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Three Phase Flow Characteristics in Inclined Eccentric Annuli

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Abstract

Gasified (aerated) fluids, having two-phases, are commonly used in drilling operations, especially for achieving underbalanced conditions. While adjusting the flow rates for each phase, common application is to adjust liquid phase for proper cuttings transport, and to adjust gas phase for controlling bottomhole pressure. Unfortunately, each of these phases flow with relatively different local velocities, causing various flow patterns to occur, which leads to fluctuations in hole cleaning performance as well as frictional pressure losses. These flow patterns are influenced by hole inclination, geometry, and presence of cuttings.

This study addresses the hydrodynamic behavior of two-phase drilling fluids in inclined section of wellbores with the presence of cuttings as a third phase with inner pipe rotation, considering eccentricity. Extensive experiments were conducted at a cuttings transport flow loop using air-water mixtures under a wide range of flow rates, rate of penetrations (ROPs), pipe rotations and hole inclinations. During the experiments, frictional pressure losses, in-situ flow rates for each phase, ROP, inclination and pipe rotation speed were recorded. The experimental data was also used to investigate the cuttings transport mechanisms.

A comprehensive mechanistic model was developed for determining the frictional pressure losses and hole cleaning performance of two-phase drilling fluids based on the experimental observations. It has been concluded that the proposed model is estimating the frictional pressure losses reasonably accurate when compared with the measured values.

Introduction

The oil and gas industry is facing a situation whereby the exploration is more challenging and the production cost is increasing, considering that most of the existing reservoirs have relatively depleted pressures. Also, at the same time, oil prices are fluctuating significantly. In addition to the reservoir related drilling problems, the fractured formations as well pose a risk of losing time, sidetracking the well if not losing the well at some circumstances while drilling due to the use of improperly selected drilling fluids. Therefore, application of proper technologies, even emerging ones, is important in order to contribute new reserves, enhance the recovery from existing formations, reduce cost, and increase revenue (Babajan and Qutob 2010). Drilling in unconventional resources and its challenges to get into deeper horizons triggered research into the area of high pressure and temperature drilling (Lee et al. 2012; Shadravan and Amani 2012). In conventional drilling operations, the hydrostatic pressure of drilling fluid is more than the pore pressure in the formation rock. If a depleted or a sub-normal pressured formation is drilled with conventional methods, problems such as lost circulation, pipe sticking, formation damage, etc. will likely to occur due to narrow operational mud weight window (Shahri et al. 2013, Salehi et al. 2013). Aligned with this, underbalanced drilling (UBD) is adopted in many oil and gas fields with the objectives of preventing formation damage, improving reservoir benefits, improving drilling performance and preventing conventional drilling problems (Babajan and Qutob 2010).

UBD, sometimes coupled with managed pressure drilling (MPD), is one of the most widely used drilling techniques while operating at low-pressure formations and it has been tested in several cases for years (Shadravan, Khodadadian et al. 2009; Shadravan, Nabaei et al. 2009a, 2009b). In this integrated technology, the drilling fluid pressure is less than the pore pressure in the formation rock. Therefore, the balance between the borehole pressure and formation pore fluid pressure is established. Air, gas, foam and gasified drilling fluid (Arabloo et al. 2012) are some of the most widely used light fluids during UBD applications. The number of wells drilled using this technology is increasing as a result of the advantages of underbalanced drilling. Increased penetration rate, minimized circulation loss especially in naturally fractured or pressure depleted reservoirs, prolonged bit life, minimized differential sticking, improved formation evaluation, reduced formation damage and environmental benefits are among the main advantages of UBD. This enhanced technology diminishes the risks of contaminating the reservoir and eliminates the potential pollution of drilling mud to environment (Guo and Ghalambor, 2002).

The hole cleaning efficiency is an important criterion that should be well determined during drilling operations. The carrying capacity, the ability of transporting the drilled particles to surface, is one of the major roles of drilling fluids (Ozbayoglu et al. 2010). Especially during UBD operations in horizontal and deviated wells, flow behavior of the two-phase fluid should be well determined in order to improve the hole cleaning efficiency. Otherwise, an improper hole cleaning may result in differential pipe sticking, increased torque and drag and hence a severe economic loss. The efficiency of the hydraulic program during drilling operations and the economic success of the operation are directly related to the better understanding of cuttings transport phenomenon. The minimum volumetric flow rates and the liquid and gas interface distributions are the most important requirements for hole cleaning efficiency (Vieira, 2000). Therefore, a more accurate two-phase flow model is essential for an improved transportation of cuttings from the wellbore to the surface.

