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Multiphase drag reduction: Effect of eliminating slugs

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Abstract

Two-phase pressure drop measurements were taken for air/water mixtures in a 0.052-m diameter horizontal pipe with special focus on the superficial liquid velocity range of 0.03–1.2 m/s at superficial gas velocities of 3.8, 5.2, and 6.6 m/s. It was found that the addition of 400 ppm of sodium dodecyl sulfate (SDS) to the water reduced the pressure drop by 25–40% when compared to equal flow rates without SDS. The pressure drop reduction occurred where the SDS eliminated the occurrence of the intermittent flow present with water. It was also found that the same concentration of SDS had virtually no effect on single phase liquid pressure drop. The pressure drop reduction appears to be due solely to the suppression of intermittent flow patterns.

Keywords: Slug flow; Two-phase flow; Drag reduction; Surfactant

1. Introduction

Drag reduction is important to the increase of oil and gas production rates and to the reduction of transportation costs. Drag reducing agents (DRA) have been investigated for industrial and military applications since the discovery of Toms (1949). Single phase drag reduction due to polymer based additives has been thoroughly studied and the mechanisms are beginning to be understood to be related to dampening of turbulent bursts and reduction of Reynolds stresses. In addition to mechanisms available to single-phase flow (e.g., dampening turbulent bursts, wall roughness reduction, pipe wall wettability reduction), multiphase pipe flow has numerous additional unique mechanisms available to reduce pressure loss, including but not limited to: interfacial stress reduction, holdup change, flow pattern change, and reduction of effective density (vertical flow).

Two critical issues exist with polymer DRAs in terms of hydrocarbon transport; dry out and shear degradation. Polymer DRA requires a co-solvent. During high gas–liquid ratio multiphase flow these co-solvents have a tendency to vaporize (i.e., dry out). This leads to precipitation of the DRA and a loss of drag reduction benefit. Shear degradation is a phenomenon that has been well documented. Under high shear conditions,

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long polymer DRA chains are permanently broken, thus permanently reducing or eliminating the drag reduction capabilities of the DRA.

These critical issues could be eliminated with the use of surfactant drag reducing agents (SDRA). Surfactants are soluble in most liquid phases and therefore do not require a co-solvent and therefore they are not subject to dry out.

SDRA also have much smaller molecular chains than those of the polymers used in DRA. With surfactants the mechanism of single phase drag reduction is related to the formation of micelles. When surfactants are added to a liquid they go to the liquid surface and act to reduce the surface tension. Above the critical micelle concentration (CMC) additional surfactant molecules no longer migrate to the surface and they begin to form micelle structures within the liquid. It has been proposed that in single-phase flow, surfactant drag reduction occurs if the micelle structures formed are rod-like (Ohlendorf et al., 1986). These rod-like micelles then mimic the performance of long chain polymers in dampening turbulent bursts near the pipe wall. The benefit of these self-assembling structures is that they break apart when subjected to conditions of high shear but then reassemble downstream when the high-shear condition is gone. Thus it does not need to be re-injected following a high-shear condition, such as a pumping station or a choke.

Elimination of intermittent flow, in particular slug flow, is seen as a key to increasing throughput in gas/liquid flow due to the high pressure losses associated with these flow patterns. Ability to control formation of intermittent flow may also provide key insights into the mechanism of slug formation and pave the way towards a comprehensive model for gas/liquid flow in pipes. The focus of this work will be to quantify the flow pattern effect on pressure drop. More specifically, it will focus on the effect of eliminating slug flow on pressure drop through the use of SDRA.

2. Literature review

2.1. Single phase

The primary drag reduction mechanism that occurs within the liquid phase is one that acts to disrupt turbulent structures and is probably the best understood. When the generic term DRA is used, it is generally a long chained polymer that is added to the liquid phase, generally with a co-solvent. This DRA reduces drag within the liquid phase. The popular polymer DRA mechanisms proposed involve the interference of the polymer with the turbulent structures in the fluid near the wall. For example, turbulent fluctuations normal to the pipe wall have been measured to be significantly reduced in the presence of a DRA (Warholic et al., 2001). While arguments persist as to exactly how such interference occurs, the bottom line is that drag reduction occurs within the liquid. The end effect is reduction of the drag between the liquid and the wall. For surfactant drag reduction to occur with the same mechanism then it must mimic the performance of the long chain polymer. Proper micelle formation is necessary for the equivalent surfactant drag reduction to occur, as described previously.

Virk (1975) analyzed the drag reduction performance of numerous polymer solutions reported in the literature. He found that all tended towards a maximum drag reduction. Fig. 1 demonstrates the observed drag reduction limit. He found that polymer-turbulence interaction occurs in the location of peak turbulence production indicating an interference with turbulent bursting processes.

2.2. Multiphase

Manfield et al. (1999) provide a literature review of drag reduction. They report very limited work in the areas of SDRA and drag reduction in multiphase flow. Spedding and Hand (1997) reported observations of 100 ppm of Chemtreat 271 surfactant in an air–water 0.0935-m diameter horizontal pipe. They reported that the surfactants delayed the transition from stratified smooth to stratified wavy flow. The drag reduction led to increased liquid holdup. Wave damping was also found in the liquid film in annular flow. They further found that the surfactant caused a modification to the slug front region, leading to drag reduction. Oliver and Hoon (1968) also reported that slugs exhibited considerably less circulation in non-Newtonian two-phase flow leading to lower pressure drop.

