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Effect of Drag-Reducing Agents in Multiphase Flow Pipelines

The effect of drag reducing agents (DRA) on pressure gradient and flow regime has been studied in horizontal and 2-deg upward inclined pipes. Experiments were conducted for different flow regimes in a 10-cm i.d., 18-m long plexiglass system. The effectiveness of DRA was examined for concentrations ranging from 0 to 75 ppm. Studies were done for superficial liquid velocities between 0.03 and 1.5 m/s and superficial gas velocities between 1 and 14 m/s. The results indicate that DRA was effective in reducing the pressure gradients in single and multiphase flow. The DRA was more effective for lower superficial liquid and gas velocities for both single and multiphase flow. Pressure gradient reductions of upto 42 percent for full pipe flow, 81 percent for stratified flow, and 35 percent for annular flow were achieved in horizontal pipes. In 2 deg upward inclination, the pressure gradient reduction for slug flow, with a concentration of 50 ppm DRA, was found to be 28 and 38 percent at superficial gas velocities of 2 and 6 m/s, respectively. Flow regimes maps with DRA were constructed in horizontal pipes. Transition to slug flow with addition of DRA was observed to occur at higher superficial liquid velocities.

Introduction

The flow of multiphase mixtures is common in the oil and gas industry. Many oil wells are located in remote sites such as Alaska or subsea. It is very expensive to have separation facility at each well site. Therefore, the multiphase mixture is transported in a single pipeline to one common separation site. The mixture often consists of gas, water, and oil. The distance of transportation is often many miles and the pressure drop in these pipelines can be significant. The benefits of DRA use in existing system are increased production without mechanical modification, reduction of operation costs such as pumping power, reduction of pipeline pressure while maintaining throughput, and to facilitate refinery debottlenecking and loading/unloading operations. The design benefits of DRA in new systems are reduction in pipeline diameter and pumping costs. The deferment of capital expenditure is also of economic value where pumps are introduced at a later stage in the life of an oil field.

Lee et al. (1993) constructed flow regime maps for three liquid compositions in oil-water-gas in horizontal pipes. They showed that the flow patterns for oil-water-gas three phase flow are stratified flow (smooth, wavy and rolling wave), intermittent flow (plug, slug, and pseudo-slug), and annular flow. Stratified flow occurs at low superficial liquid and gas velocities. Intermittent flow is observed at higher superficial liquid and gas velocities. Increasing the liquid velocity in smooth stratified flow results in plug flow. Increasing gas velocity then results in rolling waves that bridge the pipe, thus causing a transition to slug flow. Further increase in gas velocity produces pseudo-slug flow. Pseudo-slugs are similar to slugs, but are shorter and frothier with more gas entrainment. Annular flow occurs at even higher gas velocities. In annular flow, the gas flows as a core carrying liquid droplets, with a liquid film flowing around the pipe circumference.

Jepson and Taylor (1989) showed that the transition from stratified to slug flow occurs at higher liquid velocities in large diameter pipes. The transition from slug to annular flow was observed at lower gas velocities in larger pipelines. They also concluded that the results from small pipe diameters could not be easily extrapolated to larger pipes.

Drag-reducing agents were discovered by accident by Toms (1947), though it had been known that concentrated water-coal and wood pulp-water slurries could produce lower friction factors than those of water alone. DRA is usually polymer molecules such as polymethylmethacrylate (PMMA), polyethyleneoxide (PEO), polyisobutylene (PIB), and guar gum (Virk, 1975).

The first use of DRA in oil fields was to reduce pressure loss while pumping fluids downhole into fracture tight formation. Initially, DRA were used in quantities in excess of 600 ppm by weight. For these concentrations, an 80 percent reduction in drag was observed in single-phase flow.

Drag reducing agents can be beneficial in reducing frictional pressure loss in turbulent flow but not in laminar flow, since drag reduction occurs by interaction of the polymer molecules of the DRA with the turbulence of the flowing fluid (Lester, 1985). Drag-reducing polymers stretch in the flow and then absorb the energy in the streak. The polymers then prevent bursts that create the turbulence in the core and interfere with the turbulence from being formed, or reduce the degree of turbulence (Nijs, 1995). The effectiveness of a DRA decreases with increasing diameter (Lester, 1985).

