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# THE PERFORMANCE OF DRAG REDUCING AGENT IN THREE PHASE SLUG FLOW AND ANNULAR FLOW

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## ABSTRACT

Experiments have been carried out in a 36-m long, 10-cm diameter multiphase horizontal flow system to examine the effect of drag reducing agents (DRA) on average pressure drop, maximum pressure drop and slug characteristics with the presence of water. Superficial liquid velocities between 0.5 and 1.5 m/s and superficial gas velocities between 2 and 14 m/s were investigated. Oil with a viscosity of 2.5 cP at 25 °C was used for the study. ASTM salt was used as a substitute for seawater and carbon dioxide was used as the gas. Water cut was 50%. Temperature and pressure were maintained at 25 °C and 0.13 MPa. The DRA concentrations of 0, 20 and 50 ppm were used in this study.

The results show that the average pressure drop in both slug flow and annular flow decreased significantly with addition of DRA. Under special conditions, it was found that DRA changed the flow pattern from pseudo-slug to annular resulting in a 74% reduction in pressure drop. For annular flow, the average pressure drop reduction of up to 53% was achieved. The maximum pressure drop across the slug also decreased with the presence of DRA. The average and maximum pressure drops at a DRA concentration of 50 ppm were more effective than 20 ppm for all cases.

The slug frequency and effective height of the liquid film decreased significantly when DRA concentrations were added. This led to a decrease in the average pressure drop. However, the slug translational velocity did not change significantly with addition of DRA.

## INTRODUCTION

Co-current flow of oil, water and gas (three-phase) in the pipeline is common in the oil and gas industry. As the oil well gets older, the reservoir pressure decreases and enhanced oil recovery methods, which inject gases and water into the reservoir, are commonly used to maintain the reservoir pressure. Thus the water cut increases up to 90% during the life of the well.

The three-phase flow in horizontal multiphase pipelines results in several flow patterns such as stratified flow (smooth, wavy and rolling wave), intermittent flow (plug flow, slug flow and pseudo-slug flow) and annular flow depending on the velocities of liquid and gas. Here, the slug flow and annular flow are a common occurrence in the petroleum industry when multiphase mixture is transported through a single pipeline to a central gathering station.

Stratified flow exists at low gas and liquid velocities. A smooth interface exists between the liquid film flowing at the bottom of the pipe and gas above it.

An increase in the liquid velocity causes the waves to grow and fill the pipe cross section resulting in plugs of liquid with intermittent gas pockets.

At a higher gas velocity, the typical flow pattern observed in the flow lines is slug flow. This is similar to stratified flow except that there is an intermittent flow of the liquid slugs, which propagate between the stratified flow. Here, slug flow is a major concern since the front of the slug creates a highly turbulent mixing zone with a high void fraction, which leads to high corrosion rates. Also, there is a big pressure drop in this flow condition due to the deceleration. Here, accelerational pressure drop dominates rather than frictional pressure drop.

At higher gas velocities, pseudo-slug flow occurs. Pseudo-slugs have a similar structure to slugs. Pseudo-slugs are shorter and the frothiness is greater than in a slug flow.

Annular flow occurs at very high gas velocities. In annular flow, there is a liquid film flowing along the pipe wall with the gas in the central core.

Currently, DRA in single and multiphase pipeline is of great interest in petroleum and pipeline industries since production can be increased by decreasing the pressure drop. Several field tests for drag reduction work in crude oil pipelines have been reported.

It has been published by Burger [1] that the DRA use in Trans Alaska Pipeline System was to increase production while pump stations were constructed. Construction of two pump stations was stopped because of effectiveness of DRA. The capacity of average daily throughput was 1.4 million barrels per day without the use of DRA. However, 2.0 million barrels per day can be obtained with the use of DRA.

In Iraq-Turkey crude oil pipelines, the throughput increased from 0.7 to 1.0 million barrels of oil per day when 40 ~ 50 ppm DRA were injected at each pump station [2].

The test for drag reduction in heavy crude oil with a viscosity of 125 cP at 26 °C in transition zone has been carried out in South America. Effectiveness of 16% was obtained at Reynolds number between 3,400 and 3,800 when 3.7 ppm DRA was injected [2].

