EFFECTS OF OIL VISCOSITY ON DRA EFECTIVENESS AND THE COMPONENTS OF PRESSURE DROP IN INCLINED SLUG FLOW

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ABSTRACT

Computational analysis along with experimental work has been carried out to study the effects of oil viscosity on each component of pressure drop in inclined slug flow and the effectiveness of drag reducing agents. Predicted values corresponded very well with experimental results. Accelerational component was dominant and reached values as high as 86% of total pressure drop. Most of the drag reduction took place in this component.

The DRA was more effective in reducing both frictional and gravitational components of total pressure drop in the 26 cP oil more than in the 2.5 cP. Meanwhile, it was more effective in reducing accelerational component, hence total pressure drop, in the 2.5 cP oil.

NOTATION

f = friction factor
Re = Reynolds number
R = liquid holdup
l, L = length, m
V_S = average no-slip velocity of the fluid in the slug body, m/s
V = velocity, m/s
Fr = film Froud number
h_{EFF} = effective height of liquid film, m
A = cross-sectional area, m^2
τ = shear stress, N/m^2
S = perimeter length, m

ρ = density, kg/m^3
ν = frequency, min^{-1}
M = rate of mass pickup, kg/sec
x = distance in the slug body, m
g = local gravity, m/s^2
ΔL = total distance between pressure taps, m
ΔP = pressure drop, Pa
X_{lg} = lag distance, m
X_{ld} = lead distance, m

Subscripts
f = frictional
a = accelerational
T = total
t = translational
film = liquid film
*f*e = liquid film just prior to pickup
s, slug = slug
body = slug body
MZ = mixing zone
G = gas
L = liquid
WG = wall-gas
WL = wall-liquid
i = gas-liquid

1. INTRODUCTION

Experimental studies along with quantitative analysis have been carried out to predict pressure drop in slug flow with the presence of DRA, using two types of oil of different viscosities, namely 2.5 and 26 cP, in a 2-degree inclined pipes. Effects of oil viscosity on each component of the total pressure drop and DRA effectiveness were determined.

Pressure drop in slug flow was broken down to three components; frictional, accelerational, and gravitational components. Frictional component of total pressure drop takes place due to the friction between the pipe wall and the liquid in both slug body and liquid film. The pressure drop that results from accelerating the slow moving liquid film ahead of the slug to slug velocity is called the accelerational component of slug pressure drop. For the flow in inclined pipelines, gravity resists upward flow, and the force spent in driving the fluid upward against the gravity manifests itself as gravitational pressure drop.

In order to find out the effect of oil viscosity on each component of total pressure drop in slug flow and DRA effectiveness in reducing each component, two types of oil of 2.5 and 26 cP viscosity were examined with and without the presence of DRA. Carbon dioxide was used as the gas phase.

Pipe inclination was believed to have significant effect not only on flow characteristics but also on the structure of pressure drop and DRA performance. Experiments using 2.5 cP oil were carried out in both horizontal and 2-degree inclined pipelines whereas the 26 cP oil was tested only in 2-degree inclined pipes.

All experiments have been carried out in a 20-m long, 10-cm inside diameter pipeline. The DRA was examined in dosage of 0, 10, 20, and 50 ppm based on volumetric basis. Superficial liquid velocity had the values of 0.5, 1, and 1.5 m/s, while superficial gas velocity varied in the range from 2 to 14 m/s. Flow patterns were reported and measurements taken for slug flow were only considered in this study. There was no attempt to predict any measured quantity, and independent models were used to predict other quantities when needed.

2. BACKGROUND

Hubbard and Dukler (1975) introduced equations to calculate the contributions of both frictional and accelerational components to total slug pressure drop in air-water system. In their model, they assumed that within the slug body the two phases are homogeneously mixed with negligible slip and the frictional contributor could be calculated using an equation similar to ones in single phase flow after modifying the density of the mixture and the friction factor. The accelerational contribution was calculated under the assumption that a stabilized slug can be considered as a body receiving and losing mass at equal rates. The velocity of the liquid in the film just before pickup is lower than that in the slug and a force is therefore necessary to accelerate this liquid to slug velocity. This force manifests itself as accelerational pressure drop.

Greskovich and Shrier (1971) used Hubbard-Dukler model along with independent correlations for in situ holdup and slug frequency to predict pressure drops for two-phase slug flow. The holdup and frequency correlations were for the most part based on data for air-water flowing in a 1.5-in diameter pipe. Predictions of pressure drop using this approach were compared with experimental data taken from studies utilizing various systems and pipes. Their approach was equivalent to another method developed by Dukler and Hughmark.

Fan, Ruder, and Hanratty (1993) introduced a new model to predict the pressure drop across a stable slug. In their model, they assumed the slug as a hydraulic jump. Further more, they assumed that pressure change occurs in the rear of the slug. This pressure change could be positive or negative depending on whether the slug was decaying or growing.

Petalas and Aziz (1996) developed new model for multiphase flow in pipes. According to their model, pressure drop and holdup in pipes could be predicted for all pipe geometries and fluid properties. Their model lends itself for implementation in a computer program in that a significant number of calculations were required and several of these required iterative procedures. Unfortunately, accelerational component of the pressure drop in slug flow was not considered in their model at all making their model questionable.

Andritsos and Hanratty (1987) studied the influence of interfacial waves in stratified gas-liquid flows. Interfacial stresses were calculated from their measurements of liquid height and pressure drop for fully developed horizontal stratified flow. They improved a design method to predict pressure drop in stratified flow.

Vlachos and Karabelas (1998) studied the shear stress circumference variations in stratified flow. They developed a computational approach based on momentum balances for both phases to predict liquid holdup, axial pressure gradient and average liquid to wall shear stress, for the wavy stratified and stratified/atomization gas/liquid flow in horizontal pipes. The performance of the model appeared to be satisfactory and fair predictions were obtained.

