Vlachogiannis et al. (2003) studied the effectiveness of a drag reducing polymer: Relation to molecular weight distribution and structuring. They concluded that degradation was not accompanied by significant changes in the molecular weight distributions. This observation suggests that, for the system studied, clusters or aggregates of polymers have a more important effect on the turbulence than individual molecules. Therefore, degradation occurs by the destruction of these clusters. This result is consistent with the observation that larger drag reductions are realized by the injection of concentrated polymer solutions into a water flow.

3.2. Theoretical–analytical–mechanistic approaches

A mechanistic approach starting with two fluid model (combined momentum equation) may be used to solve for either the liquid holdup or the pressure drop. The input will be the pressure drop from the experimental results, the relation between the pressure drop and liquid holdup and the other parameter can be developed then a correlation for that case may be established. It is worth to be mentioned that the combined momentum equation can be applied to the flow with DRP because of the stratification action of the DRP. Several researcher have indicated that the DRP tends to change the flow pattern to stratified in many cases

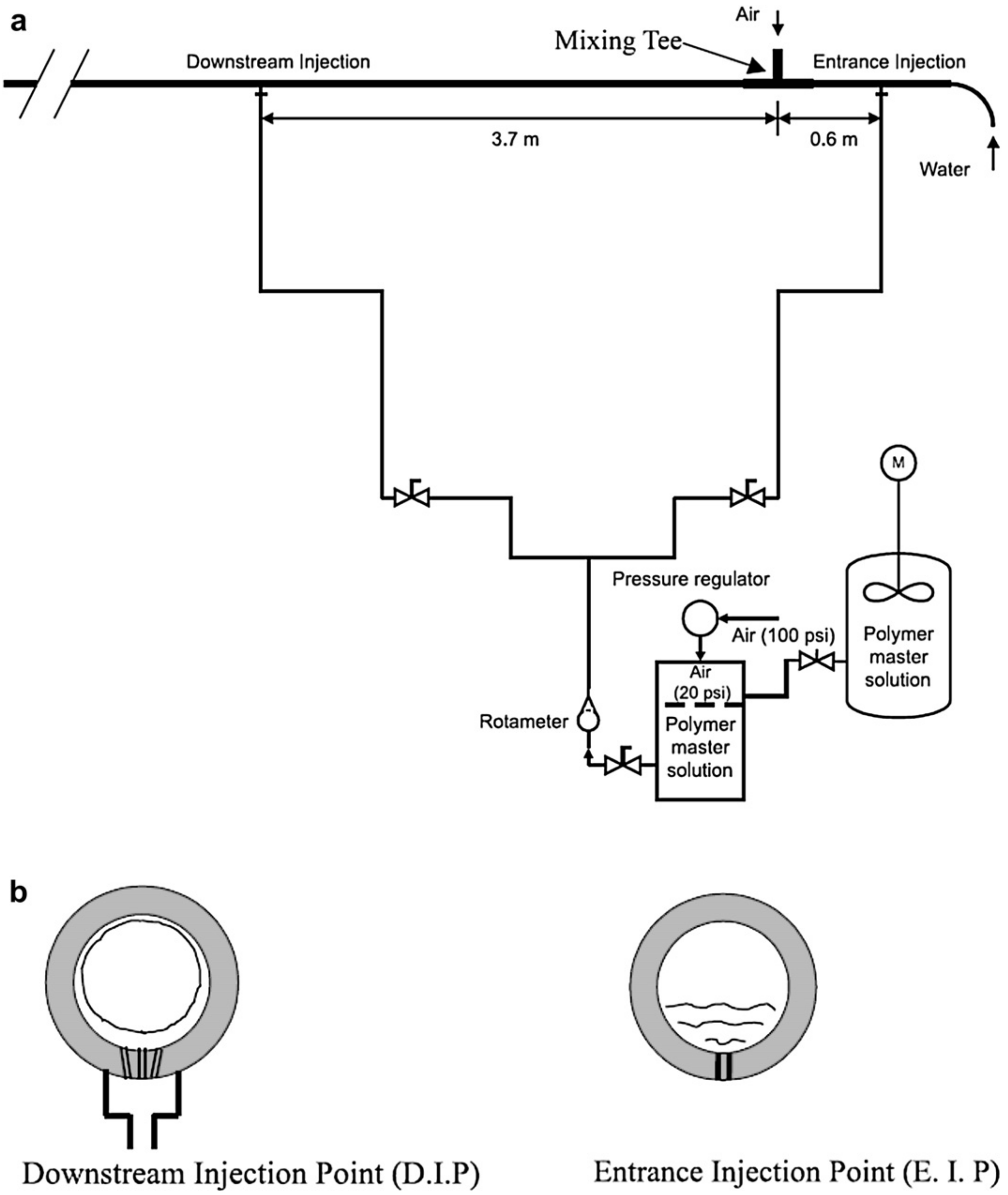


Fig. 1. (a) The experimental setup and locations of injection points; (b) the method of injection the master PDRA solution, after Al-sarkhi and Hanratty (Al-Sarkhi and Hanratty, 2001).

(Al-Sarkhi and Hanratty, 2001, 2002; Soleimani et al., 2002; Al-Sarkhi and Soleimani, 2004; Al-Sarkhi et al., 2006; Al-Wahaibi et al., 2007).

Al-Sarkhi and Hanratty (2001) showed that the effect of the addition of polymer to the annular flow of air-water 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. Other researcher has found similar results for gas-liquid stratified flows. The DRP damped the high amplitude waves (for certain operation conditions) and a smooth stratified resulted due to the addition of DRP. For smooth stratified and even for an annular flow with no drops in the gas core the two-fluid model should work and a correlation between the maximum drag-reduction and pressure gradient and the liquid holdup can be developed. Another way of looking at the stratified flow after the addition of the DRA is by controlling the interfacial shear stress and the wall frictional shear stress for simple cases two-equation model can be applied specially for stratified flow. For that new correlations or factors for the interfacial shear stress can be introduced. Dimensional analysis also is another approach to have self similar behavior of many experimental data and then develop a correlation for drag reduction similar to that found by Al-Sarkhi et al. (2006) in small diameter pipe.