Virk and Baher (1970) examined the effect of Reynolds number on drag reduction by polyacrylamide and polyethyl-

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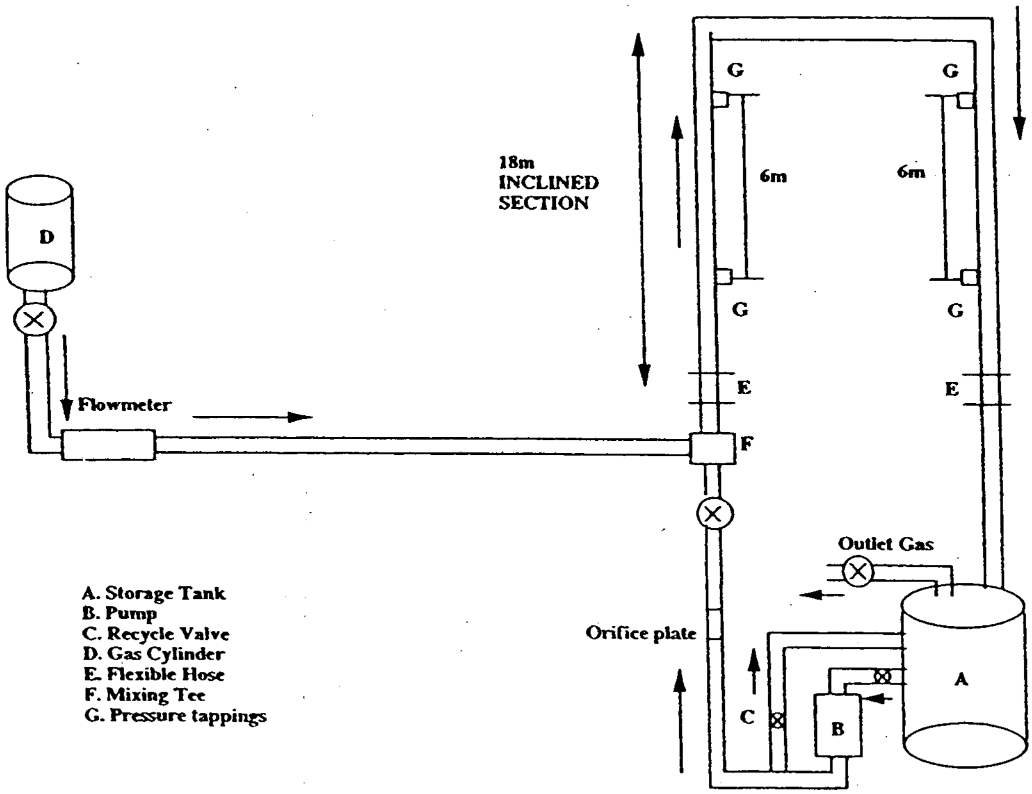

Fig. 1 Experimental layout of the flow loop

eneoxide in single-phase water flow in a 0.945-cm i.d. pipe. They defined four different flow regimes: laminar, transition, turbulent without drag reduction, and turbulent with drag reduction. The DRA was effective only in the most turbulent flow.

Rosehart et al. (1972) investigated a polyacrylamide polymer drag reducer in co-current, gas-liquid slug flow in 2.5-cm i.d. pipelines. They indicated that drag reduction in two-phase flow was greater than that in single-phase flow at the same superficial liquid velocities.

Effectiveness of DRA can be defined as follows:

$$\text{Effectiveness of DRA} = \frac{\Delta P_{\text{without DRA}} - \Delta P_{\text{with DRA}}}{\Delta P_{\text{without DRA}}}$$

There is a conspicuous absence of drag reduction work for three-phase oil-water-gas flows in horizontal and inclined pipes. Experiments were conducted to measure the pressure gradient in single and multiphase flows and produce flow regime maps in three-phase oil/water/gas flows with DRA concentrations. The results were compared to those determined by Lee (1993).

Experimental Setup

Figure 1 shows the layout of the experimental flow loop. The specified amount of oil-water mixture is stored in a 1.2 m^3 stainless steel tank (A). The tank is equipped with 6-m (2.5-cm i.d.) stainless steel cooling coils to maintain a constant temperature. The oil-water mixture from the storage tank is then pumped into a 10-cm i.d. PVC pipeline by means of a 76-hp low-shear progressing cavity pump (B). The liquid flow rate is controlled by varying the speed of the pump using a variable-speed controller.