Barea and Brauner (1985) investigated holdup of the liquid slug in two-phase intermittent flow. They proposed a physical model for the prediction of gas holdup in liquid slugs in horizontal and vertical two-phase pipe slug flow. This model was based on the assumption that the gas within the developed liquid slug behaves as dispersed bubbles, and thus the liquid slug will accommodate the same gas holdup as the fully dispersed bubble flow on the transition boundary with the same mixture velocity.

Mantripragada (1997) studied the effect of inclination on slug characteristics at the Corrosion Center in Ohio University. He concluded that gravity had more influence on flow characteristics at low superficial liquid and gas velocities than at high ones. He also found that the height of liquid film was inversely proportional to liquid film velocity, which decreased with the increase in inclination due to gravity effects. Slug translational velocity was found independent on pipe inclination for certain oil and superficial liquid and gas velocities.

Maley (1997) studied the void fraction distribution in a stationary slug with various liquids and gases also correlating it to the Froude number with a lead-lag process model for large diameter pipes. This model was used to predict the liquid holdup in the slug body. The advantage of using such model is due to the similarity between the system used in developing this model and the system used in current study.

3. EXPERIMENTAL SETUP

Figure 1 shows the experimental layout of the system. A 1.2 m^3 stainless steel storage tank (A) was used as a liquid reservoir. The oil was pumped from the tank (A) using low shear progressive cavity pump (B) to avoid shear degradation of the DRA. Carbon dioxide, that was stored in a 20,000 kg storage tank (C), was injected into the pipeline at a T junction (T) where gas and oil mixed. The oil-gas mixture was then allowed to flow through a 20-m long Acrylic pipe of 4" ID. Pressure transducers were used to measure the pressure drop between pressure taps (E) 4.7-m apart from each other. A super VHS camera, digital VCR and a high resolution TV were used to track slugs along the test section. The mixture then returned to the tank where oil and gas were separated. Oil is to be recycled, whereas gas is vented to the atmosphere.

The DRA was examined in dosages of 0, 20, and 50 ppm based on volumetric basis. Superficial liquid velocity had the values of 0.5, 1, and 1.5 m/s, while superficial gas velocity varied in the range from 2 to 14 m/s.

Flow patterns were reported and measurements taken only for slug flows were considered in this study. There was no attempt to predict any measured quantity, and independent models were used to predict other quantities when needed.

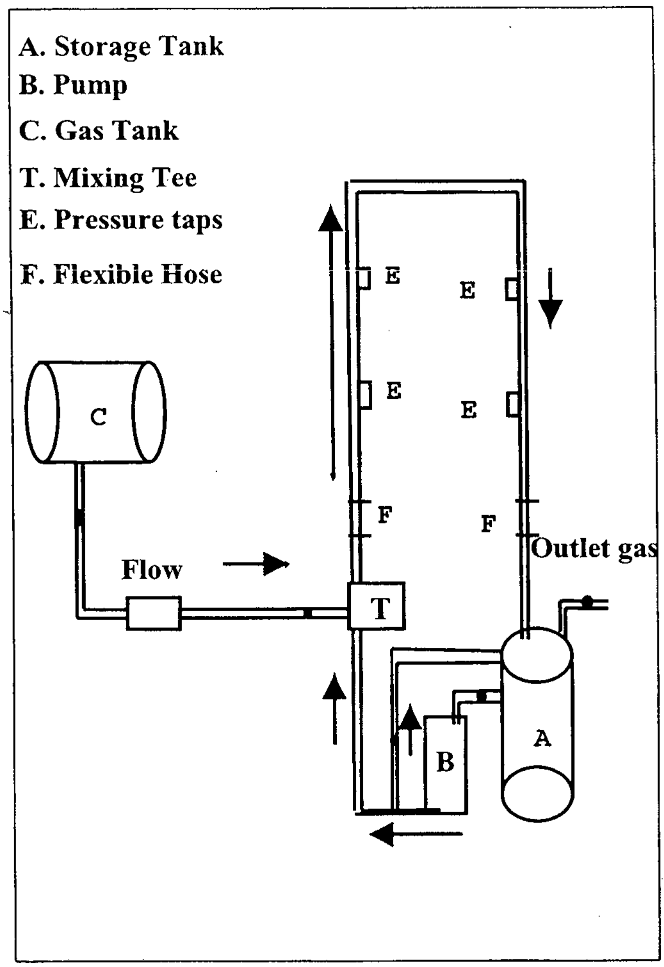

Figure 1 Experimental setup

4. MODELING PROCEDURE

A schematic diagram of a stable slug is shown below in Figure 2. This Figure indicates that a unit slug constitutes of four regions. These regions are mixing zone characterized as highly turbulent froth zone, slug body with gas bubbles entrained in, slug tail that results from liquid shedding, and stratifies liquid film between the tail of this slug and the succeeding one.

