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Quantitative analysis of Drag Reduction in Horizontal Slug Flow

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Abstract

Calculations have been done to predict the components of pressure drop in slug flow. This analysis is aimed to understand, in quantitative manner, the contributions of both frictional and accelerational components to total pressure drop in horizontal slug flow and the effect of DRA's on each component. Experimental results were in good agreement with predicted values.

The DRA used in this study was effective in reducing both components of the pressure drop. The accelerational component was found to be dominant and formed over 80% of the total pressure drop. It increased dramatically with increasing superficial gas velocity. With the addition of 20 ppm DRA, the accelerational component was noticed to decrease by a factor of 67% as well as the frictional component. At DRA concentration of 50 ppm, they decreased by a factor of 78%. Total drag reduction was found to generally decrease at higher superficial gas velocities.

In sharp contrast with expectations, the drag reduction was recovered mainly from the accelerational component indicating that the DRA worked not only in the buffer zone but also in the mixing zone in the slug body. The accelerational drag reduction reached values as high as 88% out of total drag reduction.

Introduction

Since the discovery of darg reduction phenomenon in 1947 by Toms, extensive work has been carried out in horizontal and inclined pipelines to examine the effect of the addition of drag reducing agents on pressure drop. Drag reducing agents were found to have significant influence in decreasing the frictional pressure drop in single-phase flow. Since that time, drag reducing agents were believed to work only on the frictional component of the pressure drop of multiphase flow, and not influencing the other contributions to total pressure drop, e.g. accelerational and gravitational components.

Although several theories were introduced regarding drag reduction phenomenon, a precise and exact understanding of the mechanism of drag reduction is not established yet especially in multiphase flow. It is believed that DRA's work mostly in the region near the wall, namely buffer zone, by reducing the friction factor of the flow through diminishing the turbulent structures and changing the velocity profile there. This study may help to recognize where drag reduction takes place in a quantitative manner so as developing current theories about how and where DRA's work. A new proposed mechanism may be achieved with the help of such analysis.

Several models were examined, but few were applied in the above study to break down the pressure drop in slug flow in a horizontal system into its components. Hubbard and Dukler (1975) introduced equations to calculate the contributions of both frictional and accelerational components. In their model, they assumed that with in 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 the 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 (Hubbard & Dukler, 1975).

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.

Theory

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 the 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 center for flow improvement. 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.

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 degredation 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 data examined here were developed from earlier experimental studies that examined the effects of drag reducing agents on the average pressure gradient and flow regimes in horizontal multiphase systems. The experiments have been carried out in a 20-m long, 10-cm inside diameter multiphase flow system. A light oil with a viscosity of 2.5 cP and a density of 800 kg/m^3 was used as the liquid phase whereas carbon dioxide was the gas phase.

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.

Modeling

For slug flow, Hubbard and Dukler (1975) produced a model for horizontal systems and defined three parts to the flow. These are mixing zone (L_{MZ}), slug body (l_s), and liquid film behind the slug (l_f). This model was used to determine frictional loss in both slug body and the liquid film behind the slug and the accelerational contribution that takes place at the front of the slug. A schematic diagram of a stable slug is shown below in Figure 2.

Frictional Contribution. 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:

$$\Delta P_{f,body} = \frac{2f_{slug}\left[\rho_L < R_S > + \rho_G < \alpha_s >\right]V_S^{\,2}(l_s - l_{MZ})}{D} \quad (1)$$

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

$$f_{slug} = 0.0791\left(Re_{slug}\right)^{-0.25} \quad (2)$$

Where:
Re_{slug} = Reynolds number in the liquid film
R_s = liquid holdup in slug
l_s = length of slug body
l_{MZ} = length of mixing zone
V_S = average no-slip velocity of the fluid in the slug body