Carbon dioxide is stored in a 20-ton liquid receiver and is introduced into the system at an inlet pressure of 0.27 MPa through a 5-cm i.d. copper pipeline and mixed with the liquid at a tee junction (F). The gas flow rate is measured using a variable area flow meter. The multiphase mixture then flows through 3.1-m long flexible hose (10-cm i.d.) which is used to aid the inclination of the pipes from horizontal to vertical. The multiphase, oil-water-gas, mixture then flows into an 18-m long plexiglass section (10-cm i.d.) where pressure gradient, flow pattern and phase distribution are measured. The multiphase mixture then returns to the storage tank where the liquid is recycled and carbon dioxide gas is vented to the atmosphere.

The pressure drop along a 6-m length of the pipeline is measured using pressure taps (G). Two methods, a U-tube manometer with Miriam 175 Blue fluid for low-pressure gradients and A-5/882-12 Sensotec pressure transducers for high-pressure gradients are used for pressure drop measurements. Flow pattern is determined both visually and with a high-speed video camera.

Oil (density 800 kg/m^3 and viscosity 2 cp at 40°C) and deionized water are used in this study. The gas used was carbon dioxide. The effectiveness of DRA was examined for five concentrations; 0, 5, 10, 25, 50, and 75 ppm. Oil concentrations were varied from 20 to 100 percent. The DRA concentration is calculated on a total volume basis as follows:

$$V_{\text{DRA}} = \frac{C_{\text{DRA}} \times V_{\text{total}}}{1 \times 10^6}$$

Nomenclature

ΔP = pressure drop, N/m^2
V = volume, m^3
C = polymer concentration, ppm
DRA = drag reducing agents
V_{sl} = superficial liquid velocity, m/s

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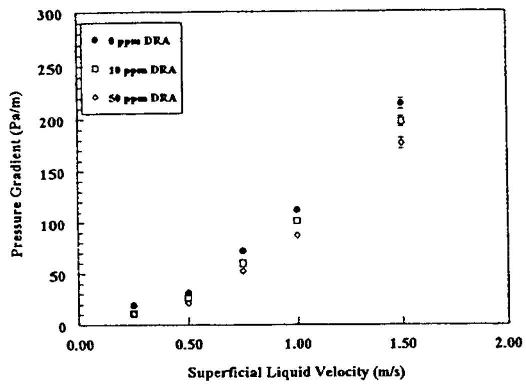

Fig. 2 Full pipe pressure gradient in horizontal pipes 100 percent oil

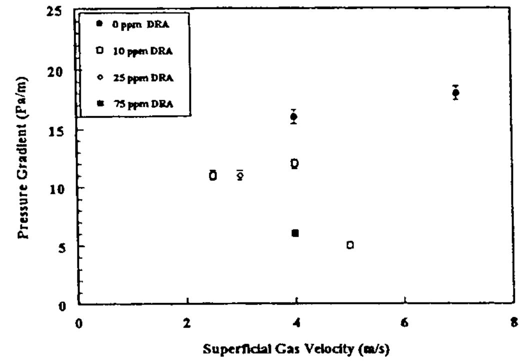

Fig. 4 Stratified pressure gradient in horizontal pipes 20 percent oil-80 percent water, V_{sl} = 0.11 m/s

where

V_{DRA} = volume of the DRA to be added
C_{DRA} = desired DRA concentration (ppm)
V_{total} = total liquid volume of the system

Experiments were conducted for full pipe, stratified slug, and annular flows in horizontal and 2 deg upward inclinations. Superficial liquid velocities between 0.06 and 1.5 m/s and superficial gas velocities between 1.0 and 14 m/s were studied.

Results

Figure 2 shows a plot of the pressure gradient results for full pipe flow of 100 percent oil with 10 and 50 ppm DRA in horizontal pipes. The pressure gradient without DRA increased from 19 to 214 Pa/m with an increase of the liquid velocity from 0.25 to 1.5 m/s. Increasing the DRA concentration to 10 ppm indicates that the DRA is effective in reducing the pressure gradient for all superficial liquid velocities. The pressure gradient decreases from 19 to 11 Pa/m, from 31 to 26 Pa/m, from 72 to 60 Pa/m, from 112 to 101 Pa/m, and from 214 to 197 Pa/m at superficial liquid velocities of 0.25, 0.5, 0.75, 1, and 1.5 m/s, respectively. These correspond to an effectiveness of 42, 16, 17, 10, and 8 percent. A much better performance is obtained with addition of more DRA (50 ppm). In this case, pressure gradient reduction of 31 to 21 Pa/m, 72 to 52 Pa/m, 112 to 87 Pa/m, and 214 to 176 Pa/m are noted at superficial liquid velocities of 0.5, 0.75, 1, and 1.5 m/s, respectively. It can be seen from these results that the effectiveness of DRA at lower superficial liquid velocities is much greater than that at higher superficial liquid velocities.