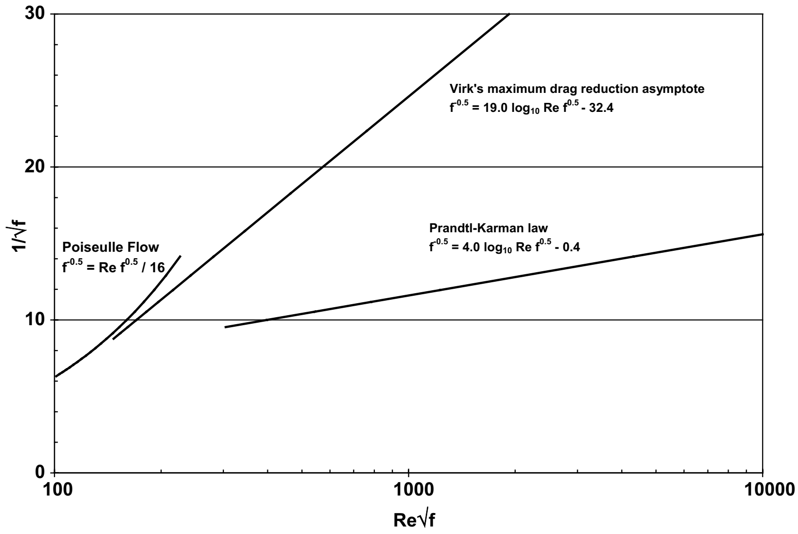

Fig. 1. Virk's maximum drag reduction asymptote compared to the Fanning friction factor for laminar flow and the Prandtl–Karman correlation for Newtonian turbulent flow.

Sylvester and Brill (1976) studied polymer DRA in annular flow in a 0.0127-m diameter horizontal pipe. They found drag reduction of up to 37% at high flow rates if the DRA was not recycled.

Greskovich and Shrier (1971) studied polymer DRA in a 0.038-m diameter horizontal pipe. They reported drag reduction of 40–50% in air–water slug flow. They attributed this to a reduction in frictional losses as opposed to accelerational changes within the slug.

Rosehart et al. (1972) studied polymer DRA (polyacrylamide) in slug flow in a 0.0254-m diameter horizontal pipe. In general they found no changes to the slug characteristics. There was no change in the slug translational velocity. At the highest DRA concentrations there was a decrease in slug frequency, primarily due to increased viscosity. The greatest drag reduction benefit came at the highest slug velocities. They proposed that this is due not only to a reduction in skin frictional losses, but also due to lost energy (accelerational). Increasing the DRA concentration also increased the drag reduction up to a saturation concentration beyond which there was no additional drag reduction. Therefore for equal flow pattern and slug properties drag reduction was found. Drag reduction was observed in single-phase flow as well. Their flow loop was single-pass due to significant degradation of the polymer DRA they used when it was recirculated.

Otten and Fayed (1976) found similar results, adding that the observed pressure drop was always lower than predicted by the Lockhart–Martinelli correlation. Their findings supported the Arunnalchum modification of Virk's drag reduction asymptote.

A reduction of interfacial roughness can also reduce pressure drop. Glassmeyer (2003) has shown that significant drag reduction can occur in stratified gas–liquid flow with low concentrations of surfactant (i.e., low enough not to form drag reducing micelles). He proposed that this is due to the reduction of interfacial stress and modification of interfacial wave structures. For the flow to remain stratified the pressure gradient in the gas and liquid phases must balance. As the pressure drop in the gas phase decreases, the liquid holdup must now change. An increase in liquid holdup leads to lower liquid velocity and more wetted wall and thus lower pressure drop in the liquid phase. At the same time the gas velocity now increases leading to a higher pressure drop in the gas phase. When these changes balance the new liquid holdup is established.

A change in flow pattern is also expected to reduce pressure losses. Al-Sarkhi and Hanratty (2001) studied polymer DRA in a horizontal, 0.0953-m diameter multiphase pipe. They compared air/water flow with and without the DRA at equal flow rates for high gas flow conditions. They found that annular flow became stratified with the injection of the DRA. This was due to damped disturbance waves which led to reduced atomization. They found a reduced pressure gradient that reached a plateau with increasing DRA concentration. They also found sensitivity to injection technique. The reduced pressure gradient observed was a combined effect of flow pattern change and a liquid phase mechanisms as their polymer solution presented single phase drag reduction.

Fernandes et al. (2004) studied polymer DRA in a high pressure (1.9 MPa) horizontal, 0.019-m diameter multiphase pipe. They compared methane/condensate flow with and without DRA for high gas flow rate conditions. They found drag reduction in annular flow due to both reduction of entrainment and reduced interfacial friction due to a reduced liquid film roughness, with a negligible contribution of liquid turbulence. They proposed a model for estimating the drag reduction.