In UBD, the presence of two phases in the drilling fluid makes the estimation of ECDs more difficult. Therefore, phase concentration distributions and mixture density changes due to temperature and pressure variations inside the wellbore should be taken into consideration during the ECD calculation (Ettehadi et al. 2013). In this study, cuttings transport experiments were conducted in inclined wells by using water and air as the drilling fluid. The cuttings concentration and cuttings distribution were detected using image processing techniques. This study aims to investigate the effects on volumetric cutting concentration and pressure drop while drilling incline wells for various flow conditions.

Literature Review

Theoretical and experimental studies as well as simulations have been carried out for better understanding of cuttings transport mechanism. By reviewing the publications, it is possible to identify four trends or four periods of time in the research methodologies used. Initial researches consisted of studies on setting velocity of particles for regular and irregular shapes in the fluids (Nazari et al. 2010). The initial researches were ended once studies in inclined annuli began having recognized the presence of a radial component in the cuttings settling velocity (Azaret al.1997). By the end of the 1980's, a few flow loop of various sizes and different capability levels were built such as outdoor flow loops by Tulsa University Drilling Research Projects (TUDRP) and a significant amount of experimental data was collected. Also several empirical and analytical models were developed (Pilehvariet al. 1999). Recently as more challenging wells were being drilled, the accuracy of available models need to be increased and simulation methods started to apply to better understand the cuttings transport in a wellbore at extreme conditions (Fuet al. 2013). Although there are numerous studies reported in the literature focused on the hydrodynamic behavior and carrying capacity of aerated drilling fluids, a few has been conducted on inclined annular geometries.

The efficiency of cutting transport and mud displacement by cement highly depends on the configuration of annulus. Mokhtari et al. (2012 a, b) demonstrated how the velocity profile at various eccentricities is reduced in the narrow region of annulus which can dramatically affect the efficiency of cutting transport. Moreover, they reported the effect of rheological properties (Power-Law Index and Yield Stress) and annular size, especially when the annulus is very small with regard to casing drilling technology. Eccentricity is also a critical issue to be considered in the cementing of horizontal wells, especially due to the growing number of horizontal wells in unconventional shale plays. Ermila et al. (2012, 2013) studied the time-dependent two-phase flow of mud and cement in eccentric annuli and reported the velocity profile and displacement efficiency at various eccentricities. Moreover, they proposed a new method of using magneto-rheological fluids to distribute velocity more evenly throughout the annulus

In the case of hydrodynamic behavior of gasified drilling fluid, investigations by; Beggs and Brill (1973), Sadatomi (1982), Caetano (1992) and Kabir (1988, 1992) have been conducted to characterize two-phase fluid flow through annulus. Sunthankar (2002) modified Taitel and Dukler (1976) transition equations for determining the flow patterns for annular geometries by using the definition of hydraulic diameter. He also compared the estimated results by experimental results.

Zhou (2004) suggested a similar approach like Sunthankar (2002), and modified the model to be used at higher pressures and temperatures. Experiments were also carried out under high temperature and pressure conditions. Lage et al. (2000) experimentally and theoretically studied two-phase fluid flow in horizontal and inclined annulus. Taitel and Dukler (1976) approach was used to determine flow patterns. Osgouei et al. (2010) proposed a new classification of two-phase flow patterns by using discriminant analysis. Karimi Vajargah et al. (2013a and 2013b) proposed a simplified continuous model for flow pattern determination in a transient two-phase flow simulator. Sorgun et al. (2011 and 2013) simulated gas-liquid flow inside horizontal eccentric annulus using a computational fluid dynamics (CFD) model and compared results by experimental data. Based on experimental observations, Osgouei et al. (2012 and 2013) developed also two models to estimate the total pressure losses and volumetric distribution of two phase fluids flow within the inclined wellbore for a particular drilling condition.