Finally, Fernades et al. (2004) developed a mechanistic model for drag reduction in horizontal annular two phase flow. The model takes into consideration the drag reduction as a reduction of the height of the short-wavelength waves on the liquid film, and a reduction of the entrainment rate of droplets from the liquid film into the gas core. The model motivation was based on the flow visualization of the annular flow with and without PDRA. Flow visualization showed that the injection of a DRA into an annular flow suppresses the liquid-film roughness and droplet entrainment from the liquid film into the gas core. a mechanistic drag reduction model that quantifies the drag reduction by reducing the roughness and entrainment parameters in the expression for the pressure gradient by a two different factors was established. The proposed model does not consider the effect of the rheological properties of drag-reducing agents on the drag reduction. Instead, the experimental data were used to determine appropriate values of the model parameters and the model closure relations for two factors, for both gas-condensate and air–water flows. There was a reasonable quantitative agreement between the model predictions and their experimental data.

3.3. *Molecular dynamics and dissipative particle dynamic approach*

Dissipative particle dynamics (DPD) is a computational method for simulating dynamical and rheological properties of both simple and complex fluids. It is a stochastic simulation technique. Liquid and polymer molecules can be simulated in two phase gas-liquid flow focusing on the interface region between the liquid and the gas. Clear picture can be achieved about the role of the polymers molecules at different conditions. The challenges in the Molecular dynamic (MD) and dissipative particle dynamics (DPD) simulation is that with larger number of particles and with greater level of detail. The computation requirements for these complex MD simulations far exceed the capability of today's supercomputers. Moreover, not every research group can afford to build a large supercomputer to run MD simulations. However, simple cases can be simulated and several conclusions can be drawn.