Figures 3 and 4 show plots of the pressure gradient for stratified flow for 20 percent oil-80 percent water-carbon dioxide in horizontal pipes at superficial liquid velocities of 0.03 and 0.11 m/s and superficial gas velocities from 2.2 and 7 m/s. It is seen from Fig. 3 that the pressure gradient decreases from 12 to 7 Pa/m and from 16 to 9 Pa/m at superficial gas velocities of 4 and 7 m/s as 10 ppm DRA was added. The pressure gradient reduction increases with further addition of DRA. The results for a concentration of 75 ppm DRA for the same superficial gas velocities are better than those with 10 ppm DRA, reducing the pressure gradient from 12 to 4 Pa/m and from 16 to 3 Pa/m. These correspond to an effectiveness of 67 and 81 percent, respectively. The general trend of decreasing pressure gradient with DRA for a superficial liquid velocity of 0.11 m/s is the same as for the previous superficial liquid velocity. At the superficial liquid velocity of 0.11 m/s and superficial gas velocity of 4 m/s, the pressure gradient reduces from 16 to 12 Pa/m and from 16 to 6 Pa/m with 10 ppm and 75 ppm DRA, respectively. It is seen from these figures that the pressure gradient at superficial gas velocity of 4 m/s increases from 12 to 16 Pa/m with increasing superficial liquid velocity from 0.03 to 0.11 m/s. Increasing the liquid velocity increases the height of the liquid film, resulting in larger pressure gradients.

Results of the pressure gradient for annular flow in 60 percent oil-40 percent water-carbon dioxide in horizontal pipes are shown in Fig. 5. At the superficial liquid velocity of 0.06 m/s and superficial gas velocity of less than 11 m/s, stratified flow regime is observed. A transition to annular flow begins to occur as superficial gas velocity is increased to 12 m/s. At a superficial gas velocity of 10 m/s, the pressure gradient decreases from 48 to 42 Pa/m, from 48 to 30 and from 48 to 24 Pa/m with 5, 10, and 25 ppm DRA concentration respectively. The pressure gradient for annular flow decreases from 101 to 78 Pa/m for a concentration of 5 ppm DRA and a superficial gas velocity of 14 m/s and to 75 Pa/m when increasing DRA concentration to 10 ppm. Increasing the DRA concentration to 25 ppm results

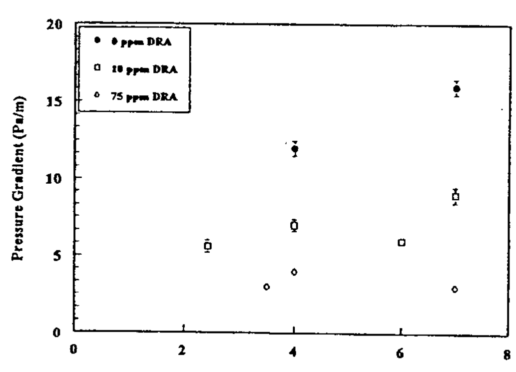

Fig. 3 Stratified pressure gradient in horizontal pipes 20 percent oil-80 percent water, V_{sl} = 0.03 m/s

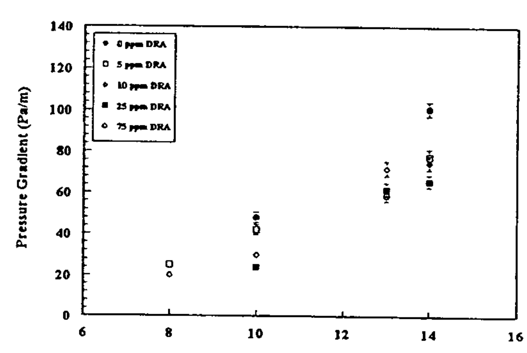

Fig. 5 Annular pressure gradient in horizontal pipes 60 percent oil-40 percent water, V_{sl} = 0.06 m/s