However, there is little work on drag reduction for multiphase (two-phase and three-phase) flow in large diameter pipelines in spite of the request of industry.

Recently, Kang and Jepson [3, 5-8] have published laboratory test results for drag reduction in multiphase flow. They have noted that DRA works not only frictional pressure drop but also accelerational pressure drop in slug flow regime. For slug flow, maximum and average pressure drops have been introduced in their paper. The maximum pressure drop is defined as the pressure drop across the slug. The average pressure drop refers to the pressure drop including liquid film and slug units. They mentioned that the transition to the slug flow regime occurred at higher superficial liquid velocities with addition of DRA. It has been also mentioned that the corrosion rate could be reduced by the change of flow characteristics.

Effectiveness of DRA depends on a lot of parameters such as types of DRA, temperature, pH, DRA concentration, oil viscosity, pipe diameter, liquid and gas flow rates, pipe roughness, composition oil, and so on [8]. Therefore, it is suggested that laboratory test for drag reduction should be performed due to the technical and economic aspects before DRA is used in the field.

The effectiveness of DRA can be calculated as follows [10]:

$$\text{Effectiveness of DRA (\%)} = \frac{\Delta P_{wDRA} - \Delta P_{noDRA}}{\Delta P_{wDRA}} \times 100 \quad (1)$$

This paper examines the effect of DRA on the flow characteristics with the presence of water and the subsequent performance of the DRA.

## NOMENCLATURE

| | |
|---|---|
| ΔP | = Pressure drop, Pa |
| ID | = Inside diameter, m |
| DRA | = Drag reducing agents |
| ASTM | = American Society Testing Material |
| Vsl | = Superficial liquid velocity, m/s |
| Vsg | = Superficial gas velocity, m/s |
| ppm | = Parts per million |
| $\Delta P_{w\,DRA}$ | = Pressure drop without the presence of DRA, Pa |
| $\Delta P_{no\,DRA}$ | = Pressure drop with the presence of DRA, Pa |

## EXPERIMENTAL SETUP AND TEST MATRIX

The experimental layout of the flow loop is shown in Figure 1. The amount of oil-water mixture is stored in a 1.2 $m^3$ stainless steel storage tank. The tank is equipped with a 3.8-KW heater and 6-m long (2.5 cm ID) stainless steel cooling coils to maintain a constant temperature. The oil-water mixture from the storage tank is then pumped into a 10-cm ID PVC pipeline by means of a 76 HP very low shear progressing cavity pump. The liquid flow rate is controlled by varying the speed of the pump using a variable-speed controller.

Carbon dioxide gas from a 20,000-kg receiver is introduced into the system. The gas flow rate is determined with a variable area flow meter. The gas is then mixed with the liquid at a mixing tee junction. The multiphase mixture then flows through 3.1-m long flexible hose (10 cm ID), allowing the inclination to be set at any angle. The oil-water-gas mixture then flows into an 18-m long Plexiglas pipeline (10 cm ID) where pressure drop, flow pattern and slug characteristics are determined. The pressure drop is measured along a 4.7-m length of the pipeline using pressure tappings. Pressure transducer was used for the measurement of pressure drop.

A Super-VHS camera was used to record the images of moving slugs. Slug frequency and slug velocity were measured by following slugs movements frame by frame using a digital VCR and high resolution monitor.

The DRA was injected into the top of the test section through an inlet valve mounted especially for this purpose by preparing a batch of the required concentration of DRA.

Experiments were conducted for slug and annular flows in horizontal pipes with ASTM (American Society Testing Material) salt water. Test runs of three times for each data point have been performed to obtain dependable data. Table 1 shows a test matrix for the study.

**Table 1. Test Matrix**

| | |
|---|---|
| Oils Tested | 2.5 cP oil |
| Temperature | 25 °C |
| Pressure | 0.13 MPa |
| Water Cut | 50 % |
| Superficial Liquid Velocity | 0.5, 1.0 and 1.5 m/s |
| Superficial Gas Velocity | 2, 4, 6, 10, 12, 14 m/s |
| DRA | Oil-Soluble DRA |
| DRA Concentrations | 0, 20 and 50 ppm |
| Inclinations | Horizontal pipes |

## RESULTS AND DISCUSSIONS

### Slug Characteristics

The effective height of the film with DRA concentrations is shown in Figure 2. It can be seen that the effective height of the film decreased with increase in superficial gas velocity as expected.