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:

$$l_{MZ} = 0.051Fr_f + 0.18 \quad (3)$$

$$Fr_f = \frac{(V_t - V_f)}{\sqrt{g \times h_{EFF}}} \quad (4)$$

Where:
Fr_f = film Froud number
V_t = slug translational velocity
V_f = film velocity
h_{EFF} = effective height of liquid film

Liquid Holdup. 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 liquid holdup at distance x in the slug body, R_s, is calculated using the following equation:

$$R_s(x) = \frac{x_{lg} - x_{ld}}{x_{lg}} e^{(-\frac{x}{x_{lg}})} \quad (4)$$

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

$$\langle R_{S,MZ} \rangle = \frac{x_{lg} - x_{ld}}{l_{MZ}}\left[1 - \exp(-\frac{l_{MZ}}{x_{lg}})\right] \quad (5)$$

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 void fraction 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:

$$\langle R_s \rangle = \frac{\langle R_{S,MZ} \rangle \times l_{MZ} + R(x = l_{MZ}) \times (l_S - l_{MZ})}{l_S} \quad (6)$$

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.

Carrying momentum balance over each phase of the stratified gas-liquid flow behind the slug lead to a single equation for each phase. These two famous equations are as follows for gas and liquid phases respectively:

$$-A_G\left(\frac{dP}{dx}\right) - \tau_{WG}S_G - \tau_i S_i = 0 \quad (7)$$

$$-A_L\left(\frac{dP}{dx}\right) - \tau_{WL}S_L + \tau_i S_i = 0 \quad (8)$$

Where $\left(\frac{dP}{dx}\right)$ is the pressure gradiant in each phase. Although interfacial waves had some influence on the liquid-gas shear stress, smooth stratified flow was assumed between slugs for which $\tau_i \cong \tau_{WG}$. The pressure drop across the liquid film can be calculated using the equations below:

$$\Delta P_{f,film} = \left(\frac{dP}{dx}\right) \times l_f \qquad (9)$$

$$l_f = \frac{V_t}{v_s} - l_s \qquad (10)$$

l_f is the length of slug body, V_t is slug translational velocity, and v_s is slug frequency.

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 accelerational component of slug pressure drop, ΔP_a and can be calculated by the following equations (Hubbard & Dukler, 1975):

$$\Delta P_a = \frac{x}{A}(V_S - V_{fe}) \qquad (11)$$

Hubbard & Dukler performed mass balance over the front of a slug and came out with the following equation to calculate the rate of mass pickup by the front of the slug, x:

$$x = \rho_L A R_{fe}(V_t - V_{fe}) \qquad (12)$$

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

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

$$\frac{\Delta P_T}{\Delta L} = \left[\left(\Delta P_a + \Delta P_{f,body} + \Delta P_{f,film}\right)\right] \times \frac{v_S}{V_t} \qquad (13)$$

Where $\frac{v_S}{V_t}$ is the number of slugs per unit length of the test section at any moment. Note that the term in brackets represents total pressure drop per unit slug.

Results

The pressure gradients in horizontal slug flow using 2.5 cP-oil were calculated by estimating both frictional and accelerational components. It was found that the main component of pressure gradient is the accelerational component where its percentage to the total pressure gradient ranges from 77% to 89%. On the other hand, less than 23% of the pressure gradient was attributed to the frictional component.

The drag reducing agent used in this study was effective in reducing the pressure gradient at all superficial liquid and gas velocities. A dosage of 20 ppm of DRA caused the pressure gradient and both of its components to decrease. Further addition of DRA to a concentration of 50 ppm was accompanied with more drag reduction and higher effectiveness of the DRA.

In sharp contrast to what is believed, most of the gained drag reduction took place in the accelerational component, while smaller fraction was attributed to the drag reduction gained in the frictional component. However, there is still significant reduction in the frictional component of the pressure gradient as will be seen later.

Predicted versus Measured Values. Figures 3 through 5 show the total calculated and measured pressure gradients as well as the estimated frictional and accelerational components at superficial liquid velocity of 1.5 m/s and DRA concentrations of 0, 20, and 50 ppm respectively.