Soleimani et al. (2002) studied polymer DRA in a horizontal, 0.0254-m diameter multiphase pipe. They compared air/water flow with and without DRA at equal flow rates in the range of pseudo-slug flow. They found the transition to slug flow to occur at higher superficial liquid velocities in the presence of the DRA; there were no slugs present from 0.25 to 0.8 m/s at a superficial gas velocity of 6 m/s. Despite this delay in the onset to slugging, they did not compare the pressure drop for equal flow conditions where air/water generated slugs and air/(water + DRA) was only generating roll waves. Where the flow patterns were the same they reported drag reduction. They reported the ratio of interfacial friction factor to gas–wall friction factor to be decreased with the presence of the DRA. This ratio was linear with increasing superficial liquid velocity. At the transition to slug flow for air/water the ratio was about 35. For DRA the maximum was about 25, and at a much higher superficial liquid velocity. The ratio was much less dependent on gas flow rate. The DRA led to a decrease in the liquid shear stress at the wall. Increasing the concentration decreased wave frequency, decreased wave velocity, decreased the small wavelength waves, dampened the high frequency waves, and increased the holdup. The pressure drop reduction was not monotonic with increasing DRA concentration due to competing effects (e.g., holdup, interfacial drag) at each concentration. They suggested that the drag reduction observed was due to the elimination of small wavelength waves on roll waves rather than damping of the roll waves.

Elimination of intermittent flow patterns are expected to have a dramatic effect on drag reduction. This process can occur geometrically (e.g., increasing pipe diameter, decreasing the inclination), operationally (e.g., pipeline pressure), and chemically. Researchers have indicated that in gas–liquid flow DRA can reduce the range of conditions for which some flow patterns occur (Manfield et al., 1999; Kang et al., 1999; Spedding and Hand, 1997, etc.). More relevant to this work, surfactants have been shown to reduce the occurrence of slug flow (Glassmeyer, 2003; Wilkens et al., 2006). Studies to date have not quantified the effect that elimination of slug flow occurrence alone has on pressure drop. In slug flow gas forces slugs of liquid to completely fill the pipe cross-section, accelerate to the mixture velocity, and dramatically increase the pressure drop. Thus, drag reduction could occur due solely to changing the flow pattern, for example, from slug flow to stratified flow.

3. Experimental setup

Experiments were arranged to study the effect of slug flow elimination via surfactant addition on air/water pressure drop in a pipe. A horizontal multiphase flow loop, shown in Fig. 2, was used for the measurements. A

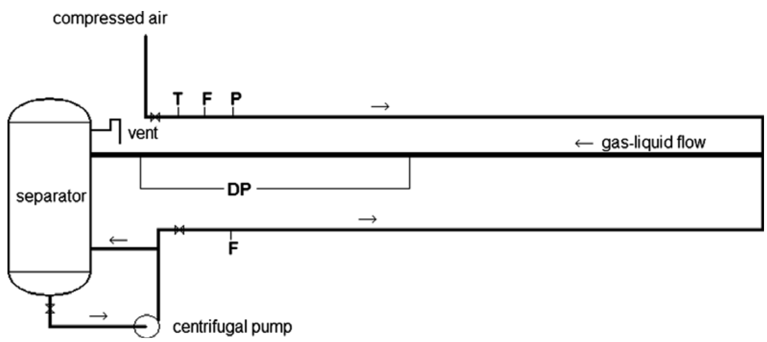

Fig. 2. Gas–liquid flow loop, with measurement locations of temperature (T), flow rate (F), pressure (P), and differential pressure (DP) indicated.

100-gal predetermined liquid composition was charged into a 200-gal (0.76 m^3) storage and separation tank. The liquid was pumped with a 3-hp (2.2 kW) centrifugal pump through a flow metering section to the inlet of the multiphase pipe. Air was supplied at 100 psig (0.79 MPa). The air flow rate was measured in a metering section upstream of the multiphase pipe inlet.

The multiphase flow occurred in a 2-in Sch. 40 (0.052 m-id) clear PVC pipe. For clarity, all locations in the piping system are listed by their length to diameter (L/D) ratio. The storage/separation tank is located at $L/D = 300$. The flow patterns are visually determined at $L/D = 275$. Pressure taps at $L/D = 145$ and $L/D = 280$ are connected to an OMEGA PX293-006D5 V pressure transmitter. These were used to record pressure drop for a 7 m straight, horizontal flow section. Differential pressure and liquid flow rate are recorded 1000 times in approximately 27 s, giving a measure of both the average value and the variability of the data. Each recorded data point is an arithmetic average of 10 measurements. The flow section is transparent, allowing visual correlation of flow patterns with measured pressure drop. Instrumentation details for this system have been reported elsewhere (Glassmeyer, 2003).

After the multiphase flow enters the separator, the air is vented to the atmosphere. The pressure in the test section is effectively atmospheric (<1 psig). The temperature of the fluid in the test section ranged from 19 °C to 23 °C. Fluctuations within this range are not expected to have a significant impact on the flow pattern observed or the pressure drop measured.

Hard water (10 gpg, or grains per gallon municipal supply) was used for experimentation. The surfactant used in this study was sodium dodecyl sulfate (SDS).

4. Results and discussion

4.1. Single phase

It is critical in this work to verify that any pressure drop reduction for this SDRA is due to flow pattern elimination rather than being by some other mechanism. SDRA have been shown to be effective in single-phase flow. It has been proposed that this can only occur well above the CMC with the formation of rod-like micelles. Here, the concentrations of SDS were kept low. In order to verify that no single phase drag reduction was occurring, the pressure drop of the hard water was measured with the following concentrations of SDS: 0, 140, 400, 800 and 1000 ppm. No air was injected. These results were compared to the single-phase non-drag reduced pressure drop, ΔP, prediction of Eq. (1)

$$\Delta P = 4f\frac{L}{D}\frac{\rho u^2}{2} \tag{1}$$

L is the pipe length, D is the pipe inner diameter, ρ is the water density, and u is the average velocity. The turbulent Fanning friction factor for the smooth PVC pipe, f, was estimated using Eq. (2)

$$f = 0.0014 + \frac{0.125}{Re^{0.32}} \tag{2}$$

The results are plotted in Fig. 3. All pressure differentials are within the experimental uncertainty of the predicted pressure drop. The lack of reduction in the pressure drop verifies that no single phase mechanism will be a factor at these concentrations. Wall roughness will also not be a factor due to the pipe selection and through validation of this first experiment. Pressure drop due to elevation change has also been eliminated by the selection of a horizontal pipe.