The effective height of the film decreased with addition of DRA for all cases. For example, at superficial liquid and gas velocities of 1.0 and 4 m/s, the effective height of the film decreased from 3.3 to 3.1 cm and from 3.3 to 2.8 cm respectively when 20 and 50 ppm DRA were added. This is because the liquid film spreads around the pipe wall with addition od DRA. Decreasing the height of the film leads to change of slug frequency and pressure drop. This will be discussed later.

Figure 3 shows the effect of DRA on the slug frequency at a superficial liquid velocity of 0.5 m/s. It can be seen that the slug frequency decreased with both 20 and 50 ppm DRA concentrations. For example, at superficial gas velocities of 2 and 6 m/s, the slug frequency decreased from 7 to 3 slugs/minute and from 12 to 4 slugs/minute respectively when 50 ppm DRA was added.

It should be noted that at a superficial gas velocity of 8 m/s, the flow pattern was changed from pseudo-slug flow to annular flow by decreasing the slug frequency from 5 to 0 slugs/minute when 20 ppm DRA was added. This is due to the fact that the liquid is easily spread around the pipe wall with addition of DRA. The change of flow pattern from slug to stratified/annular flow leads to a decrease in the average pressure drop and corrosion rate. It has been noted by Jepson (1997) that the corrosion rate increases with increase in the slug frequency. Therefore, decreasing the slug frequency with the use of DRA in the pipeline can also reduce the corrosion rate.

As shown in Figure 4, increasing superficial liquid velocity to 1.5 m/s resulted in increasing the slug frequency due to the increase in the height of the liquid film.

Similar results were noticed when 20 and 50 ppm DRA were added. For example, at superficial gas velocities of 2 and 4 m/s, the slug frequency decreased from 41 to 36 slugs/minute and from 39 to 33 slugs/minute respectively with 20 ppm DRA. The slug frequency decreased more when 50 ppm DRA was added. At the same liquid and gas velocities, the slug frequency decreased from 41 to 31 and from 39 to 30 slugs/minute respectively. _

Figure 5 shows the effect of DRA on slug translational velocity at a superficial liquid velocity of 1.0 m/s. The slug translational velocity increased from 4.3 to 11.1 m/s with increase in superficial gas velocity from 2 to 8 m/s. It is seen that the slug translational velocity did not change significantly with DRA concentrations. For example, at a superficial gas velocity of 2 m/s, the slug velocity is 3.3, 3.2 and 3.4 m/s with 0, 20 and 50 ppm DRA respectively.

### Average Pressure Drop

The effect of DRA on the average pressure drop at a superficial liquid velocity of 0.5 m/s is presented in Figure 6. The corresponding effectiveness is shown in Figure 7. It can be seen from both Figures that in all cases, DRA was effective in reducing the average pressure drop in the presence of water. At superficial gas velocities of less than 10 m/s, slug flow and pseudo-slug flows were observed. At higher superficial gas velocities, annular flow was noticed. At superficial gas velocities of 2 and 6 m/s, the average pressure drop decreased from 805 to 650 Pa and from 1347 to 685 Pa respectively as 20 ppm DRA was added. It can be seen from Figure 7 that these correspond to an effectiveness of 19% and 49% respectively. As it was mentioned earlier, at a superficial liquid velocity of 8 m/s, the flow pattern was changed from pseudo-slug flow to annular flow with DRA, which led to high average pressure drop reduction at this velocity. For annular flow, DRA also reduced the average pressure drop from 1076 to 692 Pa and from 1242 to 633 Pa at superficial gas velocities of 12 and 14 m/s respectively.

It can be seen that 50 ppm DRA was more effective than 20 ppm DRA for all cases. At superficial gas velocities of 6 and 8 m/s, the average pressure drop for slug flow decreased from 1347 to 444 Pa and from 1129 to 299 Pa respectively. The effectiveness at these velocities was 67% and 74% respectively. At superficial gas velocities of 12 and 14 m/s, the average pressure drop for annular flow decreased from 1076 to 537 Pa and from 1242 to 587 Pa. In this regime, it can be seen from Figure 7 that the effectiveness of DRA was around 50%.