4. Suggested mechanisms and procedure of drag reduction by DRP in two phase flow

Although several theories were initiated trying to explain the drag reduction phenomenon by DRA, an accurate and specific understanding of the mechanism of drag reduction or the procedure as a function of DRA concentration is not developed yet, especially in multiphase flow. In liquid phase flow, it is believed that DRA work generally in the region near the wall, or in the buffer zone, by reducing the friction factor of the flow through diminishing the turbulent production source and structures. Warholic et al. (1999) believed that 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, are that for which the Reynolds stresses are approximately zero or close to zero.

Al-Sarkhi and Hanratty (2001) reported in their experimental work of air-water annular flow that there is a minimum threshold concentration for the onset of drag reduction by PDRA and a maximum drag reduction asymptote which is function of the PDRA concentration and the method by which it is introduced to the liquid in the pipe. It was also reported that the maximum drag reduction and the gradual changes happens to the flow pattern with the addition of PDRA is a function of the master solution being injected and a 1000 ppm was found to be the optimum for their experiment.(see Fig. 2). The drag reduction was also found that strongly function of superficial gas (U_{SG}) and liquid velocity (U_{SL}). The procedure of drag reduction from zero concentration of PDRA to that at which maximum drag reduction achieved is done on steps, for example consider an annular flow of air and water, then the concentration of PDRA is increased gradually, first the disturbance waves start to disappear then the droplets in the core of the annular flow disappear (so the atomization process of the droplets stops) then finally at maximum drag reduction point the pattern changes into stratified. It was argued by many that the reduction of frictional drag in an annular flow is primarily due to the modification of the flow regime or flow pattern; however the author believes that this is an effect and not a source, the drag reduction always accompanied with changes in the flow pattern. The effect of the addition of polymer to the annular flow is illustrated as follows. For an annular air-water flow the liquid wetting the whole pipe circumference and the presence of a large-scale disturbance wave is in the pipe. A flow with the same rates of liquid flow and gas flow, but with as much as 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 (Al-Sarkhi and Hanratty, 2001).

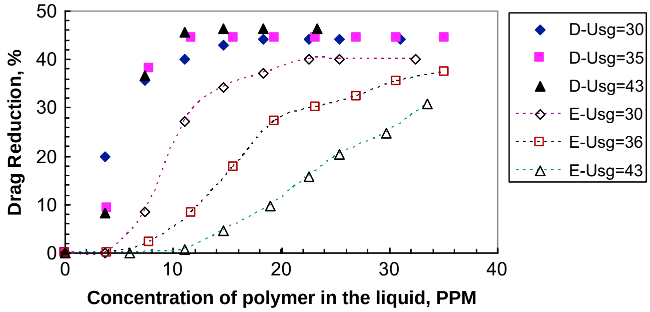


Fig. 2. Drag reduction at $U_{SL} = 0.0601$ m/s (D, downstream injection, E, entrance injection) U_{SG} in m/s, after Al-Sarkhi and Hanratty (2001).

This procedure 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. Fig. 2 also shows clearly that there must be a minimum threshold for the onset of drag reduction and a maximum drag reduction asymptote. As the concentration of PDRA increases from zero to the asymptotic value the flow pattern is gradually changing until it reaches the final new pattern.

Al-Yaari et al. (2009) argued about a possible explanation of the flow pattern change from water continuous dispersed flow to stratified flow by adding 50 ppm of water soluble PDRA is that the injection of PDRA into water continuous dispersed flow substantially reduces turbulent mixing forces. In addition, it increases the droplets coalescence rate which eventually leads to stratification due to a prevailing gravitational force.