4.2. Flow rate selection

Three factors influenced the selection of flow rates for this study. The first was the air/water separation in the storage tank. At superficial liquid velocities above 0.9 m/s with surfactant present, air was visibly entrained in the liquid flow line. While observations could continue to be made at higher liquid flow rates, the actual liquid flow rate for the given pressure drop could not be comfortably discerned.

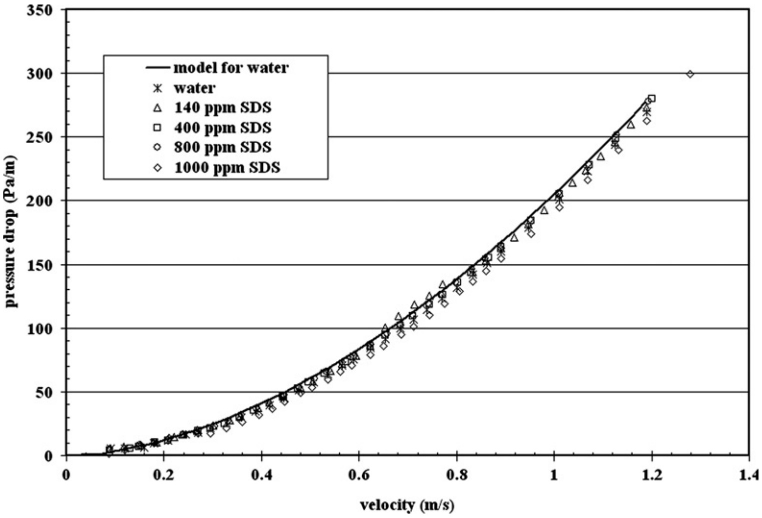

Fig. 3. Pressure drop for single-phase (liquid) flow. The surfactant does not affect the pressure gradient.

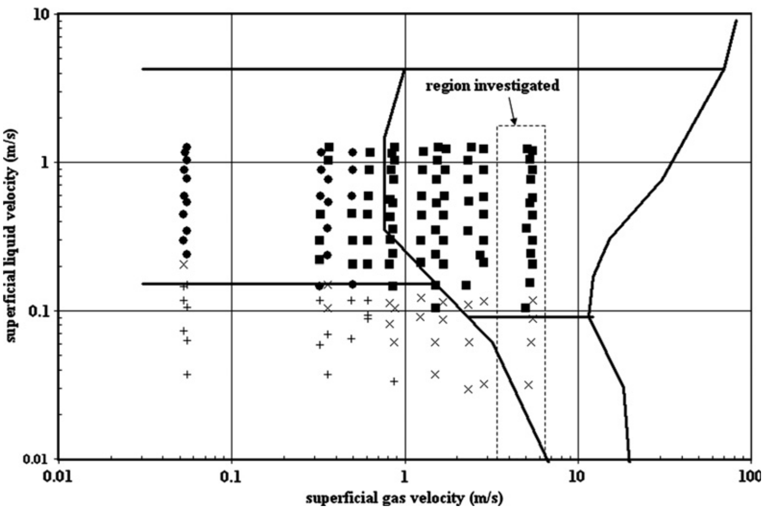

Fig. 4. Flow pattern map for air/water flow in the flow loop with no surfactant. The lines represent Mandhane et al. (1974). Circles (plug flow) and squares (slug flow) are intermittent flow. Plusses (stratified smooth) and crosses (stratified wavy) are stratified.

Secondly, at superficial gas velocities in excess of 6.6 m/s excessive foam from the SDS was generated and began to carry out the vent line. This caused concern about the gradual reduction in surfactant concentration with time. It also created safety concerns.

Thirdly, it was necessary that conditions be found that would give slug flow with air/water and stratified flow at the same flow rates with the addition of surfactant. Fig. 4 illustrates the flow pattern map for the flow loop with air/water flow and no surfactant.

4.3. Air/water baseline

As a baseline for comparison to the surfactant measurements, air/water pressure drop was recorded. Reporting the pressure drop during intermittent flow is non-trivial. Consider the pressure-drop fluctuations for the sample conditions shown in Fig. 5. As a slug enters the test section the pressure drop increases sharply.