It was mentioned earlier, the height of the liquid film and slug frequency decrease with addition of DRA, which leads to decrease the average pressure drop. The decrease in the maximum pressure drop of slug with DRA also leads to decrease in the average pressure drop.

Figures 8 and 9 show equivalent plots for a superficial liquid velocity of 1.5 m/s. It can be seen from Figures 6 and 8 that at 0 ppm DRA, the average pressure drop increased dramatically with an increase in superficial liquid velocity from 0.5 to 1.5 m/s. For example, at 0 ppm DRA, the average pressure drop increased from 805 to 2374 Pa and from 1347 to 3686 Pa at superficial gas velocities of 2 and 6 m/s respectively. This is the due to the fact that the height of the liquid film and slug frequency increases with an increase in superficial liquid velocity, which leads to higher-pressure drop.

It is seen from Figure 8 that the transition to annular flow regime occurs at superficial gas velocities of greater than 11 m/s.

At a superficial liquid velocity of 1.5 m/s, similar results were obtained. The average pressure drop decreased significantly for both slug flow and annular flow when 20 and 50 ppm DRA concentrations were added. The average pressure drop at a DRA concentration of 50 ppm is also more than 20 ppm for all cases.

### Maximum Pressure Drop

Figure 10 shows the effect of DRA on the maximum pressure drop at a superficial liquid velocity of 1.5 m/s and the corresponding effectiveness is given in Figure 11. It can be seen from Figure 10 that at all superficial gas velocities, the maximum pressure drop slightly reduced with addition of 20 ppm DRA. The corresponding effectiveness was less than 10% in all cases as shown in Figure 11.

Further increasing DRA concentration to 50 ppm was accompanied with more reduction in the maximum pressure drop at all superficial gas velocities. At superficial gas velocities of 2 and 10 m/s, the maximum pressure drop decreased from 9100 to 7700 Pa and from 19500 to 15900 Pa respectively when the concentration of DRA was changed from 0 to 50 ppm. These correspond to an effectiveness of 15% and 18% respectively.

It is expected that void fraction in slug body can be decreased by decreasing the maximum pressure drop with addition of DRA, which leads to a decrease in turbulent intensity.

## CONCLUSIONS

Experiments have been carried out to test the effect of DRA with the presence of water in a 10 cm diameter horizontal pipelines. Flow characteristices such as effective height of the liquid film, slug frequency, slug translational velocity, average pressure drop, and maximum pressure drop with the DRA concentrations of 0, 20 and 50 ppm has been studied.

The effective height of the film decreased in all cases with addition of DRA since the liquid film is spread around the pipe. The effective height decreased more in all cases with addition of 50 ppm DRA.

The slug frequency decreased significantly with the addition of DRA concentrations. At superficial liquid and gas velocities of 0.5 and 8 m/s, the flow pattern was changed from pseudo-slug to annular flow, which led to high pressure drop reduction. Decreasing the slug frequency can lead to a decrease in the average pressure drop and corrosion rate.

The slug translational velocity did not change significantly with DRA concentrations of 20 and 50 ppm in all cases.

The DRA was effective in reducing the average and maximum pressure drop in all cases. The DRA concentration of 50 ppm was more effective than 20 ppm for all cases. At superficial liquid and gas velocities of 0.5 and 6 m/s, the average pressure drop and maximum pressure drop for slug flow decreased from 1347 to 444 Pa and from 11500 to 9500 Pa respectively. The corresponding effectiveness of DRA was 67% and 17% respectively. At a superficial liquid velocity of 1.5 m/s, the DRA effectiveness for annular flow was around 30% with 50 ppm DRA.