By considering the previous paragraph, it can be argued that adding water soluble PDRA maintains a stratified wavy flow pattern for even higher water velocities and delay stratified wavy with drops flow regime and damp high amplitude waves on interface which cause water drops formation and entrainment into oil layer. Consequently, transition into stratified mixed with water layer, three layers and water continuous dispersed flow regimes occur at higher oil and water velocities after the addition of PDRA.

The effect of PDRA molecular weight on the drag reduction phenomenon in water–oil flow was reported by Al-Yaari et al. (2009). The injecting polymer solutions, with identical chemical structures and concentrations but with different molecular weights into water continuous dispersed flow regime. 50 ppm polyethylene oxide polymer solutions with molecular weights of 3×10^5, 4×10^6 and 8×10^6 were used for an input water volume fraction range of (0.2–0.9) at a superficial mixture velocity of 2 m/s. The results of the effect of PDRA molecular weight on pressure drop reduction are presented in Fig. 3. When a 3×10^5 molecular weight was used,

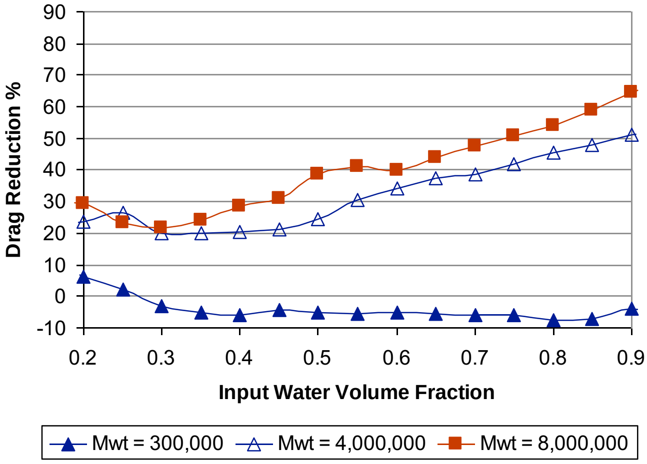


Fig. 3. Measurements of the effect of PDRA molecular weight and water fraction on oil–water pressure drop at mixture velocity of 2 m/s, after Al-Yaari et al. (2009).

a negative effect was observed. On the other hand, pressure gradients were reduced significantly when 4×10^6 and 8×10^6 molecular weights were used. Drag reduction decreased slightly with increasing water volume fraction, and then increased gradually to 51.1% and 64.5% at 0.9 water fraction when 4×10^6 and 8×10^6 molecular weights were used respectively.

Furthermore, when a 3×10^5 molecular weight was used, stratified mixed oil layer flow pattern became narrower and dispersed flow pattern was extended for a wider water fraction range (0.2–1). However, when 4×10^6 and 8×10^6 molecular weight were used, the three layers flow pattern was observed at lower water fraction, and the stratified mixed water layer flow pattern was created. In addition, the transition to dispersed flow pattern was delayed to higher water fractions.

A possible explanation of the increase in the PDRA effectiveness with increasing its molecular weight (4×10^6 g/mole and 8×10^6 g/mole) is that, increasing the molecular weight of the PDRA enhances polymer entanglement. As a result, the formation of aggregates, which plays an important role in the drag reduction phenomenon, is improved as reported by Vlachogiannis et al. (2003) and Cox et al. (1947).

However, the negative results of the PDRA with molecular weight of 3×10^5 g/mole are in close agreement with those reported by Sellin et al. (1982), who argued that drag reducing polymers are not effective unless their molecular weight is greater than a million.