Measured and calculated values were in good agreement. Total pressure gradient was found to increase with superficial gas velocity due to the increase in both of its components. For example, Figure 3 shows that, at 0 ppm DRA and superficial liquid velocity of 1.5 m/s, the total pressure gradient increased from 406 to 933 Pa/m when increasing superficial gas velocity from 2 to 6 m/s. The corresponding increases in both accelerational and frictional components were from 314 to 794 Pa/m and from 91 to 139 Pa/m, respectively.

At a DRA concentrations of 20 and 50 ppm, very good agreement between the calculated and measured values was noticed as can be seen in Figures 4 and 5.

The Contribution of ΔP_a and ΔP_f to ΔP_T. The accelerational component, ΔP_a, was found to be the dominant contributor to the total pressure gradient at all superficial liquid and gas velocities and DRA concentrations. This fraction had the values of 77%, 85%, and 85% at superficial liquid velocity of 1.5 m/s, DRA concentration of 0 ppm and superficial gas velocities of 2, 4, and 6 m/s, respectively, as shown in Figure 3. The corresponding values at DRA concentration of 50 ppm were 82%, 86%, and 89%, respectively as can bee shown in Figure 5.

The fractions of both accelerational and frictional components of total pressure gradient did not change much with increasing superficial liquid velocity holding all other variables constant, despite the increase in the liquid film height and hence the frictional component. This is due to the increase in the slug frequency that increased the accelerational contribution. The DRA had little or no effect on the contribution of each component to total pressure gradient.

For example, Figures 3, 4, and 5 indicate that the percentages of the frictional component at 20 ppm DRA and superficial gas velocity of 6 m/s were 13%, 15%, and 13% for the superficial liquid velocities of 0.5, 1, and 1.5 m/s, respectively. The corresponding values at DRA concentrations of 50 ppm were 13, 12, and 11%, respectively.

Effectiveness of DRA. To estimate the performance of the DRA on each component of pressure gradient, the following quantities were defined, total Effectiveness of the DRA, $Eff._T$:

$$\text{Eff.}_T\% = \frac{\left(\Delta P_{T,\,\text{NoDRA}} - \Delta P_{T,\,\text{DRA}}\right)}{\Delta P_{T,\,\text{NoDRA}}} \times 100 \qquad (14)$$

accelerational ffectiveness:

$$\text{Eff.}_a\% = \frac{\left(\Delta P_{a,\,\text{NoDRA}} - \Delta P_{a,\,\text{DRA}}\right)}{\Delta P_{a,\,\text{NoDRA}}} \times 100 \qquad (15)$$

and frictional effectiveness:

$$\text{Eff.}_f\% = \frac{\left(\Delta P_{f,\,\text{NoDRA}} - \Delta P_{f,\,\text{DRA}}\right)}{\Delta P_{f,\,\text{NoDRA}}} \times 100 \qquad (16)$$

Figure 6 shows the changes in the effectiveness of the DRA with superficial gas velocity at superficial liquid velocity of 1 m/s and DRA concentrations of 20. The corresponding Effectiveness for 50 ppm DRA are shown in Figure 7.

It can be seen from these figures that the total, accelerational, and frictional DRA effectiveness all increased with increasing DRA concentration from 20 to 50 ppm. Figures 6 and 7 indicate that at superficial liquid and gas velocities of 1 and 4 m/s, respectively, Total effectiveness increased from 30 to 50% when increasing DRA concentration from 20 to 50 ppm. The corresponding changes in Accelerational effectiveness and Frictional effectiveness were from 28 to 50% and from 41 to 50%, respectively.