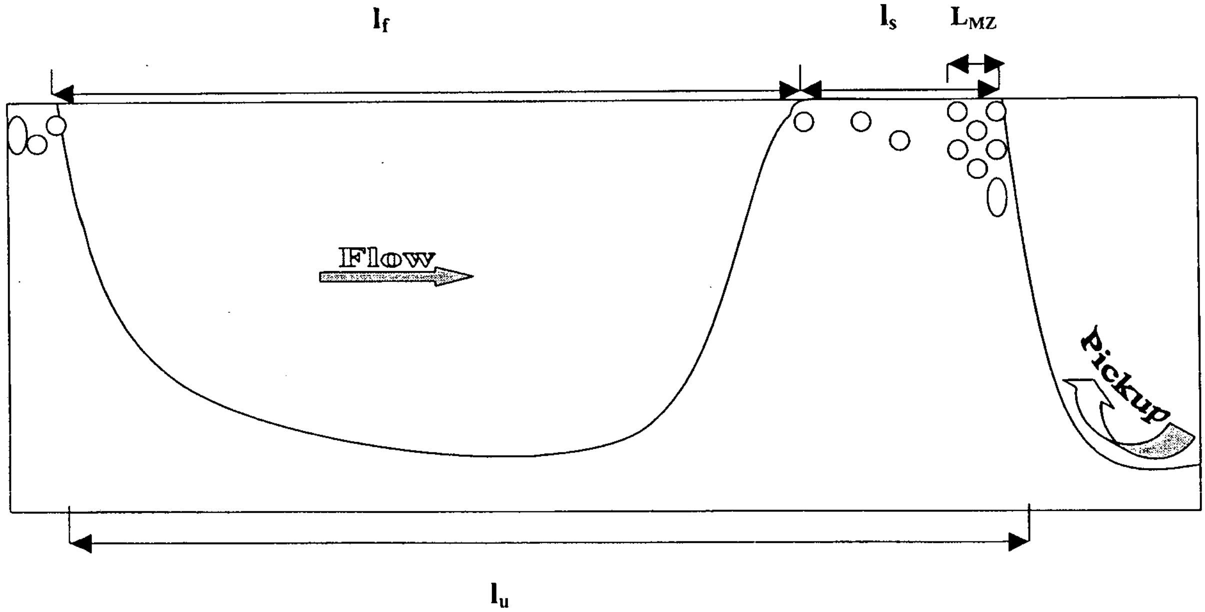

Figure 2 Schematic diagram of a stable moving slug

4.1. Frictional contribution

4.1.1. Frictional pressure drop in the slug body

Behind the mixing zone in the body of the slug pressure drop takes place due to wall friction. For the calculation of this term, the similarity analysis for single-phase frictional pressure drop developed by Dukler and others in 1964 is applied. The recommended pressure drop equation is:

$$\Delta P_{f,body} = \frac{2f_{slug}\left[\rho_L < R_S > + \rho_G < \alpha_s >\right]V_S^{\,2}(l_s - L_{MZ})}{D} \qquad (4.1.1)$$

The slug friction factor, f_{slug}, was calculated using an equation similar to Blasius equation:

$$f_{slug} = 0.0791\left(Re_{slug}\right)^{-0.25} \qquad (4.1.2)$$

4.1.2. Length of mixing zone

An equation developed by Kouba and Jepson (1990) for the prediction of the length of mixing zone, L_{MZ}, based on Froud number of the liquid film right behind the slug body, Fr_f, was used:

$$L_{MZ} = 0.051 Fr_f + 0.18 \quad (4.1.3)$$

$$Fr_f = \frac{(V_t - V_f)}{\sqrt{g \times h_{EFF}}} \quad (4.1.4)$$

4.1.3. Liquid holdup in the slug

Maley (1997) studied the void fraction distribution in a stationary slug with various liquids and gases also correlating it to the Froude number of the slug with a lead-lag process model for large diameter pipes. This model was used to predict the liquid holdup in the slug body. The advantage of using such model is due to the similarity between the systems used in developing this model and the system used in this study. The average liquid holdup, $<R_S>$, is calculated using the following equations:

$$R_s(x) = \frac{x_{lg} - x_{ld}}{x_{lg}} e^{(-\frac{x}{x_{lg}})} \quad (4.1.5)$$

Thus, the average liquid holdup within the mixing zone can be established by a simple integration from zero to L_{MZ}.

$$\langle R_{S,MZ} \rangle = \frac{x_{lg} - x_{ld}}{L_{MZ}} \left[1 - \exp(-\frac{L_{MZ}}{x_{lg}}) \right] \quad (4.1.6)$$

Where X_{lg} and X_{ld} are lag distance and lead distance respectively. They were found to be proportional to film Froud number and varied according to oil viscosity.

After the mixing zone, the lead-lag model no longer applies. Here, at higher gas velocities, the liquid holdup becomes constant at the end of the mixing zone until the end of the slug body. This constant value can be determined by evaluating the original model at the end of the mixing zone. Thus, the average liquid holdup in the slug body can be taken as:

$$\langle R_s \rangle = \frac{\langle R_{S,MZ} \rangle \times L_{MZ} + R(x = L_{MZ}) \times (l_S - L_{MZ})}{l_S} \quad (4.1.7)$$

The void fraction in the slug is then calculated as follow:

$$\langle \alpha_S \rangle = 1 - < R_s > \quad (4.1.8)$$

However, at lower gas velocities and at liquid velocities close to the stratified/slug transition, the holdup is not constant but increase to almost unity with distance into the slug.

Consequently, at these conditions, the holdup predicted by the above equations will be under estimated.

4.1.4. Frictional pressure drop in the liquid film

According to Dukler and Hubbard (1975), carrying out momentum balance over each phase of the stratified gas-liquid flow behind the slug lead to a single equation for each phase. The outcome of the momentum balance over the gas phase was used to predict the pressure gradient in the liquid film.

$$-A_G\left(\frac{dP}{dx}\right)-\tau_{WG}S_G-\tau_i S_i=0 \qquad (4.1.9)$$

$$\tau_{WG}=f_G\frac{\rho_G V^2{}_G}{2}=\tau_i \qquad (4.1.10)$$

$$f_G=0.046\left(\frac{D_G V_G}{\nu_G}\right)^{-0.2} \qquad (4.1.11)$$

For smooth stratified flow $\tau_i \cong \tau_{WG}$. The pressure drop across the liquid film can be calculated by the equations below:

$$\Delta P_{f,film}=\left(\frac{dP}{dx}\right)\times l_f \qquad (4.1.12)$$

$$l_f=\frac{V_t}{v_S}-l_s \qquad (4.1.13)$$

4.2. Accelerational contribution

A slug that has stabilized in length can be considered as a body receiving and losing mass at equal rates. The pressure drop that results from accelerating the slow moving liquid film to slug velocity is called the acceleratonal component of slug pressure drop, ΔP_a and can be calculated by the following equations (Hubbard & Dukler, 1975):

$$\Delta P_a=\frac{M}{A}(V_S-V_{fe}) \qquad (4.2.1)$$

$$M=\rho_L A R_{fe}(V_t-V_{fe}) \qquad (4.2.2)$$

It is evident that accelerational component is a strong function of both slug velocity and liquid film velocity. To simplify the calculations, V_{fe} is considered equal to liquid film velocity, V_f, while R_{fe} was given a value equal to liquid film holdup, R_f.