5. DRP applications in multiphase flow

Several papers in the open literature have been listed the practical applications of the DRA mostly in single phase liquid flows (Manfield et al., 1999). In this paper the focus will be on the specific possible applications in multiphase flow. DRA can be used in multiphase flow in the following applications:

- *Liquid–gas and liquid–liquid transportation*: it can be used to increase the flow rate per unit ΔP, or reduce the frictional pressure loss for same flow rate.
- Oil-reservoir fracturing (hydrofrac) to reduce pumping power requirements. Also it can be tested to reduce the pumping power of the injected emulsified acidic fluid (emulsion) into the porous medium.
- *Multiphase flow pattern changes*: the finding that the annular flow regime (and some other flow regimes) is changed to a stratified pattern at large drag-reductions (reported by many) could, in some applications, be of more importance than the finding of a large decrease in frictional pressure loss. In some application some flow patterns are desirable over others.
- *Two-phase flow separation*: injection of DRA into the water continuous layer or the water continuous dispersed flow regime in oil–water immiscible flow changes the flow pattern map and causes a higher degree of stratification. adding water soluble PDRA maintains a stratified wavy flow pattern for even higher water velocities and delay stratified wavy with drops flow regime and damp high amplitude waves on interface which cause water drops formation and entrainment into oil layer. Consequently, transition into stratified mixed/water layer, three layers and water continuous dispersed flow regimes occur at higher oil and water velocities after the addition of PDRA. This can be looked at as a means of oil–water separation.

6. Recommendations for future research needs

The findings of this study point to the important effect of DRPA into gas–liquid as well as liquid–liquid flows. For gas–liquid flows, farther investigation are needed to identify the ranges for which the drag reduction can be achieved, the boundary or new flow pattern map for gas–liquid flow with DRA and a method of analytical/numerical prediction for drag reduction by DRA. For oil–water flows, further investigations are needed to quantify the changes in the interfacial shape, and the drop sizes and its distribution in both oil and water phases. The mechanism of drag reduction for water soluble and oil soluble DRPA in oil–water flows are also needed. DRA effect on emulsion stability and characterization research is still not satisfactory. PDRA degradation in multiphase flow as a function of pipe length, temperature and pressure is needed. The effect of pipe inclination is partially done in small pipe diameter only by (Al-Sarkhi et al., 2006), more work needed in larger pipe diameter. Finally, High viscosity oils are produced from many oil fields around the world. Oil production systems are currently flowing oils with viscosities as high as 10 Pa s. commonly used laboratory liquids have viscosities less than 0.020 Pa s. performance of PDRA in multiphase flow of high viscosity oil as a liquid phase should be investigated. Effect of PDRA on Bubbly flow needs to be investigated and not available in literature. In vertical flows this could affect the effect the transition from bubbly flow to slug or churn flow but it has not been done in literature.

7. Summary

Clearly, there is a need to present a unifying interpretation for the effect of DRPA in multiphase flow. The work has been done still unsatisfactory. Studies on air-water flows in horizontal pipes identified several mechanisms:

(1) *Annular flow*: the destruction of disturbance waves (because of wave damping) and, as a consequence, the discontinuance of atomization and of the spreading of the liquid layer up the walls of a horizontal pipe. A change to stratified flow occurs.
(2) *Stratified flow*: polymers damp waves. This can have two effects, a decrease of interfacial drag and an increase of gas velocity because of the increase of the height of the stratified liquid layer. These have opposite influences on the pressure gradient.
(3) *Slug flow*: a damping of turbulence in the liquid decreases the wall drag and changes the behavior of the gas bubble just behind the back of the slug (Soleimani et al., 2002). PDRA also reduces the slug frequency.

(4) *Bubbly flow*: polymers have the possibility of affecting turbulence and bubble size. The maximum drag reduction usually occurs when a slug, pseudoslug or annular flow changes to stratified flow by adding drag reducing polymers. The effectiveness of a drag-reducing polymer is sensitive to the technology used to introduce polymer into the flow and the concentration of the injected master polymer solution. The aggregates of polymers have a more important effect on the turbulence and drag reduction than individual molecules. Therefore, degradation occurs by the destruction of these groups or aggregates.

In vertical flows this could affect the effect the transition from bubbly flow to slug or churn flow. PDRA also resulted in a significant increase in the liquid holdup (Fernandes et al., 2009). Liquid–liquid flows may be investigated in similar way. Differences related to the use of oil soluble or water soluble DRP should be identified.