In order to test the effect of superficial gas velocity on the DRA effectiveness, experiments were carried out at superficial gas velocities ranging 2 through 14 m/s. Total, accelerational and frictional DRA effectiveness were found to decrease dramatically with increasing superficial gas velocity. This could be due to the dramatic increase in the slug translational velocity, and hence the force required to accelerate the slow moving liquid, ahead of the slug, to the slug velocity. For example, Figure 6 shows that at superficial liquid velocity of 1 m/s and DRA concentration of 20 ppm, an increase in superficial gas velocity from 2 to 6 m/s caused the total effectiveness, accelerational effectiveness and frictional effectiveness to decreased from 65 to 22%, from 66 to 23% and from 61 to 16%, respectively. The corresponding changes at superficial liquid velocity of 1.5 m/s were from 44 to 15%, from 42 to 16% and from 52 to 14%, respectively as shown in Figure 8.

Fractional Drag Reduction. Drag reducing agents are believed to work in the region near the wall, namely the buffer zone, so that reducing the flow friction factor by lowering the intensity of the turbulence and recovering some energy that otherwise would have been dissipated in creating cross flows.

This study shows that most of the drag reduction could be gained from the accelerational component of the total pressure gradient while smaller fraction, not exceeding 26%, was recovered from the frictional component of the total pressure gradient.

Two definitions of drag reduction were established. Accelerational and frictional fractions of drag reduction, , DR_a & , DR_f, are defined as follow, respectively:

$$DR_a\% = \frac{DR_a}{DR_T} \times 100 \qquad (17)$$

$$DR_f\% = \frac{DR_f}{DR_T} \times 100 \qquad (18)$$

It was noticed that increasing superficial gas velocity was accompanied with an increase in DR_a% and a decrease in DR_f% due to the increasing amount of gas content in the slug body. Meanwhile, It is important to remeber that the accelerational and overall pressure gradients increased significantly with increasing gas velocity resulting in a decrease in both total and accelerational effectiveness regardless of the increase in the amount of accelerational drag reduction, DR_a. Figure 9 indicates an increase in the DR_a% from 77% to 86% for an increase in superficial gas velocity from 2 to 6 m/s at DRA concentration of 20 ppm and superficial liquid velocity of 1 m/s. At superficial liquid velocity of 1.5 m/s the corresponding increase was from 74% to 87% as shown in Figure 10.

Conclusions

Physical models have been used to prdict the frictional and accelerational components of the total pressure gradient. Good agreement with the measured values is obtained except at low gas velocities and at conditions near to the stratified/slug transition. Here, the holdup is not uniform and the calculated values are an under-estimate of the holdup. The following conclusions were made:

1. Pressure drop due to accelerational effects was the dominant contributor to total pressure drop. The fraction of this component was in the range from 80 to 90%.
2. Total pressure drop as well as frictional and accelerational components increased as a result of increasing superficial liquid and gas velocities.
3. The percentage of accelerational pressure gradient to total pressure gradient increased with superficial gas velocity while it did not change much with superficial liquid velocity.

4. The DRA was found to be effective in reducing pressure gradient and its two components.

5. The effectiveness of DRA increased with increasing DRA concentration.

6. The effectiveness of the DRA decreased dramatically when increasing superficial gas velocity.

7. The dominant part of the drag reduction was recovered from the accelerational component, indicating that the DRA worked mainly on reducing the accelerational pressure drop.

8. The percentage of accelerational drag reduction to the total drag reduction reached vales as high as 88%.

9. At the DRA concentration of 20 ppm, an increase in superficial gas velocity caused the percentage of accelerational drag reduction to increase, while it decreased with superficial liquid velocity. This percentage decreased with superficial liquid velocity too

10. Increasing superficial liquid velocity would cause both frictional and accelerational components of the total pressure gradient to increase leaving the percentage of each component to the total pressure gradient unchanged.