In Hubbard and Dukler's model, the holdup in the slug body was assumed to be constant throughout the slug. Again, this is not true at low gas velocities and at liquid velocities near to the stratified-slug transition.

4.3. Gravitational contribution

Fluid density along with pipe inclination played an important role in determining gravitational component. The gas layer flowing above and parallel to the stratified liquid film was omitted in gravitational computations. Gravitational component was calculated using the following equations:

$$\Delta P_g = \Delta P_{g,body} + \Delta P_{g,film} \tag{4.3.1}$$

For slug body:

$$\Delta P_{g,body} \equiv \rho_{slug} \times g \times l_s \times \sin(\theta) \tag{4.3.2}$$

And for the liquid film:

$$\Delta P_{g,film} \equiv R_f \times \rho_{oil} \times l_f \times \sin(\theta) \tag{4.3.3}$$

Total pressure drop per unit length of test section, $\frac{\Delta P_T}{\Delta L}$, was estimated as follow:

$$\frac{\Delta P_T}{\Delta L} = \left(\Delta P_a + \Delta P_{f,body} + \Delta P_{f,film} + \Delta P_{g,body} + \Delta P_{g,film}\right) \times \frac{v_S}{V_t} \tag{4.3.4}$$

Where $\frac{v_S}{V_t}$ is the number of slugs per unit length of the test section at any moment.

5. RESULTS & DISCUSSIONS

The results and discussions constitute of three sections. In the first two sections, a quantitative description of the contribution of each component to the total slug pressure drop shall be provided for both oils. The effects of oil viscosity on each component and its contribution to total pressure drop and DRA effectiveness in reducing each component are discussed in the third section.

5.1. Results for the 2.5 cP oil, 2-degree upward flow

It is evident that the calculated and measured values were in good agreement except at high superficial liquid and gas velocities of 1.5 & 6 respectively at which the height of the liquid film was over estimated as will be shown later. Figure 4 describes the changes in pressure drop and its three components with superficial gas velocity at DRA concentration of 50 ppm and superficial liquid velocity of 1.5 m/s. All components increased with increasing superficial gas velocity except gravitational component, which was found to decrease linearly when increasing superficial gas velocity at certain liquid flow rate and DRA concentration due to the decrease in slug liquid holdup and liquid film height behind the slug. For example, accelerational component increased from 1386 to 3982 Pa as a result of increasing superficial gas velocity from 2 to 6 m/s. Frictional component increased from 382 to 475 Pa for the same increase in gas velocity. On the other hand, gravitational component decreased from 730 to 576 Pa as a result of increasing superficial gas velocity from 2 to 6 m/s. Similar results were found at different superficial liquid velocities of 0.5 and 1 m/s and at all DRA concentrations.

One can see that accelerational component was dominant. Figure 4 shows that more than 80% of total pressure drop came from the accelerational contribution, 11% from gravitational contribution and the rest from frictional contribution.

DRA was added into the flowing stream to examine its effect on each component. In sharp contrast to results found in previous work in horizontal flow utilizing the same oil and at the same superficial liquid and gas velocities and DRA concentration, calculations showed that frictional component increased after the addition of DRA at higher superficial liquid and gas velocities. This could be explained due to the overestimation of the actual height of liquid film ahead of each slug. The addition of DRA caused the height of the liquid film to decrease and the surface of the film to concave down forcing the liquid around the circumference due to the decrease in surface tension, hence increasing the contact area between the liquid and the inner wall of the pipe. As oil viscosity increased, this influence of the DRA was found to decrease substantially and the surface of the liquid film kept most of its semi-flat shape except at high DRA concentrations and superficial gas velocities. Increasing superficial gas velocity resulted in a force-buildup upon the liquid film, thus decreasing its height and reshaping its surface. The combined effects of the addition of DRA and increasing superficial gas velocity were enlarged at higher liquid flow rates during which more liquid presented. Figure 3 shows a qualitative description of the effect of oil viscosity on the shape of a liquid film of two kinds of oil of different viscosities at certain superficial liquid and gas velocities and DRA concentration.

At low superficial liquid and gas velocities, DRA was found to slightly decrease frictional component. Figure 5 describes the effect of DRA on frictional component at superficial liquid velocity of 0.5 m/s. For example, this Figure shows that at superficial gas velocity 2 m/s the frictional component decreased from 78 to 28 Pa after the addition of 50 ppm of DRA. The corresponding decrease at superficial gas velocity of 6 m/s was from 163 to 149 Pa.

Accelerational component was found to decrease significantly with the addition of DRA especially at higher superficial gas velocity of 6 m/s. This is due to the associated decrease in liquid film height, hence the rate of mass pickup by slug, and slug frequency. Figure 6 indicates the significant decrease in accelerational component as a result of adding 50 ppm of DRA at a superficial liquid velocity of 1 m/s. For example, a decrease in accelerational component of pressure drop from 1797 to 887 Pa occurred at superficial gas velocity of 2 m/s. The corresponding decrease in accelerational pressure drop at superficial gas velocity of 6 m/s was from 4186 to 2405 Pa.