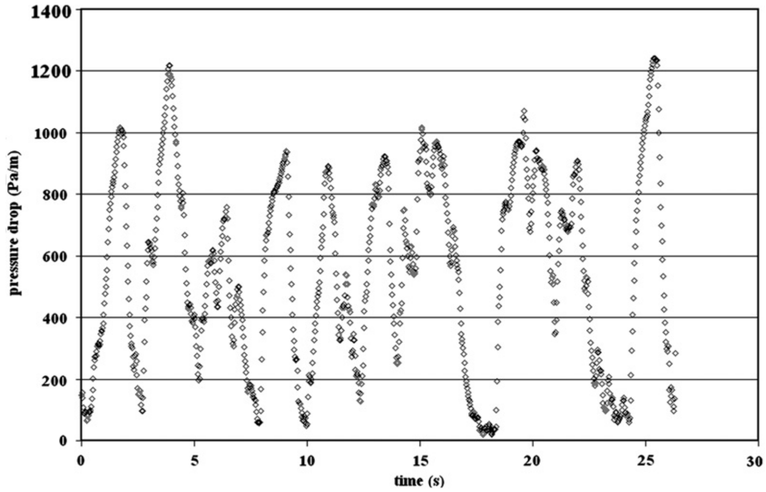

Fig. 5. Pressure-drop fluctuations during slug flow (no surfactant, superficial liquid velocity = 0.74 m/s, superficial gas velocity = 3.8 m/s).

The pressure drop then decreases sharply as the slug exits the test section. A larger sample of the data from the conditions in Fig. 5 is plotted in the form of a histogram in Fig. 6. The pressure drop distribution is multimodal, as expected for slug flow (Wilkens and Thomas, submitted for publication). The pressure drop in the film region is low and the pressure drop across the slug is high. This is one reason that such a large pressure drop region was investigated (i.e., 7 m). The larger the length between the pressure tappings, the better the pressure drop measurement in intermittent flow.

Multimodal data raises the question of how best to determine the average. If the data is bi-modal, it is frequently useful to calculate each mode, and use these values in a model with the appropriate frequencies of the modal conditions to provide a thorough understanding of the data. In this study, as flow rates increase, the data changes from mono-modal to bi-modal and on through multimodal frequency distributions. For the purposes of this study, the mean value was used as the average. This practice is common in field applications and is further justified when viewing the results of this study.

Some preliminary study has been given to the multimodal behavior of the data in hopes that a model can be developed to fully analyze such data in the future. Data on slug frequency was generated using a pressure drop

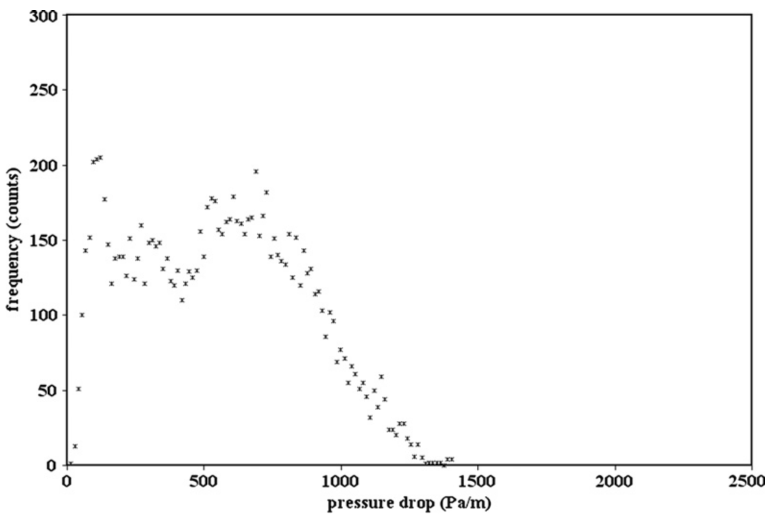

Fig. 6. Histogram of pressure drop during slug flow.

model developed in a related publication (Wilkens and Thomas, submitted for publication). It is hoped that this can be further developed to aid in determining the most appropriate averaging technique.

The air/water differential pressure data is presented later with the SDS data for comparison.

4.4. Air/water with SDS

The following concentrations of SDS in water were studied: 140, 400, 800, and 1000 ppm. The gas flow rates studied were 3.8, 5.2, and 6.6 m/s.

Fig. 7 compares the pressure drop for selected concentrations at a superficial gas velocity of 3.8 m/s. There is no pressure drop benefit for using 140 ppm. Increasing the surfactant concentration to 400 ppm creates pressure drop reduction for the flow rate range of 0.5–0.9 m/s superficial liquid velocity. For these conditions the air/water system was slugging, while the air/(water + surfactant) system was stratified flow with bubbles on top. In addition, as mentioned previously, the true superficial liquid velocity was difficult to ascertain at the high flow rates due to bubble entrainment after the separator.

Increasing the concentration to 800 ppm had only a slight effect in that it changed the endpoints of the pressure drop reduction, slightly increasing the range of benefit. For the flow rates where both 400 and 800 ppm gave pressure drop reduction the magnitude of each reduction was the same. This shows that increasing the concentration further would not likely have additional benefit in terms of magnitude of drag reduction for the flow pattern mechanism. This makes sense as the drag reduction mechanism being exploited is slug flow elimination. Once the slugs disappear, there is no further reduction to be taken using this mechanism.

No 1000 ppm data is reported for these conditions. The 1000 ppm data was difficult to ascertain due to heavy foaming.

At higher flow rates the pressure drop returned to that of the water. This is due to the flow pattern becoming annular with intermittent features.

The flow pattern transition was where it was expected to occur when compared to an earlier publication (Wilkens et al., 2006). That is, with low amounts of SDS the flow pattern is still slug flow at low liquid flow rates while there is no slug flow at higher liquid flow rates. At higher concentrations of SDS and high gas flow rates, there is also no slug flow at the low liquid flow rates.

For comparison, the OLGA-S model in Pipesim was used to predict the pressure drop of air/water flow. The results were in good agreement with the air/water data. These results are included in Fig. 7.