Acknowledgements

The author would like thank the Deanship of Scientific Research at King Fahd University of Petroleum and Minerals for its support. Prof. T.J. Hanratty is thanked for his fruitful comments in the early stages of this study.

References

Al-Sarkhi, A., Abu-Nada, E., 25–27 May 2005. Effect of drag reducing polymer on annular flow patterns of air and water in a small horizontal pipeline. In: Twelfth International Conference on Multiphase Production Technology, Barcelona, Spain.

Al-Sarkhi, A., Hanratty, T.J., 2001. Effect of drag-reducing polymer on annular gas-liquid flow in a horizontal pipe. Int. J. Multiphase Flow 27 (7), 1151–1162.

Al-Sarkhi, A., Hanratty, T.J., 2002. Effect of pipe diameter on the performance of drag-reducing polymers in annular gas–liquid flows. Trans IChemE, Chem. Eng. Res. Des. 79 (Part A), 402–408.

Al-Sarkhi, A., Soleimani, A., 2004. Effect of drag reducing polymers on two-phase gas-liquid flows in a horizontal pipe. Trans IChemE, Chem. Eng. Res. Des. 82 (A12), 1583–1588.

Al-Sarkhi, A., Abu-Nada, E., Batayneh, M., 2006. Effect of drag reducing polymer on air-water annular flow in an inclined pipe. Int. J. Multiphase Flow 32, 926–934.

Al-Wahaibi, T., Smith, S., Angeli, P., 2007. Effect of drag-reducing polymers on horizontal oil water flows. J. Petrol. Sci. Eng. 57, 334–346.

Al-Yaari, M., Soleimani, A., Abu-Sharkh, B., Al-Mubaiyedh, U., Al-Sarkhi, A., 2009. Effect of drag reducing polymers on oil–water flow in a horizontal pipe. Int. J. Multiphase flow 35 (6), 516–524.

Baik, S., Hanratty, T.J., 2003. Effects of a drag reducing polymer on stratified gas–liquid flow in a large diameter horizontal pipe. International Journal of Multiphase Flow 29 (11), 1749–1757.

Burger, E.D., Munk, W.R., Wahl, H.A., 1982. Flow increase in Trans Alaska pipeline through use of polymeric drag reduction additive. J. Petrol. Eng., 377–386.

Carcoana, A., 1992. Applied Enhanced Oil Recovery, vol. 140. Prentice Hall.

Cox, L.R., Dunlop, E.H., North, A.M., 1947. Role of molecular aggregate in liquid drag reduction by polymer. Nature (London) 249, 243.

Daas, M., Bleyle, D., 2006. Computational and experimental investigation of the drag reduction and the components of pressure drop in horizontal slug flow using liquids of different viscosities. Exp. Thermal Fluid Sci. 30, 307–317.

Fernandes, R.L.J., Jutte, B.M., Rodríguez, M.G., 2004. Drag reduction in horizontal annular two-phase flow. Int. J. Multiphase Flow 30, 1051–1069.

Fernandes, R.L.J., Fleck, B.A., Heidrick, T.R., Torres, L., Rodriguez, M.G., 2009. Experimental study of DRA for vertical two-phase annular flow. J. Energy Res. Technol. 131 (2).

Greskovich, E.J., Shrier, A.L., 1971. Pressure drop and hold up in horizontal slug flow. AIChE J. 17, 1214–1219.

Harder, K.J., Tiederman, W.G., 1991. Drag-reduction and turbulent structure in two-dimensional channel flows. Phil. Trans. R. Soc., Lond. A 336, 19–34.

Jubran, B.A., Zurigat, Y.H., Goosen, M.F.A., 2005. Drag reducing agents in multiphase flow pipelines: recent trends and future needs. Petrol. Sci. Technol. 23, 1403–1424.