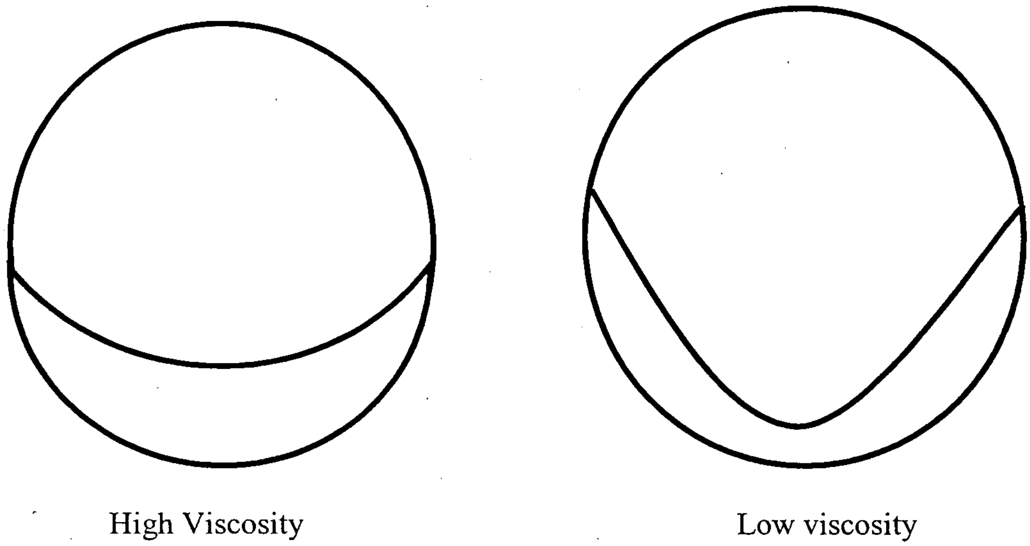

Figure 3 Surface of liquid film after addition of DRA

Results indicate some influence of DRA on the gravitational component of pressure drop. Although the addition of DRA was believed to decrease slug liquid holdup, gravitational component decreased just slightly. For example, Figure 7 shows that at superficial liquid and gas velocities of 1 & 4 m/s, gravitational component decreased slightly from 609 to 555 Pa when adding 50 ppm DRA.

5.2. Results for the 26 cP oil, 2-degree upward flow

Calculated and measured values were in very good agreement at all superficial liquid and gas velocities and DRA concentrations.

Similar to results found when testing 2.5 cP oil, all components increased with increasing superficial gas velocity except gravitational component as can be seen in Figure 8.

Once again, the accelerational component was dominant. Figure 8 shows that at superficial liquid and gas velocities of 0.5 & 6 m/s and DRA concentration of 50 ppm, 70% of total pressure drop came from the accelerational contribution, 21% from gravitational contribution and 9% from frictional contribution. Similar behavior was noticed at other liquid and gas velocities and DRA concentrations.

The DRA was found to decrease frictional component at all conditions of superficial liquid and gas velocities and DRA concentrations. The reduction in frictional component was noticed to be more significant at high gas velocity of 6 m/s. Figure 5 shows that at superficial liquid and gas velocities of 0.5 & 6 m/s respectively, frictional component decreased from 394 to 187 Pa after the addition of 50 ppm of DRA.

Accelerational component was found to decrease significantly with the addition of DRA especially at higher superficial gas velocity of 6 m/s due to the decrease in both the rate of mass pickup by the slug and the slug frequency. For example, Figure 6 indicates a decrease in accelerational component of pressure drop from 4636 to 3346 Pa at superficial liquid and gas velocities of 1 and 6 m/s respectively after the addition of 50 ppm DRA.

Results indicate reasonable effect of DRA on the gravitational component of pressure drop. This effect was greater than in 2.5 cP oil. As can be seen from Figure 7, the gravitational component decreased from 861 to 735 Pa at superficial liquid and gas velocities of 1 & 2 m/s respectively as a result of adding 50 ppm DRA. The corresponding decrease at higher gas velocity of 6 m/s was from 687 to 555 Pa.

5.3. Viscosity effects

Comparing results of total pressure drop for both oils in 2-degree upward flow indicates that total pressure drop for the 26 cP oil was always greater than its corresponding value for the 2.5 cP oil. Figure 9 describes the effect of oil viscosity on total pressure drop and overall DRA effectiveness for both oils at superficial liquid velocity of 1 m/s. This Figure shows that at superficial liquid and gas velocities of 1 & 6 m/s and DRA concentration of 0 ppm, total pressure drop for the 26 cP oil was 5791 Pa whereas it was 4884 Pa for the 2.5 cP oil. The corresponding values at DRA concentration of 50 ppm were 4222 and 3176 Pa. Similar results were found at all superficial liquid velocities and DRA concentration. One can notice also that the DRA effectiveness in reducing total pressure drop was greater in the 2.5 cP oil than in the 26 cP one. This is because the DRA was more effective in reducing accelerational component, the dominant contributor, in the 2.5 cP oil than in the 26 cP oil as will be explained later. For example, It can be seen from Figure 9 that at superficial liquid and gas velocities of 1 & 6 m/s, respectively, increasing DRA concentration from 0 to 50 ppm caused 35% reduction in total pressure drop for the 2.5 cP oil from 4884 to 3176 Pa. The corresponding reduction in total pressure drop for the 26 cP oil was only 27% from 5791 to 4222 Pa.

As oil viscosity increased, height of liquid film was noticed to increase at the same liquid and gas flow rates resulting in greater accelerational component for the 26 cP oil than for the 2.5 cP oil. This difference in accelerational component due to increase in oil viscosity was even much greater after the addition of DRA. In addition to that, slug translational velocity increased with increasing oil viscosity resulting in a greater force required to accelerate the slow liquid film ahead of the slug to slug velocity, thus increasing accelerational pressure drop.

Figure 6 describes the effects of oil viscosity on DRA efficiency to reduce accelerational component and the contribution of this component to total pressure drop at superficial liquid velocity of 1 m/s. This Figure indicates that at DRA concentration of 0 ppm and superficial liquid and gas velocities of 1 & 4 m/s, respectively, accelerational component increased from 2514 to 3147 Pa when increasing oil viscosity from 2.5 to 26 cP. The corresponding slug translational velocity increased from 6.2 to 7.6 m/s as a result of increasing oil viscosity from 2.5 to 26 cP. This Figure shows also that the corresponding increase in this contributor at the same liquid and gas velocities but at DRA concentration of 50 ppm was from 1110 to 2868 Pa. Accordingly, slug translational velocity increased form 6.5 to 7.72 m/s.