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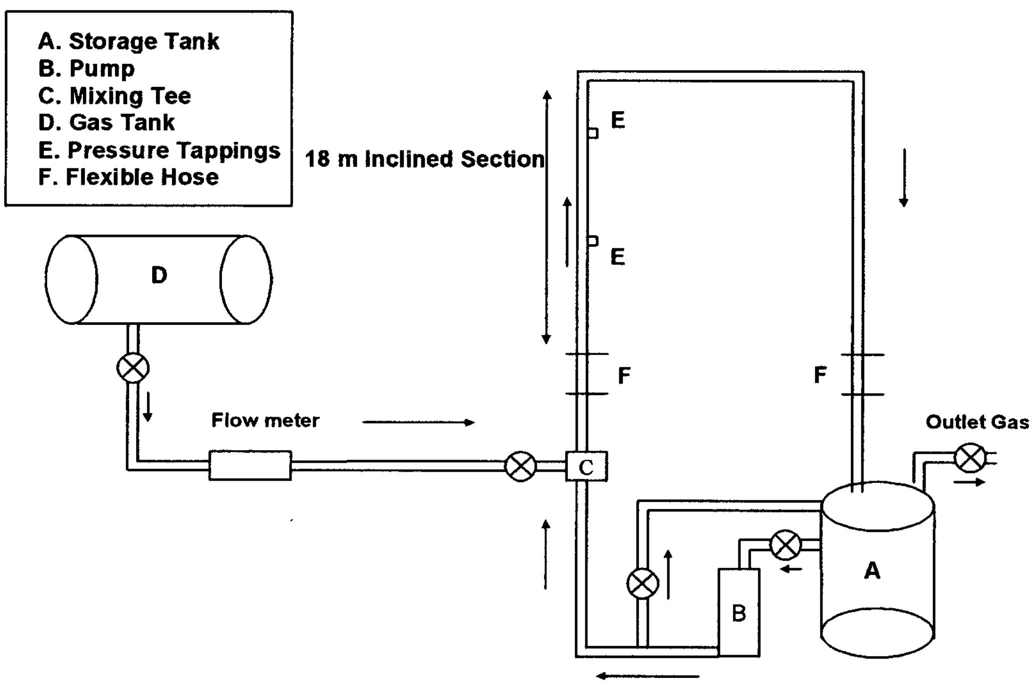


**Figure 1. Experimental Layout of the Flow Loop**

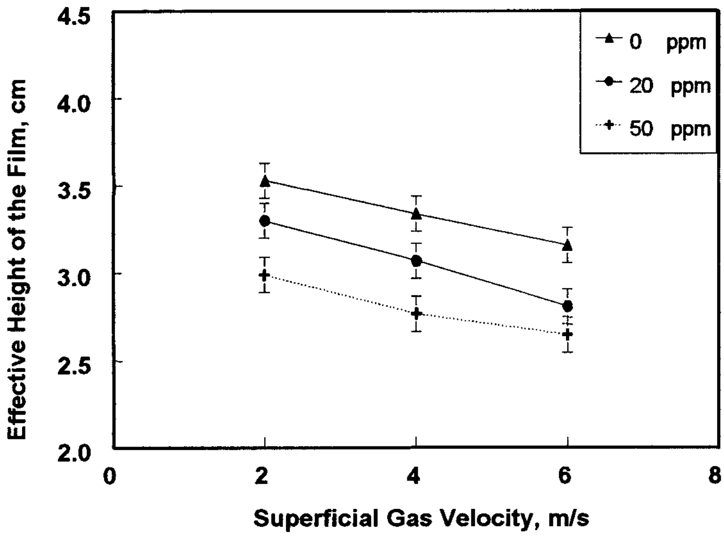


Figure 2. Effect of DRA on the Effective Height of the Film
Vsl = 1.0 m/s, 50% Oil-50% Salt Water-Carbon Dioxide