Fig. 8 compares the pressure drop at a superficial gas velocity of 5.2 m/s. Again, 140 ppm conditions showed no pressure drop reduction. 400, 800, and 1000 ppm conditions showed no slugging for the range of conditions tested. For this region of flows there is significant drag reduction. Again, additional surfactant

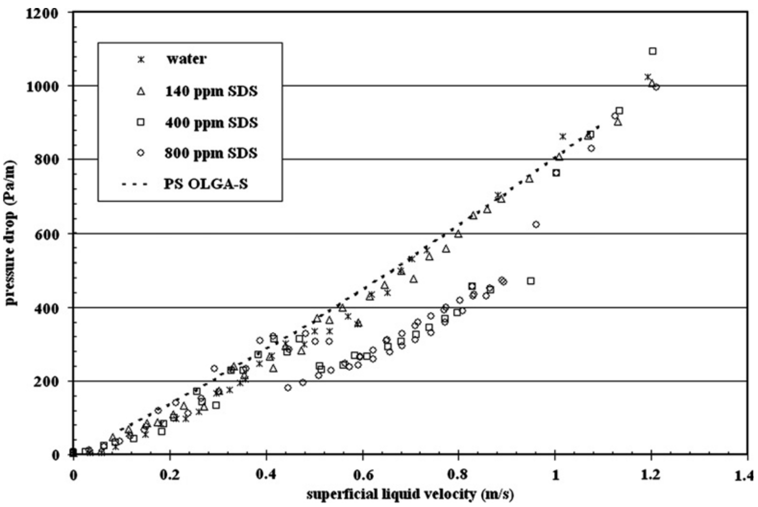

Fig. 7. Pressure drop at a superficial gas velocity of 3.8 m/s.

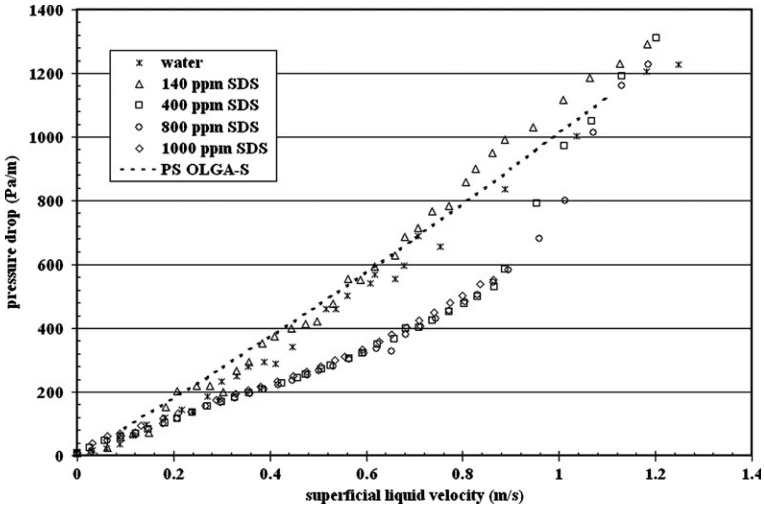

Fig. 8. Pressure drop at a superficial gas velocity of 5.2 m/s.

does not increase the drag reduction. At higher flow rates the flow became annular. The air/water and 140 ppm data closely follow the OLGA-S prediction for air/water.

Fig. 9 compares the pressure drop at a superficial gas velocity of 6.6 m/s. The results were similar to those at 5.2 m/s. Again there is no pressure drop benefit from 140 ppm. Also, 400, 800, and 1000 ppm conditions showed no slugging and thus reduced pressure drop. Data for high flow rate 1000 ppm surfactant is not reported, again due to operational difficulty with foaming. It can be seen that the range of conditions for which drag reduction occurs at 1000 ppm is not as broad as it is at lower concentrations. The OLGA-S model matches the non-drag reduced data.

While no reduction in pressure drop for single-phase liquid flow occurred at any of these concentrations, as shown previously, pressure drop reduction occurred in multiphase flow. Pressure drop data for systems of air and water with SDS indicated that above a threshold concentration, the full effect of SDS is realized and that below the threshold concentration, no reduction in the pressure drop is observed. This threshold is apparently somewhere between 140 ppm and 400 ppm. Above this threshold, for a great portion of the region where slug flow is normally observed, the actual observed flow pattern was stratified and had a bubbly interface. This leaves slug flow suppression as the logical mechanism for any drag reduction observed in this study.

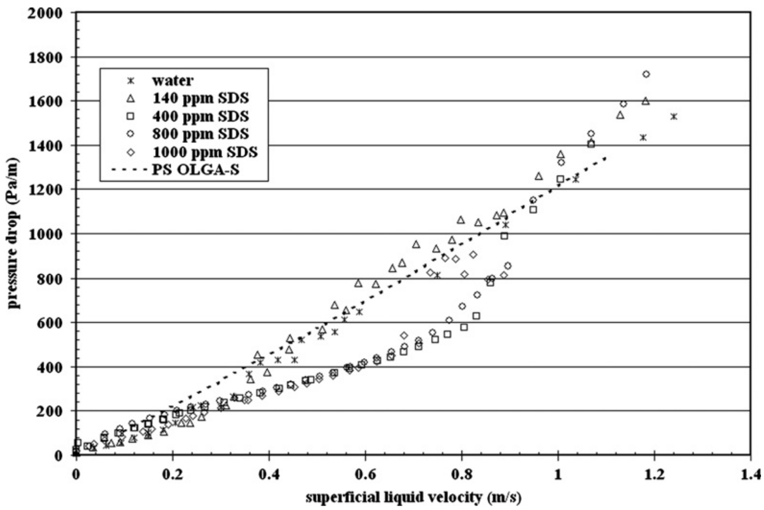

Fig. 9. Pressure drop for a superficial gas velocity of 6.6 m/s.