Rankin, et al. (1989) studied the effect of inclination on pressure loss and hole cleaning for UBD conditions. The effects of cuttings are totally ignored in this study. Tian, et al. (2000) developed a simulator that allows hydraulic design of UBD systems to predict optimum circulating flow rate for any type of fluid. However, the paper provides no information about modeling. Moreover, they claim that foam has a better carrying capacity than any other aerated mud. However, this is valid only for vertical cases and low inclination angles. Ozbayoglu et al. (2007) conducted foam flow experiments and stated that there is a relation between the bubble size and texture of the foams, and foams can be characterized using the image processing techniques, and the image processing techniques can be used for estimating the frictional pressure losses when foams are in use as drilling fluids. Doan, et al. (2000) developed a two-layer mechanistic model to describe the mechanism of transient cuttings transport in underbalanced conditions. The model simulates the transport of cuttings in an eccentric annulus, including cuttings deposition and re-suspension, formation and movement of cuttings bed. They note the importance of the wall slippage. Their model addresses the question of minimum required flow rate for effective cuttings removal in UBD. Saintpere, et al. (2000) analyzed the hole cleaning with foam in inclined wells using a fluid mechanics approach ignoring the inertial effects. They introduce a few dimensionless parameters for describing the fluid rheology, foam properties, flowing time, etc. They observed the worst hole cleaning performance at angles 40°-60°. They claimed that by extrapolation of the information developed for inclined sections; this will give an idea about the minimum circulation time necessary to remove cuttings. Li and Walker (2001) studied the effects of gas-liquid ratio, flow rate, phase slip velocities, rate of penetration, wellbore inclination, and fluid properties on cuttings bed thickness for aerated fluids systems. They observed that liquid is the dominating parameter for cuttings transport in aerated systems. As the liquid ratio increases, for a constant in-situ flow rate, cuttings transport improves. Martins, et al. (2001) experimentally studied effective hole cleaning with foam. They developed empirical equations to predict the bed erosion capacity in horizontal wells as a function of foam quality and Reynolds number. Mendez (2002) has conducted experiments on aerated drilling fluids with cuttings including pipe rotation. Cuttings bed height and pressure drop were observed. Also, a semi-empirical model was developed. Zhou (2004) has conducted an experimental study on cuttings transport with aerated drilling fluids under elevated temperature and pressure conditions at horizontal annulus.. One of the interesting observations was the influence of temperature on cuttings transport. Also, he has developed a mechanistic model. Ozbayoglu et al. (2012) studied the hole cleaning process during the flow of a drilling fluid consist of a gas and a liquid phase through a horizontal annulus. Their observations showed that the major contribution for carrying the cuttings along the wellbore is the liquid phase. However, as the gas flow rate is increased, the carrying capacity of liquid by raising turbulence effect.

Experimental Work

During this study, cuttings transport experiments were conducted in inclined wells ($12.5<\theta<75$) by using water and air mixture as the drilling circulation fluid. The study aimed to investigate the effects of liquid and gas flow rates, rate of penetration, fluid density & viscosity (for model verification purposes, since fluid properties are not variable), liquid-gas ratio and pipe rotation, as well as eccentricity on cuttings transport efficiency and frictional pressure losses while drilling inclined wells for various flow conditions experimentally.

Cuttings transport experiments with gas and liquid as the circulation fluid have been conducted at the Middle East Technical University, Petroleum and Natural Gas Engineering Department, Multiphase Flow Loop (METU-PETE-MFL). The facility consisted of liquid centrifugal pumps, a gas compressor, pneumatic flow control valves, flow meters, point and differential pressure transducers, annular test section, a multiphase 3-phase separator, a shale shaker, storage tanks for solids, and liquid, a high speed camera, and a data acquisition system which is an essential part of the experimental setup (Fig.1). The annular test section consists of approximately 21 ft. long with 2.91 inch I.D. transparent acrylic conduit with a 1.85 in O.D. inner drillpipe. The inner pipe is attached to a variable speed motor, which enables the rotation of the drillpipe at any desired speed up to 150 rpm. Liquid, solids and gas are separated using a separation tank – shale shaker system. The liquid is introduced into the system by a centrifugal pump with a flow capacity of 250 gpm, and gas is introduced to the system using a compressor of 120 scfm capacity. Flow rates for both fluids are measured and controlled by mass flow meters and pneumatic flow controllers, respectively. During the flow tests, pressure drop is measured at a fully developed section on the annular test section using a digital pressure transducer. The distance between the ports is approximately 5 ft, since entrance and end effects are taken into consideration. The cuttings are injected from an injection tank which simulates a rate of penetration of 40- 150 ft/hr using an auger to introduce the cuttings into the system. At the same time, a high speed camera is used to record all step of the experiments. These recordings were used later to determine flow patterns for various flow conditions in the annular test section.