Nomenclature

f = friction factor
Re = Reynolds number
R = liquid holdup
l = length, m
V_S = average no-slip velocity of the fluid in the slug body, m/s
V_t = slug translational 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}
x = rate of mass pickup, kg/sec
ΔP = pressure drop, Pa
DR = drag reduction, Pa
Eff = DRA effectiveness
g = local gravity, m/s^2
ΔL = total distance between pressure taps, m
X_{lg} = lag distance, m
X_{ld} = lead distance, m

Subscripts

f = frictional
a = accelerational
T = total
$film$ = liquid film
fe = 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
$NoDRA$ = without DRA
DRA = with DRA

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Appendix-Figures

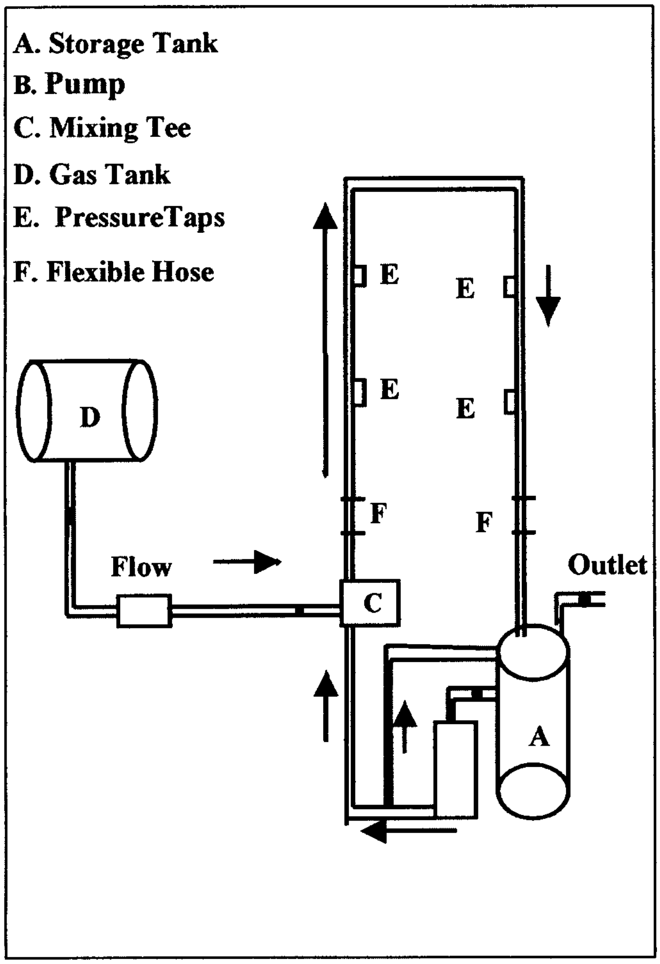