Similar to results found for the total pressure drop, DRA was found more effective in reducing accelerational component for the oil of lower viscosity. At certain superficial liquid and gas velocities and DRA concentration, the height of liquid film in 2.5 cP oil experienced more decrease than in the 26 cP oil. This cut-down in the height of the liquid film was accompanied with proportional spread of the liquid film around the pipe circumference. Such decrease in the height of the liquid film was responsible for the reduction in the rate of mass pickup by the slug and hence the accelerational component of total pressure drop. It was noticed that the height of the liquid film decreased continuously at higher DRA concentrations and superficial gas velocities, regardless of oil viscosity, until it reached minimum value after which transition in the flow pattern to stratified flow could take place.

Figure 6 shows that at superficial liquid and gas velocities of 1 & 4 m/s, respectively, increasing DRA concentration from 0 to 50 ppm caused 56% reduction in accelerational component of pressure drop for the 2.5 cP oil from 2514 to 1110 Pa. The corresponding reduction for the 26 cP oil was only 9% from 3147 to 2868 Pa.

It is important to point that oil density played a key role in determining gravitational component. The 26 cP oil has a density of 820 Kg/m^3 whereas the 2.5 cP oil has a density of 800 kg/m^3. Comparing results of gravitational component for both oils shows that this contributor was way greater for the 26 cP oil than for the 2.5 cP oil as it should be if density was the only factor determined gravitational contribution to total pressure drop. Slug liquid holdup was found greater in the 26 cP oil than its corresponding values in the 2.5 cP oil at all superficial liquid and gas velocities and DRA concentrations, possibly due to its lower surface tension. This gives another reason why gravitational component was, markedly, greater in the 26 cP oil than in the 2.5 cP oil. Figure 7 describes the effect of oil viscosity on both DRA effectiveness and the magnitude of this component at superficial liquid velocity of 1 m/s. One can find that at DRA concentration of 0 ppm and superficial liquid and gas velocities of 1 & 6 m/s, a 31% increase in gravitational component took place form 525 to 687 Pa as a result of increasing oil viscosity from 2.5 to 26 cP, whereas the increase in oil density did not reach 2.5%. The corresponding increase in gravitational component at DRA concentration of 50 ppm was 15%, from 485 to 555 Pa. Similar results were found at all superficial liquid velocities and DRA concentrations.

DRA was found more effective in reducing gravitational component of pressure drop for the oil of higher density and viscosity. Figure 7 shows again that at superficial liquid and gas velocities of 1 & 6 m/s, respectively, increasing DRA concentration from 0 to 50 ppm caused 24% reduction in gravitational component of pressure drop for the 26 cP oil from 687 to 555 Pa. The corresponding reduction for the 2.5 cP oil was only 8% from 525 to 485 Pa. Similar results were found at all superficial liquid velocities.

Frictional component of pressure drop was greater in the flow of the 26 cP oil since height of liquid film as well as Froud number where found greater. As mentioned before and shown in Figure 3, increasing oil viscosity was accompanied with an increase in the height of the liquid film. The difference in frictional drag for the two types of oil was minimized at higher DRA concentrations and superficial gas velocities since both oils had almost equivalent height of liquid film below which a transition in flow pattern could take place.

Figure 5 shows the effect of oil viscosity on frictional loss and DRA efficiency in reducing this loss at superficial liquid velocity of 0.5 m/s. It can be seen from this Figure that at DRA concentration of 0 ppm and superficial liquid and gas velocities of 0.5 & 6 m/s, respectively, frictional component increased significantly from 163 to 394 Pa when oil viscosity increased from 2.5 to 26 cP.

DRA had greater influence on frictional component for the 26 cP oil than the 2.5 cP oil. Figure 5 shows that at superficial liquid and gas velocities of 0.5 & 6 m/s respectively, increasing DRA concentration from 0 to 50 ppm caused 53% reduction in frictional pressure drop for the 26 cP oil from 394 to 187 Pa. The corresponding reduction in frictional pressure drop for the 2.5 cP oil was 9% from 163 to 149 Pa.

6. CONCLUSIONS

- Regardless of oil viscosity and pipe inclination, Accelerational component of total pressure drop was dominant and reached values as high as 86%.
- Despite the insignificant inclination of the 2-degree flow, gravity forces had great influence on the flow.
- Frictional pressure drop formed small portion of the total pressure drop regardless of oil viscosity, pipe inclination and DRA concentration.
- DRA was more effective in reducing accelerational component of pressure drop, as well as total pressure drop, in 2.5 cP oil than in 26 cP oil in the 2-degree upward flow.
- DRA had greater efficiency in reducing both gravitational and frictional pressure drops in 26 cP oil than in 2.5 cP oil in 2-degree upward flow.
- As oil viscosity increased, DRA had less influence in decreasing the height of liquid film that was important factor in determining frictional and accelerational components of total pressure drop. As the height of the liquid film decreased, liquid spread around the pipe.
- At high DRA concentrations and superficial gas velocities, and regardless of oil viscosity, height of liquid film decreased until it reached minimum, below which slug flow could no longer exist and transition in flow pattern could take place.