The standard experimental procedure followed during conducting the experiments was as follows: Using centrifugal pump, the liquid was pumped at a constant flow rate and the drill pipe was rotated at the desired rotation speed by using a variable speed motor. Then, the gas was introduced at the desired constant rate. Once both the gas and liquid flow rates were stabilized, the cuttings were injected from injection tank into the system at a constant rate. When steady state flow was established, the data acquisition system was used in order to record flow rates, pressures at critical points, pressure drop inside the test section, etc. At the same time, high-speed camera was recording the flow in the annular test section to confirm the visual observations of the flow regimes under dynamic conditions. Tests have been conducted for liquid superficial velocities of 1 ft/s to 10 ft/s, gas superficial velocities of 1 ft/s to 120 ft/s, rate of penetrations of 80 ft/hr to 120 ft/hr, and pipe rotation speeds of 80 to 120 rpm. In this study, 0 degrees of inclination is used for vertical alignment, and 90 degrees of inclination represents horizontal position.

Theoretical Work

Based on the experimental observations, a mechanistic model is developed to predict the volumetric distributions of the liquid and gas, and to estimate the total pressure losses inside the wellbore sections for homogenous disperse flow pattern.

Conformal Mapping

One of the most widely used coordinate system for analyzing fluid flow and heat transfer in an eccentric annulus is the bipolar coordinates. However, when using this coordinate system for eccentric annulus, the analytical solution of the conservation equations of mass and momentum become quite lengthy and difficult to handle, if not impossible to obtain a solution. Thus, problems involving an eccentric annulus can be solved by approximation using cylindrical coordinates (Cheng and Hwang, 1968; Trombetta, 1971; Yao, 1980; Prusa and Yao, 1983). One of the approximation methods is conformal mapping. The x-conformal mapping technique and its application for the experimental setup of this study were discussed in detail by Osgouei (2010) and Ozbayoglu et al. (2012). By applying this technique, concentric annulus geometrical properties (representative ID and OD) were calculated and presented as shown in Table 1 for METU Multiphase Flow Loop - Annular test section.

Model Assumptions

1. No mass transfer between the liquid, gas, and solid phases.
2. Fully developed steady-state flow.
3. Inter-phase momentum transfer is only caused by drag.
4. Pipe rotation in low angular velocities.
5. Particles are spherical.
6. The dispersed phase is assumed to be instantaneously reaching its terminal velocity, so the transient term on the drift velocity is neglected.
7. Gas and liquid mixture is considered as homogeneous flow.

When there is intensive bubbling, it is best to consider the gas liquid mixture from the point of view of homogeneous isotropic turbulence. Because it is know that fully developed turbulence is in fact created as a result of the liquid agitation by moving the bubble. It is assumed that all gas kinetic energy is transferred to the liquid-particle mixture, eventually being dissipated by the turbulent motion (Azbel 1981).

Calculation of Gas Void Fraction

In this study, in order to simplify the model, equal phase velocities, or no-slip condition between liquid and gas phases was assumed. Physically, liquid void fraction is simply equal to the ratio of the liquid volumetric flow rate to the total volumetric flow rate.

$$\emptyset_{avL} = \lambda_L \quad (1)$$

$$\emptyset_{avG} = 1 - \emptyset_{avL} \quad (2)$$

Definition of Gas and Liquid Homogeneous Mixture Properties

After calculation of liquid and gas void fractions using Eqs (1 and 2), the properties of gas and liquid mixture can be determined by using the following formulas:

$$\rho_{sm} = \emptyset_{avg}\rho_G + \left(1 - \emptyset_{avg}\right)\rho_L \quad (3)$$

$$\mu_{sm} = \emptyset_{avg}\mu_G + \left(1 - \emptyset_{avg}\right)\mu_L \quad (4)$$

$$V_{sm} = \frac{V_{SG}\rho_G + V_{SL}\rho_L}{\rho_{sm}} \quad (5)$$

Calculation of Cuttings Particle Relative Velocity into the Gas and Liquid Homogeneous Mixture

The determination of slip void fraction for each phase requires the knowledge of its distribution in annuli. Models for algebraic slip were first introduced by Ishii (1977) Manninen and Taivassalo (1996), providing a more general formulation which forms the basis for the implementation in this study. The phase and bulk momentum equations are first transformed to non-conservative form by combining with the phase and bulk continuity equations. Fig.2 show the free body diagram for a cuttings particle of dispersed phase (solid particle) in gas and liquid homogeneous mixture. If a non-deformable particle immersed in flowing gas-liquid homogeneous mixture is considered, this particle is a part of dispersed phase in the continuous medium.