Figure 1 System Setup

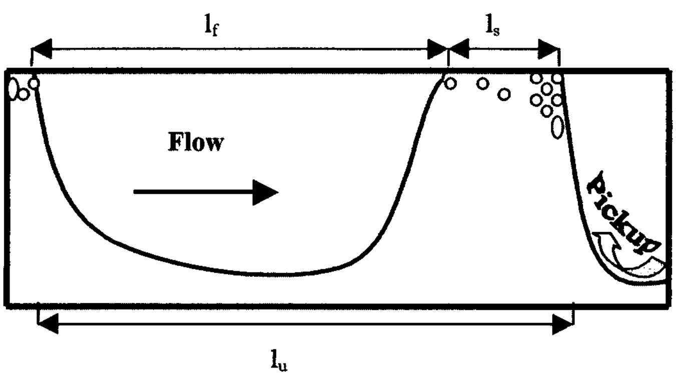

Figure 2 Schematic Diagram of a Unit Slug

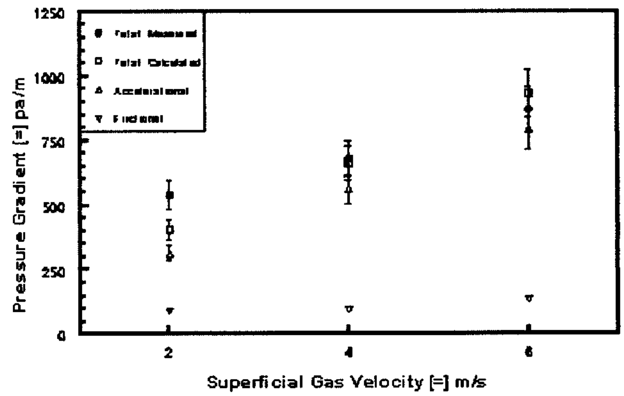

Figure 3 Pressure Gradient Vs. Superficial Gas Velocity 100% Oil (2.5 cP), 0 ppm, 1.5 m/s, Horizontal Flow

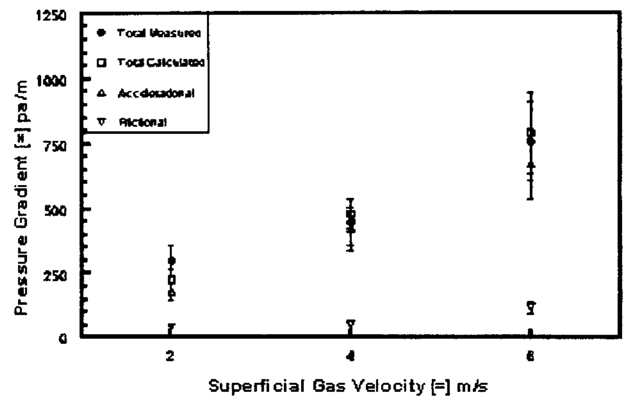

Figure 4 Pressure Gradient Vs. Superficial Gas Velocity 100% Oil (2.5 cP), 20 ppm, 1.5 m/s, Horizontal Flow

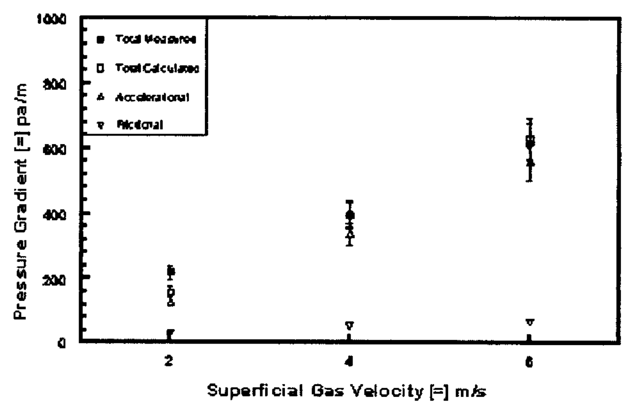

Figure 5 Pressure Gradient Vs. Superficial Gas Velocity 100% Oil (2.5 cP), 20 ppm, 1.5 m/s, Horizontal Flow

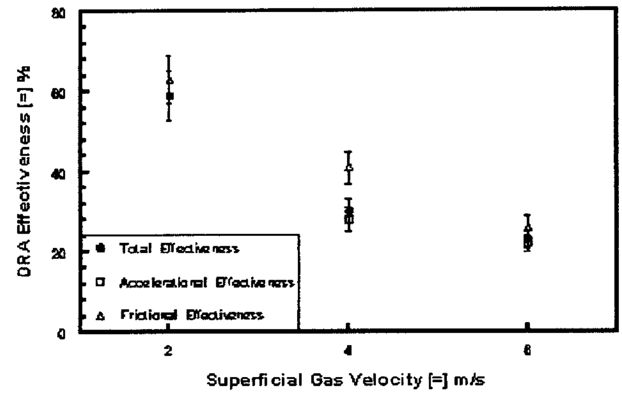

Figure 6 DRA Effectiveness Vs. Superficial Gas Velocity 100% Oil (2.5 cP), 20 ppm, 1 m/s, Horizontal Flow