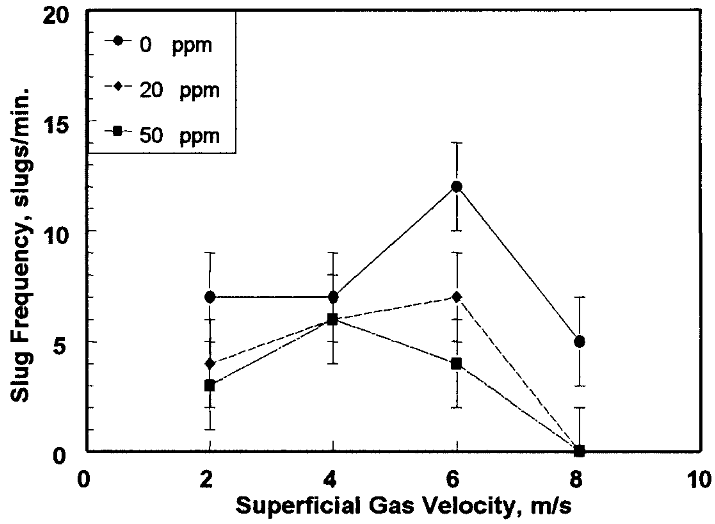


Figure 3. Effect of DRA on the Slug Frequency
Vsl = 0.5 m/s, 50% Oil-50% Salt Water-Carbon Dioxide

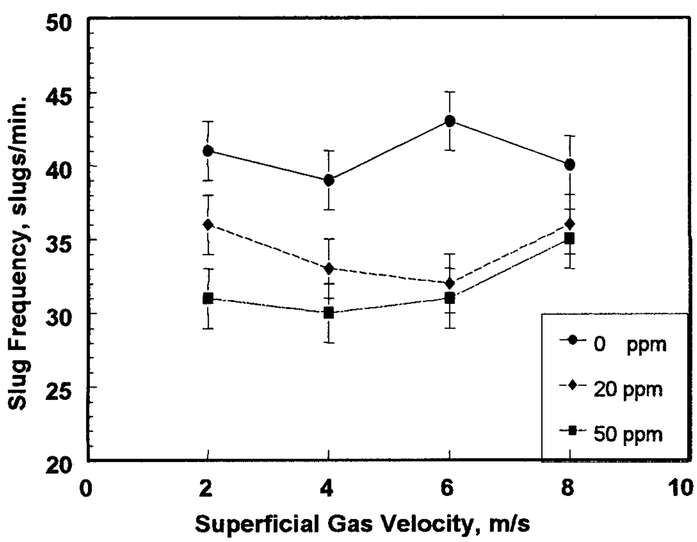


Figure 4. Effect of DRA on the Slug Frequency
Vsl = 1.5 m/s, 50% Oil-50% Salt Water-Carbon Dioxide

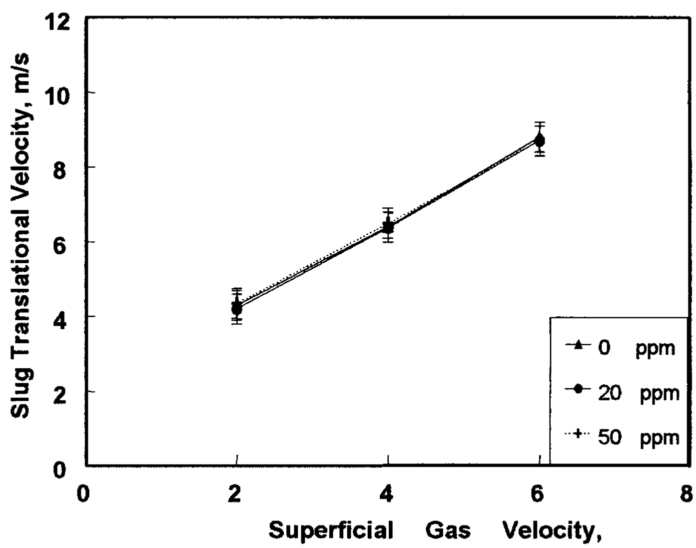


Figure 5. Effect of DRA on the Slug Translational Velocity
Vsl = 1.0 m/s, 50% Oil-50% Salt Water-Carbon Dioxide