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APPENDIX-FIGURES

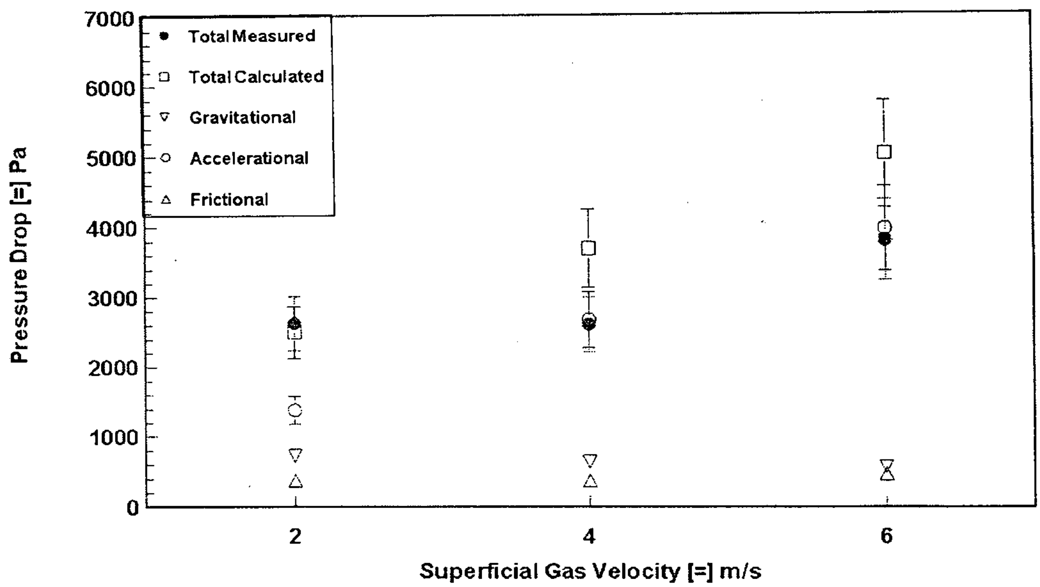

Figure 4 Pressure Drop Vs. Superficial Gas Velocity
100% Oil (2.5 cP), Vsl=1.5 m/s, 50 ppm, 2-Degree Upward

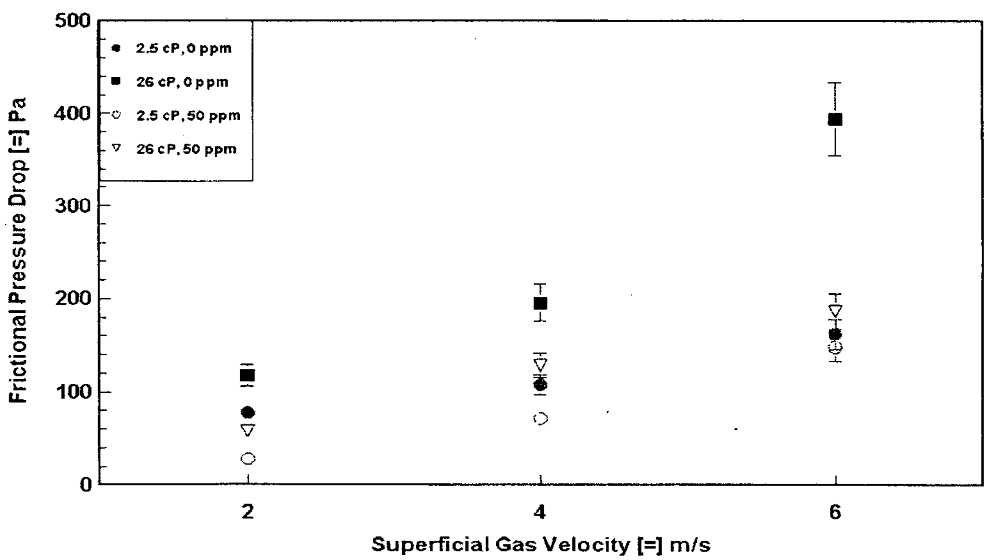

Figure 5 Effect of Viscosity on Frictional Pressure Drop
100% Oil (2.5 & 26 cP), Vsl=0.5 m/s, 2-Degree Upward

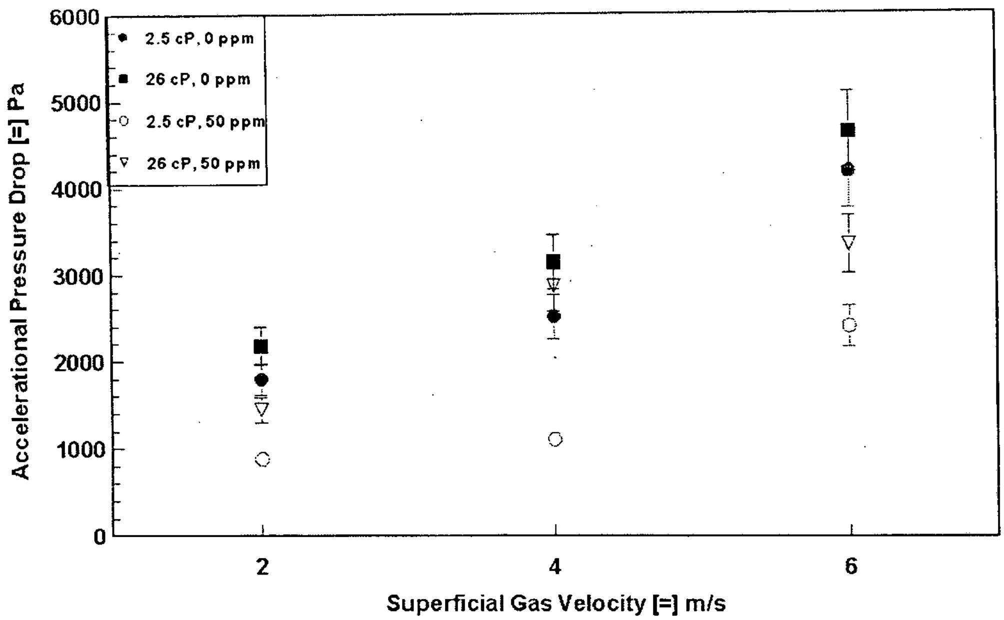

Figure 6 Effect of Viscosity on Accelerational Pressure Drop 100% Oil (2.5 & 26 cP), Vsl=1 m/s, 2-Degree Upward