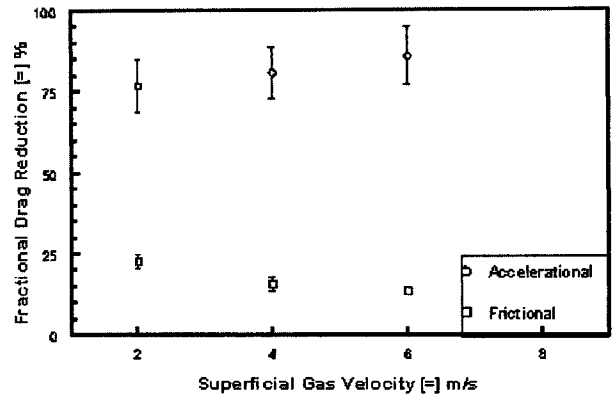

Figure 9 Fractional Drag Reduction Vs. Superficial Gas Velocity, 100% Oil (2.5 cP), 20 ppm, 1 m/s

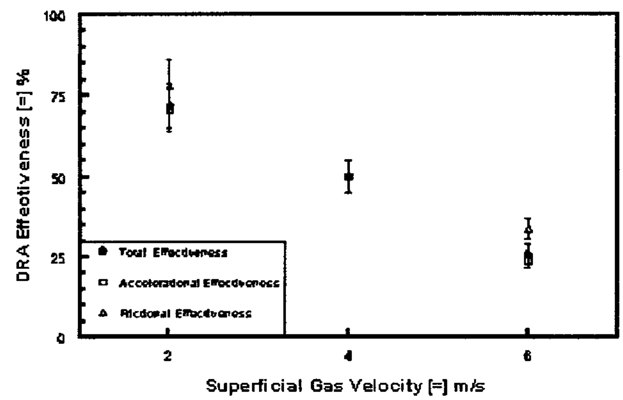

Figure 7 DRA Effectiveness Vs. Superficial Gas Velocity 100% Oil (2.5 cP), 50 ppm, 1 m/s, Horizontal Flow

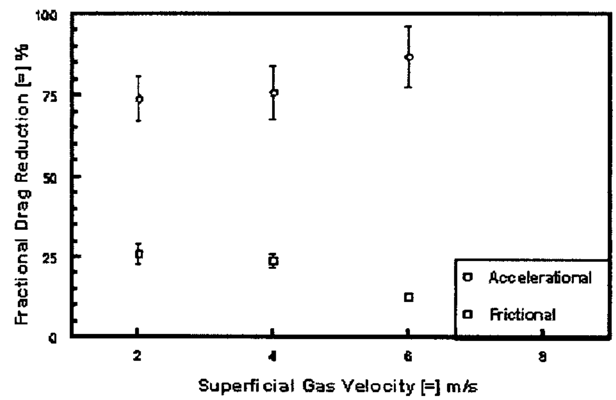

Figure 10 Fractional Drag Reduction Vs. Superficial Gas Velocity, 100% Oil (2.5 cP), 20 ppm, 1.5 m/s

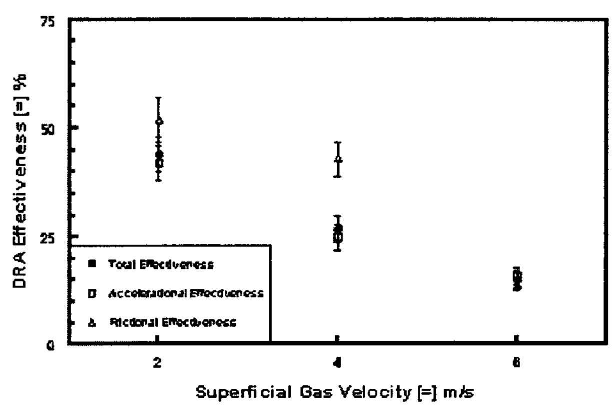

Figure 8 DRA Effectiveness Vs. Superficial Gas Velocity 100% Oil (2.5 cP), 20 ppm, 1.5 m/s, Horizontal Flow