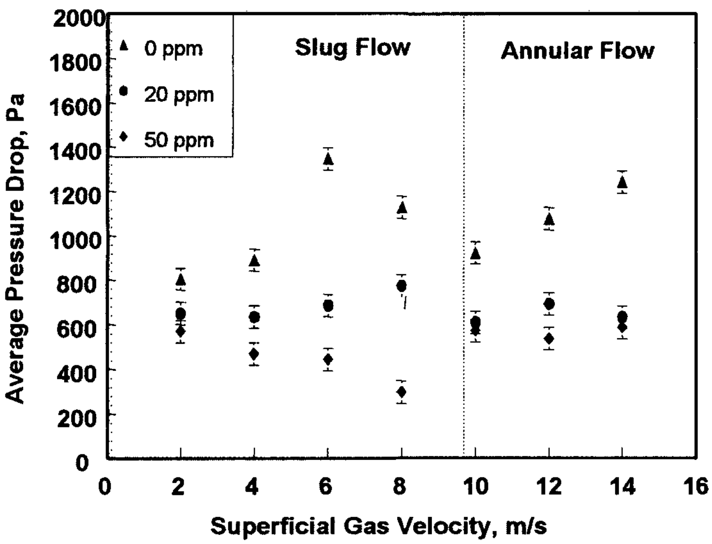


Figure 6. Average Pressure Drop vs. Superficial Gas Velocity
Vsl = 0.5 m/s, 50% Oil-50% Salt Water-Carbon Dioxide

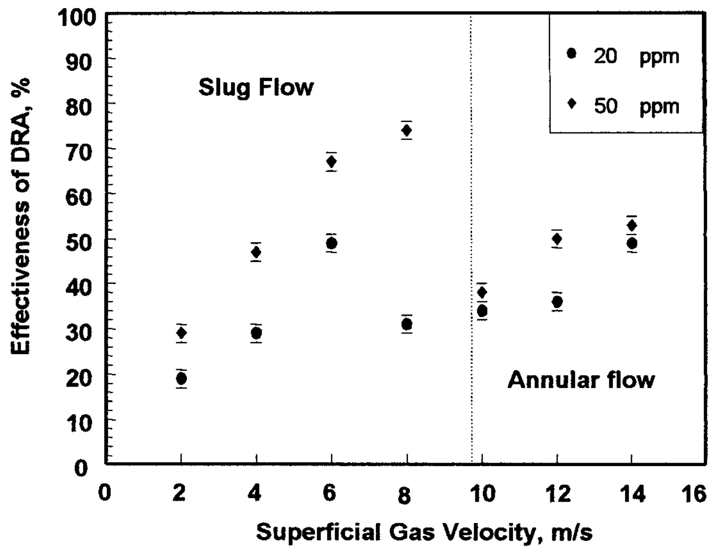


Figure 7. Effectiveness of DRA on Average Pressure Drop
Vsl = 0.5 m/s, 50% Oil-50% Salt Water-Carbon Dioxide

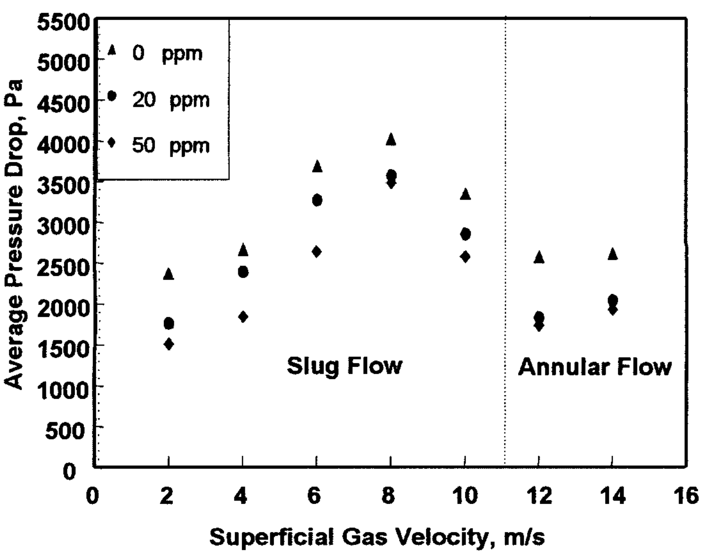


Figure 8. Average Pressure Drop vs. Superficial Gas Velocity
Vsl = 1.5 m/s, 50% Oil-50% Salt Water-Carbon Dioxide