Kang, C., Vancko, R.M., Green, A., Kerr, H., Jepson, W., 1997. Effect of drag-reducing agents in multiphase flow pipelines. J. Energy Resour. Technol. 120, 15–19.

Manfield, C.J., Lawrence, C., Hewitt, G., 1999. Drag-reduction with additive in multiphase flow: a literature survey. Multiphase Sci. Technol. 11, 197–221.

Mowla, D., Naderi, A., 2006. Experimental study of drag reduction by a polymeric additive in slug two-phase flow of crude oil and air in horizontal pipes. Chem. Eng. Sci. 61 (5), 1549–1554.

Oliver, D.R., Young Hoon, A., 1968. Two-phase non-Newtonian flow. Trans. Inst. Chem. Eng. 46, T106.

Otten, L., Fayed, A.S., 1976. Pressure drop and drag-reduction in two-phase non-Newtonian slug flow. Can. J. Chem. Eng. 54, 111–114.

Parimal, P., Cheolho, K., Alvaro, A., September 29–October 3, 2008. The performance of drag reducing agents in multiphase flow conditions at high pressure; positive and negative effects. In: Proceedings of IPC2008, Seventh International Pipeline Conference, Calgary, Alberta, Canada.

Rosehart, R.G., Scott, D., Rhodes, E., 1972. Gas–liquid slug flow with drag-reducing polymer solutions. AIChE J. 18 (4), 744–750.

Saether, G., Kubberud, K., Nuland, S., Lingelem, M.N., 1989. Drag reduction in two phase flow. In: Proceedings of the Fourth International Conference on Multiphase Flow, France, pp. 171–184.

Scott, D., Rhodes, E., 1972. Gas–liquid slug flow with drag reducing polymer solutions. AIChE J. 18, 744–750.

Sellin, R.H., W Hoyt, J., Scrivener, O., 1982. The effect of drag-reducing additives on liquid flows and their industrial applications part I: basic aspects. J. Hydraul. Res. 20 (1), 29–68.

Sifferman, T., Greenkorn, R., 1981. Drag reduction in three distinctly different fluid systems. SPE J., 663–668.

Soleimani, A., Al-Sarkhi, A., Hanratty, T.J., 2002. Effect of drag reducing polymers on pseudo-slugs-interfacial drag and transition to slug flow. Int. J. Multiphase Flow 28 (12), 1911–1927.

Sylvester, N.D., Brill, J.P., 1976. Drag-reduction in two-phase annular mist flow of air and water. AIChE J. 22 (3), 615–617.

Thwaites, G.R., Kulov, N.N., Nedderman, N.M., 1976. Liquid film properties in two phase annular flow. Chem. Eng. Sci. 31, 481.

Toms, B.A., 1948. Some observations on the flow of linear polymer solutions through straight tubes at large Reynolds numbers. In: Proceedings of the First International Congress on Rheology, vol. 2. North Holland Publication Company, Amsterdam. 135–141.

Vissman, K., Bewersdorff, 1989. The influence of pre-shearing on the elongational behavior of drag-reducing fluids. In: Sellin, R.H.J., Moses, R.T. (Eds.), Drag Reduction in Fluid Flows. Ellis Horwood Publishers, pp. 61–67.

Vlachogiannis, M., Liberatore, M.W., McHugh, A.J., Hanratty, T.J., 2003. Effectiveness of a drag reducing polymer: relation to molecular weight distribution and structuring. Phys. Fluids 15 (12), 3786–3794.

Warholic, M., Massah, H., Hanratty, T.J., 1999. Influence of drag-reducing polymers on turbulence: effects of Reynolds number, concentration and mixing. Exp. Fluid 27, 461–472.

Wei, T., Willmarth, W.W., 1992. Modifying turbulent structure with drag-reducing polymer additives in turbulent channel flows. J. Fluid Mech. 245, 619–641.