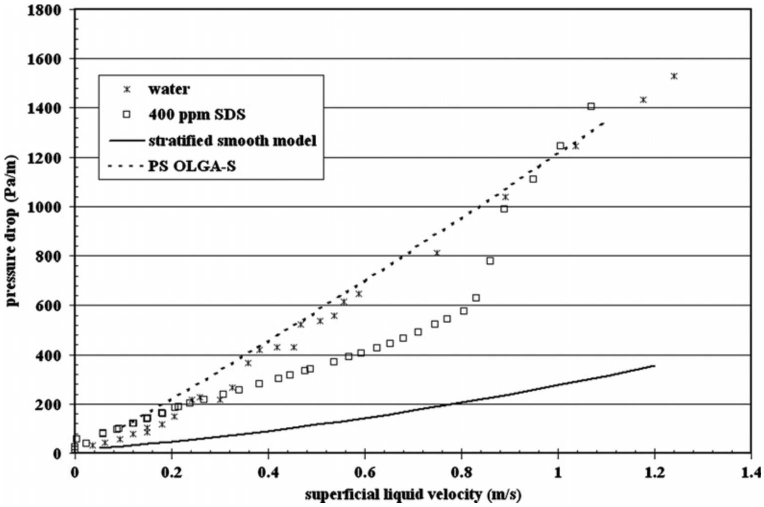

Fig. 10. Comparison of the stratified smooth model to drag reduction observed at a superficial gas velocity of 6.6 m/s.

For full flow pattern drag reduction, the resulting pressure drop would be that of stratified-smooth air/water flow. The model for this pressure drop can be found in a number of sources, such as Taitel and Dukler (1976). These values have also been plotted in Fig. 10. As expected, this represents a limiting case when the only multiphase drag reduction mechanism is flow pattern suppression. To make the data match, the ratio of the friction factor at the interface to that of the gas with the smooth wall needs to be about 40. Perhaps a better model is three-layer stratified; gas, bubbles, liquid.

4.5. Drag reduction

Kang et al. (1999) define the effectiveness of a drag reduction agent (DRA) as

$$\text{Effectiveness} = \frac{\Delta P_{\text{without DRA}} - \Delta P_{\text{with DRA}}}{\Delta P_{\text{without DRA}}} \times 100\%$$

By the same calculation method the drag reduction effectiveness of SDS as an SDRA has been determined and plotted in Fig. 11. Drag reduction of up to 40% is achievable solely from the elimination of slug flow, with

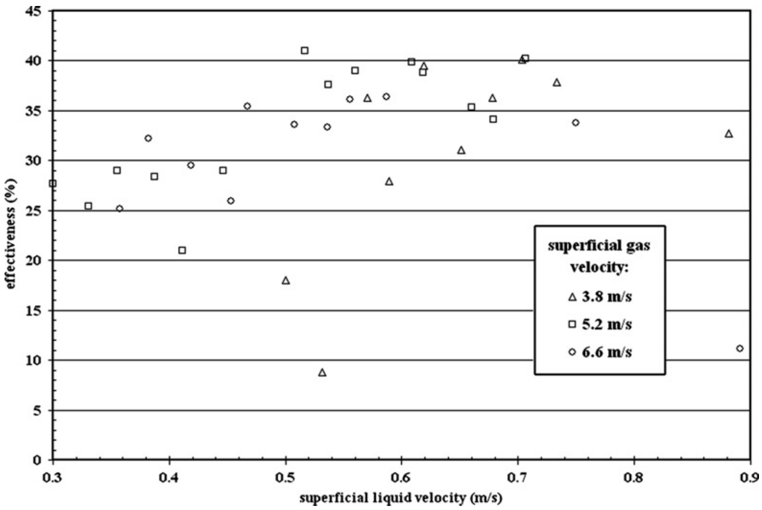

Fig. 11. Drag reduction effectiveness for slug flow elimination.

most data being in the range of 25–40%. It should be noted that only conditions with exact flow rate match to air/water data were used for this plot. The results are consistent with visual inspection of Figs. 7–9.

Verification of the pressure drop reduction is also apparent by looking at a histogram. Fig. 12 shows the pressure drop distribution for intermittent (water) and stratified (SDS) flow at equal condition (superficial liquid velocity = 0.74 m/s, superficial gas velocity = 3.8 m/s). The addition of the SDS caused a significant pressure drop reduction. Also, there are not large fluctuations in the stratified flow. The fluctuations in pressure drop seen in the intermittent flow translate into a high average pressure drop. Thus the SDS condition created a lower average value and a much lower spread due to the lack of intermittency.

These observations are further demonstrated at higher flow rates. Fig. 13 shows a histogram for the case of a superficial liquid velocity of 0.74 m/s and a superficial gas velocity of 5.2 m/s. Fig. 14 shows a histogram for a superficial liquid velocity of 0.74 m/s and a superficial gas velocity of 6.6 m/s.