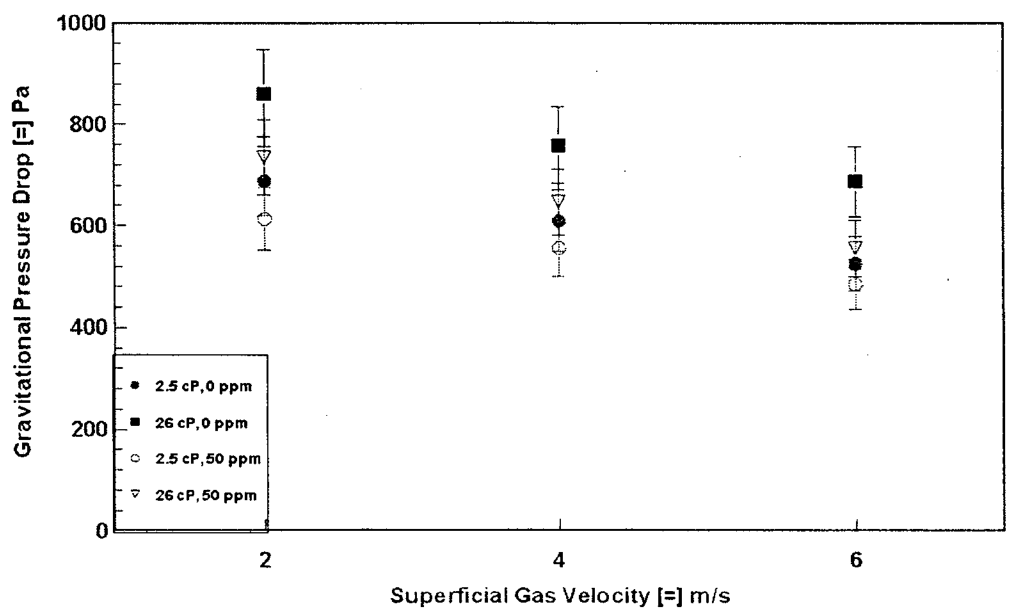

Figure 7 Effect of Viscosity on Gravitational Pressure Drop 100% Oil (2.5 & 26 cP), Vsl=1 m/s, 2-Degree Upward

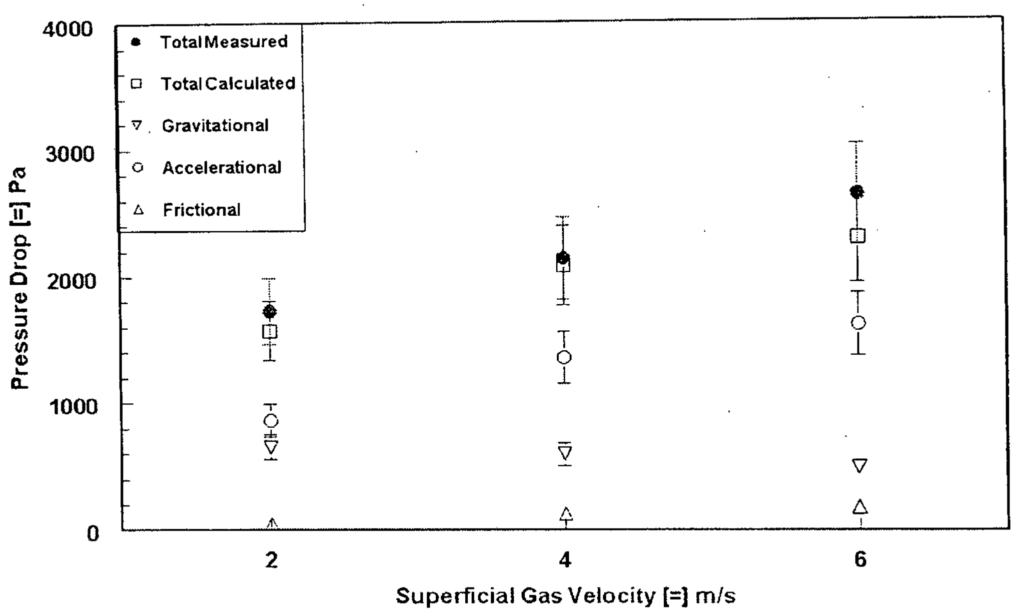

Figure 8 Pressure Drop Vs. Superficial Gas Velocity
100% Oil (26 cP), Vsl= 0.5 m/s, 50 ppm, 2-Degree Upward

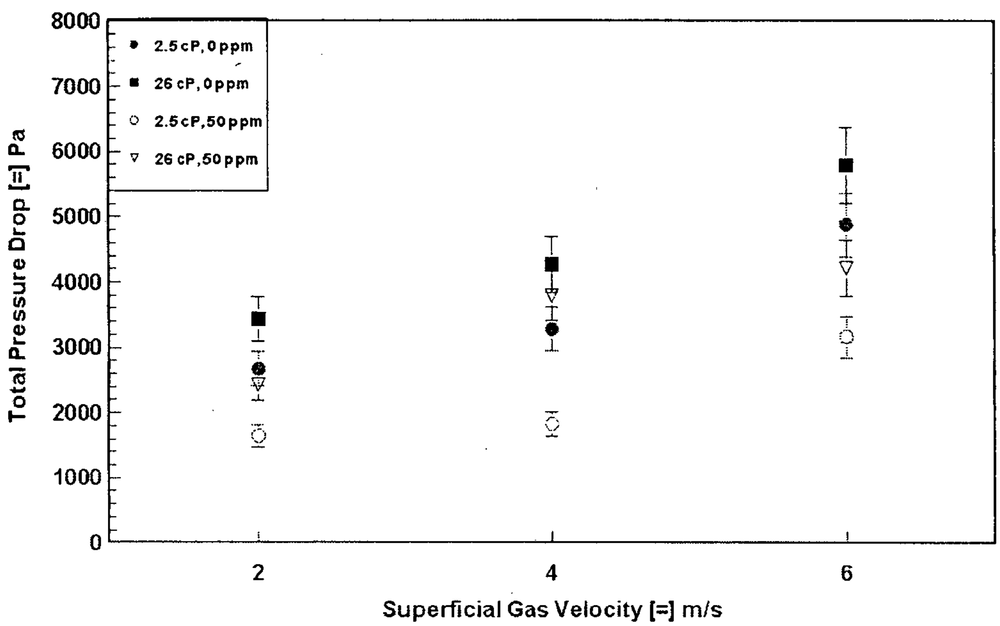

Figure 9 Effect of Viscosity on Total Pressure Drop
100% Oil (2.5 & 26 cP), Vsl=1 m/s, 2-Degree Upward