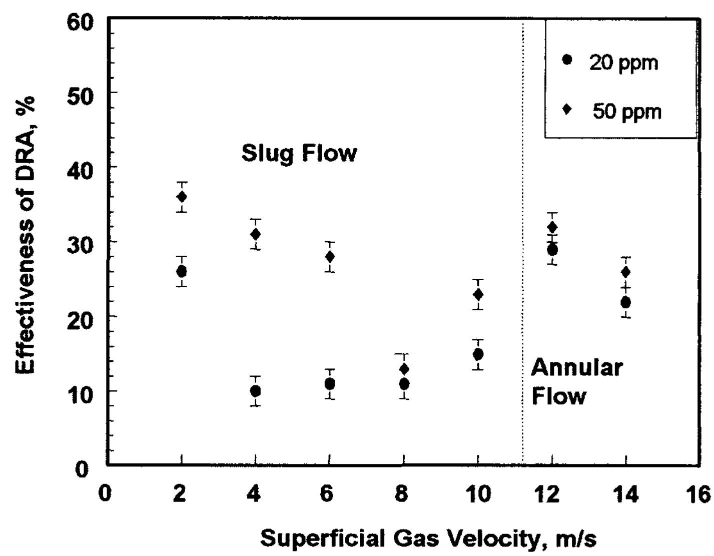


Figure 9. Effectiveness of DRA on Average Pressure Drop
Vsl = 1.5 m/s, 50% Oil-50% Salt Water-Carbon Dioxide

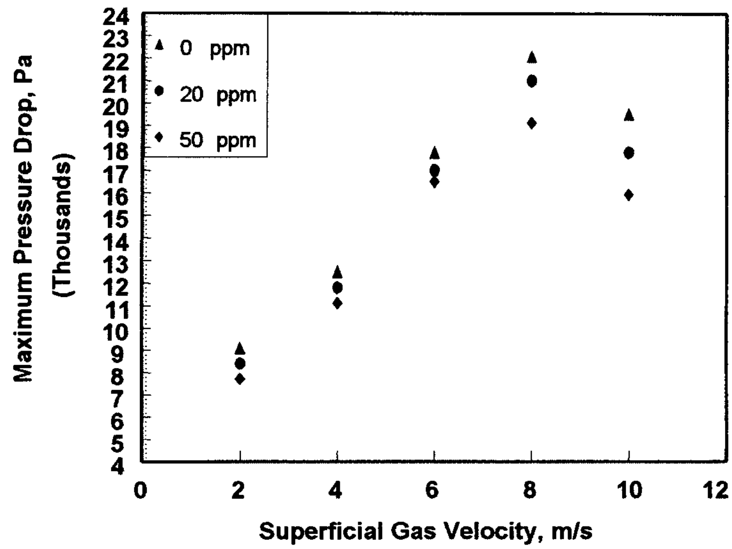


**Figure 10. Maximum Pressure Drop Reduction for Slug Flow**
**Vsl = 1.5 m/s, 50% Oil-50% Salt Water-Carbon Dioxide**

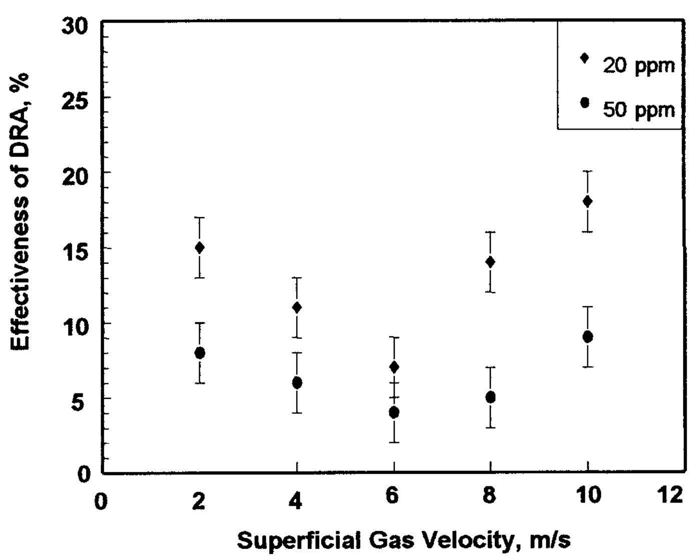


**Figure 11. Effectiveness of DRA on Maximum Pressure Drop**
**Vsl = 1.5 m/s, 50% Oil-50% Salt Water -Carbon Dioxide**