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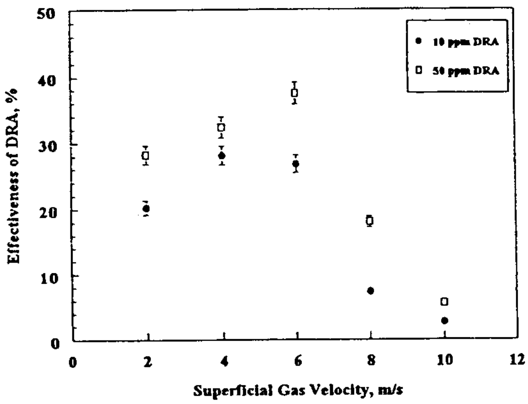

Fig. 6 Effectiveness of DRA in 2 deg inclined pipes = 0.5 m/s, 50 percent oil-50 percent water, upward flow

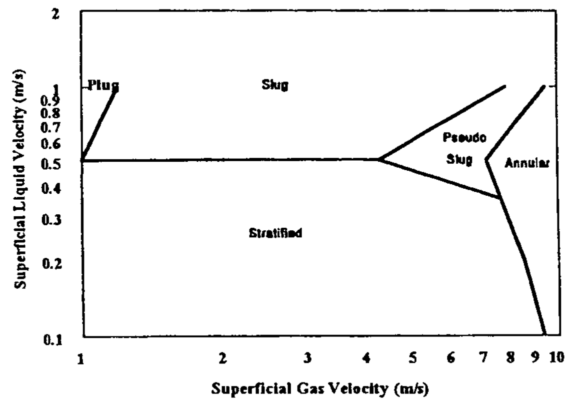

Fig. 8 Flow regime map for 75 percent oil 25 ppm DRA horizontal pipes

in a further decrease in pressure gradient to 66 Pa/m. A further increase in DRA concentration to 75 ppm does not decrease the pressure gradient beyond the 25 ppm values.

Figure 6 shows a plot of effectiveness of 10 and 50 ppm DRA at superficial liquid velocity of 0.5 m/s in 50 percent oil-50 percent water-carbon dioxide in 2 deg upward inclined pipes. At all superficial gas velocities, the pressure gradient is reduced as 10 ppm DRA concentration was added. The pressure gradient reduction was 19, 28, and 27 percent at superficial gas velocities of 2, 4, and 6 m/s respectively. At higher superficial gas velocities, the effectiveness of the DRA was less. For example, at superficial gas velocities of 8 and 10 m/s, the DRA effectiveness was 7 and 3 percent. These results indicate that the pressure gradient reduction at lower superficial gas velocities was more significant than higher superficial gas velocities for 2 deg upward inclination. Figure 6 shows a much better result of effectiveness when 50 ppm DRA is added. At superficial gas velocities of 2 and 6 m/s, the DRA effectiveness has increased from 19 to 28 percent and from 27 to 38 percent respectively. At higher superficial gas velocities of 8 and 10 m/s, the performance is improved and the pressure gradient reduction has increased from 7 to 18 percent and from 3 to 6 percent, respectively.

Figures 7, 8, and 9 show plots of flow regime maps with DRA concentrations of 0 ppm, 10 ppm and 75 ppm for 75 percent oil-25 percent water-gas flow in horizontal pipes. Flow regime maps with DRA were compared with that experimentally obtained by Lee et al. (1993) for the same liquid composition without DRA. The most important difference observed with DRA is that the transition to the slug flow regime occurs at higher superficial liquid velocities. The shift in the transition to slug flow may be due to a decrease in the degree of turbulence in the flow, which leads to a decrease in waves at the gas interface. It was also noticed that the height of the liquid film was reduced. This allows a larger cross sectional area for flow of the gas, which leads to decreasing the actual velocity of the gas. A lower actual gas velocity is less likely to develop roll waves in the liquid, which would result in the formation of a slug. It is seen from Fig. 7 that the transition to the slug flow regime occurs for superficial liquid velocities above 0.2 m/s. Adding 25 ppm DRA shifts the transition to the slug flow regime to a superficial liquid velocities above 0.5 m/s. Increasing the DRA concentration further to 75 ppm shifts the transition to slug flow further to values above 0.56 m/s. This represents a two-fold increase in superficial liquid velocity, without a transition to slug flow. The DRA also affects the transitions to plug and pseudo-slug flow regimes, which occur at higher superficial liquid velocities. Adding 75 ppm DRA shifts the transition to plug and pseudo-slug regimes over 0.56 m/s. It is seen from these figures that the presence of DRA does not affect the superficial gas velocity values of the flow regime transitions. The pressure gradient in slug flow is much higher than that in stratified flow. Reducing the range of liquid velocities, for which slug flow exists, would result in lower overall pipeline pressure gradients. Concentrations of 25 ppm DRA allow up to 0.5 m/s of liquid to flow in the stratified regime, while only 0.2 m/s are obtained without DRA. This increase in superficial liquid velocity, without a transition to slug flow, is a significant result.