The general Lagrangian equation for the motion of the particle is:

$$m_p \frac{d\vec{v}_{SC}}{dt} = m_p\vec{g} + m_m\left[\frac{D\vec{v}_{sm}}{Dt} - \vec{g}\right] + \vec{F}_D + \vec{F}_{LF} \quad (6)$$

where

m_p = Mass of solid particle (dispersed phase)

m_m = Mass of the dispersed continues phase

v_{SC} = Solid particle velocity

v_{sm} = Gas- liquid mixture velocity

$\frac{D\vec{v}_{sm}}{Dt}$ = Lagrangian fluid acceleration $\frac{D\vec{v}_{sm}}{Dt} = \frac{\partial\vec{v}_{sm}}{\partial t} + \vec{v}_{sm}.\nabla\vec{v}_{sm}$

$\vec{F}_D$ = Drag forces

$\vec{F}_{LF}$ = Lift forces

Because system is assumed as steady state without acceleration, equation 7 simplifies to:

$$0 = m_p\vec{g} - m_m\vec{g} + m_m\vec{v}_{sm}.\nabla\vec{v}_{sm} + \vec{F}_D + \vec{F}_{LF} \quad (7)$$

The first term in equation 16 is the gravitational force, the second term is the buoyancy force and the third term is the virtual mass effect. The effect of lift force is assumed negligible when compared with the other terms. Drag force exerted by a single particle on the continuous phase is:

$$\vec{F}_D = C_D\rho_m \frac{\pi D_p^2}{8}\left|\vec{v}_{sm} - \vec{v}_p\right|\left(\vec{v}_{sm} - \vec{v}_p\right) \quad (8)$$

where $\vec{v}_{sp} = (\vec{v}_{sm} - \vec{v}_p)$ can be defined as particle relative velocity (slip velocity of solid particle) in gas-liquid mixture.

Several empirical correlations are available for drag coefficient. Schiller and Naumann (1933) correlation was used in this study.

$$C_{Dp} = \left(\frac{24}{N_{Re_p}}\right)\left(1 + 0.15 N_{Re_p}^{0.687}\right) + \frac{0.413}{1 + 16300 N_{Re_p}^{-1.09}} \tag{9}$$

where

$$N_{Re_p} = \frac{\rho_{sm}(V_{sm})(D_P)}{\mu_{sm}} \frac{1}{1-\varepsilon} \tag{10}$$

The mass of each phase is the function of its density and volume.

$$m_p = \rho_C V_p \tag{11}$$

$$m_m = \rho_{sm} V_p \tag{12}$$

The volume of a single spherical particle, V_p, is given by:

$$V_p = \frac{\pi D_p^3}{6} \tag{13}$$

By inserting equations 8 to 13 into equation 7:

$$(\rho_c - \rho_{sm})\vec{g}V_p + \rho_{sm}V_p\vec{v}_{sm}.\nabla\vec{v}_{sm} + C_D\rho_{sm}\frac{\pi D_p^2}{8}|\vec{v}_{sm} - \vec{v}_{SC}|(\vec{v}_{sm} - \vec{v}_{SC}) = 0 \tag{14}$$

In cylindrical coordinate system: $\begin{cases} \vec{v}_{sm} = v_{smr}\vec{e}_r + v_{sm\theta}\vec{e}_\theta + v_{smz}\vec{e}_z \\ \vec{v}_{SC} = v_{SCr}\vec{e}_r + v_{SC\theta}\vec{e}_\theta + v_{SCz}\vec{e}_z \end{cases}$

The consideration of model assumptions and mathematical operations lead to the following closed relationships for the particle relative velocity (slip velocity) in cylindrical coordinates:

$$\vec{v}_{spz} = -\frac{4}{3}\frac{\vec{g}_z}{C_D}\frac{D_p}{|v_{sp}|}\frac{(\rho_c - \rho_{sm})}{\rho_{sm}} \tag{15}$$

$$\vec{v}_{spr} = -\frac{4}{3}\frac{D_p}{|v_{sp}|C_D}\left[\frac{(\rho_c - \rho_{sm})\vec{g}_r}{\rho_{sm}} + \frac{V_\theta^2}{(D_{wh} - D_{dp})/2}\right] \tag{16}$$

$$v_{sp} = \sqrt{v_{spr}^2 + v_{spz}^2} \tag{17}$$

where $\vec{g}_r = \frac{V_\theta^2}{(D_{wh} - D_{dp})/2} - g\sin(\theta)$ is gravity in r-direction. By solving system of Eqs 15-17; slip velocity of cuttings can be obtained.