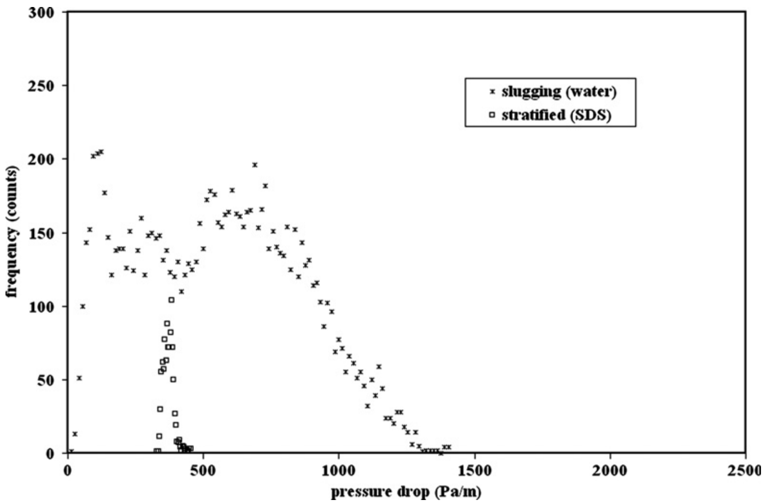

Fig. 12. Histogram for pressure drop at a superficial liquid velocity of 0.74 m/s and a superficial gas velocity of 3.8 m/s.

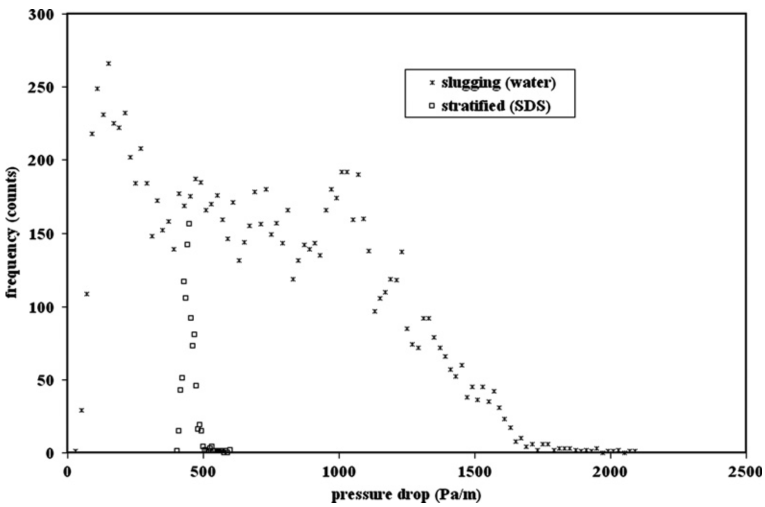

Fig. 13. Histogram for pressure drop at a superficial liquid velocity of 0.74 m/s and a superficial gas velocity of 5.8 m/s.

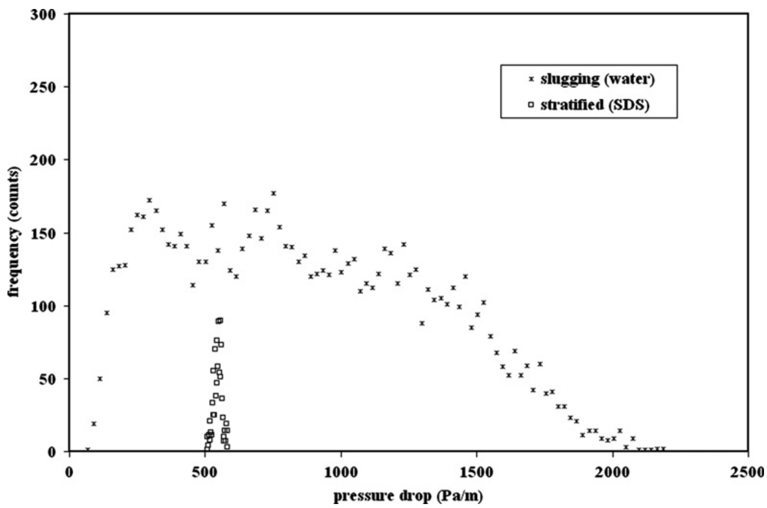

Fig. 14. Histogram of pressure drop for a superficial liquid velocity of 0.74 m/s and a superficial gas velocity of 6.6 m/s.

5. Conclusions

The mechanisms involved in multiphase SDRA have been outlined. It has been shown that drag reduction can be due to change in flow pattern alone. Surfactants such as SDS may provide an alternative to polymer DRAs for reducing pressure drop in gas/liquid systems. This is potentially very attractive due to the shear stability, relatively lower cost (e.g., SDS as opposed to an ethoxylate DRA), and the elimination of the need for a co-solvent.

A minimum surfactant concentration is necessary to provide drag reduction. However, the concentration does not have to be as significant as required for single phase drag reduction. The addition of 400 ppm or more of SDS reduced the two-phase pressure drop by 25–40%. This was due to suppression of intermittent flow patterns alone. The suppression mechanism appears to be associated with the appearance of bubbles at the liquid/gas interface, as reported previously. Additional surfactant does not further reduce drag by this mechanism, but it can affect the range of the benefit. While 400 ppm is considered high by polymer DRA standards it is low for SDRA (i.e., less than the CMC).

Additional modeling of slug frequency and length appears warranted, based on the potential for improving the understanding of the pressure-drop fluctuations in intermittent flow patterns.

Acknowledgements

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