Conclusions

Experiments have been carried out to test the effectiveness of DRA in a 10-cm (i.d.) flow system for single-phase and three-

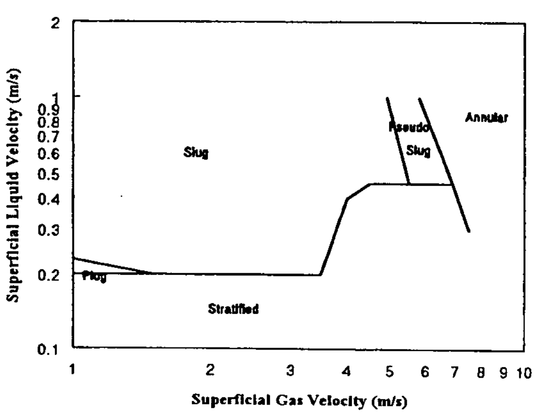

Fig. 7 Flow regime map for 75 percent oil 0 ppm DRA, horizontal pipes

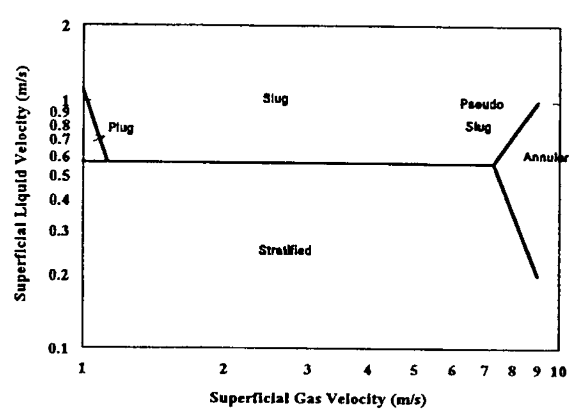

Fig. 9 Flow regime map for 75 percent oil 75 ppm DRA horizontal pipes

phase oil/water/gas flow. The DRA is effective in reducing the pressure gradients under all conditions studied.

The pressure gradient for full pipe flow was reduced by up to 42 percent with DRA concentration of 10 ppm at the superficial liquid velocity of 0.25 m/s. A much better performance is obtained with 50 ppm DRA. The effect of DRA on the pressure gradients has been found to be much greater at lower superficial liquid velocities than at higher superficial liquid velocities.

In stratified flow, the effectiveness at a DRA concentration of 10 ppm has values of over 40 percent at the superficial liquid velocity of 0.03 m/s and superficial gas velocities of 4 and 7 m/s. At 75 ppm DRA and superficial gas velocity of 4 m/s, the pressure gradient was reduced up to 67 and 81 percent at the superficial liquid velocities of 0.03 and 0.11 m/s.

In annular flow, the DRA reduces pressure gradients from 101 to 78 Pa/m at a concentration of 5 ppm and from 101 to 66 Pa/m at a concentration of 25 ppm. A further increase in DRA concentration to 75 ppm does not decrease the pressure gradient beyond the 25 ppm DRA.

The pressure gradient for 2 deg upward inclination was reduced in all cases up to superficial gas velocity of 10 m/s. The effectiveness of the DRA has been found to be much greater at superficial gas velocities below 6 m/s. At a superficial gas velocity of 6 m/s, the highest effectiveness with 50 ppm DRA was 38 percent. At superficial gas velocity of 10 m/s, the effectiveness for annular flow was 3 and 6 percent with DRA concentrations of 10 and 50 ppm.

It is observed that adding DRA shifts the transition to the slug flow regime to higher superficial liquid velocities. However, DRA does not affect superficial gas velocity for the flow regime transitions.

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