Calculation of Gas, Particle and Liquid Slip Void Fraction into the Three Phase Mixture

Azbel (1981) verified the average fraction of particles in liquid flow by using the definition of the average relative velocity of the solid phase when velocities of the two phases are low and the duct is large enough (no wall effect). In this study, his derivation is used to calculate the particle slip void fraction in gas and liquid homogeneous mixture (Eqs.18-21)

$$\emptyset_{avp} = \frac{\vec{v}_{sp} - V_{sm} - V_{SC}}{2\overrightarrow{\vec{v}_{sp}}} - \left[\left(\frac{\vec{v}_{sp} - V_{sm} - V_{SC}}{2\vec{v}_{sp}}\right)^2 + \frac{V_{SC}}{\vec{v}_{sp}}\right]^{1/2} \tag{18}$$

$$\emptyset_{m} = \left(1 - \emptyset_{avp}\right) \tag{19}$$

$$\emptyset_{Gt} = \emptyset_{avG}\emptyset_{m} \tag{20}$$

$$\emptyset_{Lt} = 1 - \emptyset_{Gt-}\emptyset_{avp} \tag{21}$$

Definition of Gas/Cutting/Liquid Homogeneous Mixture Properties

After calculation of liquid, gas and cuttings particle void fractions, the properties of gas/cuttings/ liquid mixture can be calculated by using the following formula:

$$\rho_{stm} = \emptyset_{avp}\rho_{C} + \left(1 - \emptyset_{avp}\right)\rho_{sm} \tag{22}$$

$$\mu_{stm} = \left(1 + 2.5\emptyset_{avp}10.05\ (\emptyset_{avp})^2 + \ 0.00273e^{(16.6\ (\emptyset_{avp}))}\right)\mu_{sm} \tag{23}$$

$$V_{stm} = \frac{V_{SC}\rho_{C} + V_{sm}\rho_{sm}}{\rho_{stm}} \tag{24}$$

Determination of Pressure Loss for Three Phase Gas/Cutting/Liquid Homogeneous Mixture

The total pressure gradient for steady-state flow is composed of three components: friction losses, gravity term and convective acceleration term. Convective acceleration term can be neglected for higher pressure cases. So, only friction losses component exists in horizontal annuli cases and friction losses and gravity term components exists in vertical and inclined test sections. The friction and gravitation effects defined by Eqs 34 and 35, are mainly contributed by the interfacial shear stress between the drilling fluid and the annuli walls.

$$\left.\frac{dp}{dz}\right|_{T} = \left.\frac{dp}{dz}\right|_{f} + \left.\frac{dp}{dz}\right|_{g} \tag{25}$$

$$\left.\frac{dp}{dz}\right|_{g} = g\rho_{stm} \tag{26}$$

$$\left.\frac{dp}{dz}\right|_{f} = \frac{f_{F}\rho_{stm}{V_{stm}}^{2}}{2\left(D_{wh} - D_{dp}\right)} \tag{27}$$

In this study, following equations were used to calculate friction factor for laminar and turbulent flows.

For laminar flow

$$f_{F} = \frac{16}{N_{Re_{th.mix}}} \tag{28}$$

and for turbulent flow (Chen, 1979)

$$\frac{1}{\sqrt{f_F}} = -4\log\left(\frac{{}^{\delta}/_{(OD-ID)}}{3.7065} - \frac{5.0452}{N_{Re_{th.mix}}}\log(A)\right) \tag{29}$$

$$A = \left(\frac{\left({}^{\delta}/_{(OD-ID)}\right)}{2.5497}\right)^{1.1098} + \left(\frac{7.1490}{N_{Re_{th.mix}}}\right)^{0.8981} \tag{30}$$

where $\left({}^{\delta}/_{(OD - ID)}\right)$ is relative wall roughness.

Reynolds number based on the hydraulic diameter of cylinder for liquid/cutting /gas homogenous mixture is defined as

$$N_{Re_{th.mix}} = \frac{\rho_{stm}V_{stm}}{\mu_{stm}\left(D_{wh} - D_{dp}\right)} \tag{31}$$

Results & Discussions

In this section, experimental observations and sensitivity analysis are introduced in details. Also, the proposed models results are compared with the experimental data. The effects on pressure drop in test section were investigated in sensitivity analysis section.

Experimental Observations and Sensitivity Analysis

The effects of changes in the gas and liquid flow rates, rate of penetration, and pipe rotation on pressure drop for water, air and cuttings, three phases flow were investigated. Examples are given for by considering the effects of different drilling parameters on pressure drop in different inclinations. The pressure loss data from experiments conducted using METU Multiphase Flow Loop are compared in Figs. 3-11 for different inclinations. The following important observations can be made.

a) As shown in Figs. 3-5, it is observed that by rotating the drillpipe, total pressure drop, including friction and gravity terms, increase because of the increase in the concentration of suspended cuttings in the circulating fluid. When drillpipe rotation speed becomes higher than 80 rpm, total pressure drop is not considerably changed in inclined annuli for a constant liquid and gas flow rate couple. Also it is observed that for gas superficial velocity more than 20 (ft/sec), the effect of drillpipe rotation speed can be ignored because of high turbulence effects in near vertical section. For mid-range inclinations, there is a significant difference on total pressure loss between no-rotating and rotating pipe conditions. This is most probably due to complex cutting behavior.

b) As shown in Figs. 6-8, rate of penetration cause an increase in total pressure drop at low pipe rotation speed and low gas flow rate. As the pipe rotation speed and gas flow rate are increased, the effect of rate of penetration on total pressure loss becomes negligible.

c) Figs. 9 and 10 show the effect of liquid velocity on pressure loss at constant rate of penetration and pipe rotation for three phase flow in horizontal, inclined and nearly vertical eccentric annuli. It is observed that liquid superficial velocity increase causes an increase in total pressure loss drastically for a constant gas superficial velocity due to increase in mixture density and Reynolds number. Figure 11 shows the comparison for total pressure loss in the horizontal position, inclined positions and the nearly vertical position for three phase flow in eccentric annuli. It is observed that in horizontal section, by increasing the gas velocity in the wellbore, total pressure loss change modestly, since the only effective term in pressure drop is the frictional pressure losses and its change is small when compared with pressure drop changes in other inclination sections due to the contribution of gravity term. But in inclined (θ=45.0, 75.0 &60.0) and nearly vertical sections, by increasing gas velocity, total pressure loss decrease significantly, since gravity term, which is the dominating component, decrease due to mixture density reduction at these inclinations.

Comparison between Mechanistic Models Results and the Experimental Data

The developed mechanistic model was used to predict the total cuttings concentration inside the wellbore and total pressure loss, and results are compared with the experimental data.

The experimental pressure loss data from METU Multiphase Flow Loop and model predictions for inclined wellbore configuration are compared in Figs 12-15. These figures show that the mechanistic model can estimate pressure losses successfully for a given ROP, liquid and gas flow rates, including pipe rotation in high gas superficial velocity. In low gas superficial velocity, cuttings particle have tendency to slide back and accumulate in the wellbore. Since the model is focused on estimating cuttings concentration for calculations without considering the complex transport mechanism of particles under these conditions, such as sliding backwards, avalanching, etc, the model overestimates the pressure losses.

For all inclination angles, most of the total pressure drop estimations are reasonably close to the experimental data, with an error less than 20%, but some points are out of the ± 25% window, as shown in Figs 12-15. Most of these data points belong to tests with high inner pipe rotation speeds. The major reason for this difference is the due to the vibrations developing in the experimental setup during high inner pipe rotations. These vibrations caused significant fluctuations on the pressure transducer readings.

ECD Calculation Procedure by suggested model – Well Simulation

The following procedure can be applied to calculate ECD in a well drilled with gasified fluids.

1. The pressure and mass flow rates should be measured at the surface, and superficial velocities and density of gas are calculated for a short interval (i.e., around 50 feet).
2. Based on the superficial velocities and fluid rheological properties, liquid holdup and the properties of gas/ liquid mixture in the first interval of wellbore are calculated using Eqs 1-5.
3. Slip velocity of cuttings can be obtained by solving system of Eqs 15-17;
4. The particle slip void fraction in gas and liquid homogeneous mixture and Gas/Cutting/Liquid homogeneous mixture properties are determined using Eqs 18 - 24, in the first interval of wellbore.
5. The pressure at the bottom of the first interval is calculated using Eqs 25-31.
6. ECD is calculated using following equation
$$ECD = \frac{P_{Total}}{g \times TVD} \tag{32}$$
7. The pressure at the bottom of first interval is used to estimate the fluid properties and superficial velocities at the second interval by repeating steps 1-5.
8. The procedure is repeated until ECD at the bottom hole or at the interested depth is predicted.

Since performing these calculations are lengthy, spreadsheets are prepared and used to conduct the calculations. The following example illustrates the comparison of current study model performance with the procedure presented in the GRI Underbalanced Drilling Manual [18] (which is referred as GRI method in this paper), which is modified for a horizontal well well.

Example

A long radius Type-1 horizontal well is to be drilled to 6000 feet at the TVD of 3600 feet. The kickoff point is at 2500 feet and the built rate is 5° /100 ft. Pressure and ECD distribution profile versus depth will be determined. The air injection ratio is 34.59 ft^3/bbl of drilling mud. The drilling fluid rate is 250 gpm. The rate of penetration and drillpipe rotation speed are 100 ft/hrs and 40 rpm, respectively. The hole size is 8.5 in. and the outer diameter of the drillpipe is 4.5 inches. It is assumed that the surface temperature is 90° F and the geothermal gradient is 1° F/100 feet. The returns are being vented through a mud/gas separator and the surface pressure is assumed to be 14.7 psia, i.e., no backpressure. The calculation interval length will be 100 feet. The density and plastic viscosity of drilling fluid are 9 ppg and 10 cp, respectively.

As shown in Figs 16-17, the current study model predicted annular pressure and ECD higher than the GRI method introduced in reference no: 18, because the current study model can consider the effects of cutting concentration and drillpipe rotation speed on pressure loss. It can be concluded that these factors can significantly affecting annular pressure and ECD during UBD operation and ignoring these factors can lead to poor bottomhole pressure estimation.

Conclusions

This study aims to address the hydrodynamic behavior of two-phase drilling fluids in inclined and vertical wellbores with the presence of cuttings and inner pipe rotation. Extensive experiments were conducted at a cuttings transport flow loop using air-water mixtures under a wide range of air and water flow rates, rate of penetrations (ROP), pipe rotations and hole inclinations. The experimental data was also used to investigate the cuttings transport mechanisms for different flow patterns. During the experiments, pressure losses, in-situ flow rates for each phase, ROP, inclination and pipe rotation speed were recorded. The followings are majorly concluded:

- Total flow rate has a major impact on total pressure loss and cuttings concentration in the wellbore. As the liquid flow rate increases, total cuttings concentration inside the annulus decreases. However, an increase in total pressure loss can be observed drastically for a constant gas superficial velocity due to an increase in the mixture density and mixture velocity.
- As the gas flow rate increases for constant liquid flow rate, total cuttings concentration and pressure drop decreases because of a decrease in the mixture density and an increase in the turbulence effect.
- Inclination also has a significant influence on total pressure loss and cuttings concentration. Since the gravity term is usually the dominating term in total pressure loss, decreasing the inclination leads to an increase in total pressure loss.
- As the pipe rotation speed increases, total pressure loss increases. Although cuttings bed area decreases as the rotation speed increases, this may cause an increase in the flow area which leads to a decrease in frictional losses,

but, increasing suspended cuttings concentration increases the mixture density which leads to a drastic increased in gravitational term, overall causing an increase. Since at high inclination angles gravitational term is negligible, the effect of rotation on total pressure drop is not straightforward.

- As the ROP increases, total cuttings concentration in the wellbore increases at low gas flow rates and low drillpipe rotation speed.

Based on the obtained results from this study, a mechanistic model was developed to predict the volumetric distribution of each phase in three phase flow and to estimate frictional pressure drop for well by considering the effects of drill pipe rotation.

The following important conclusions also can be made from the experimental and theoretical studies.

• Conformal mapping technique can be applied in order to contribute the effect of eccentricity in three phase flow behavior.

• By using the information obtained from this study, the minimum gas superficial velocity for a constant liquid flow rate can be calculated for optimization of flow rates for liquid and gas phases in order to obtain the minimum pressure losses inside wellbore while transporting the cuttings in an effective way.

Thus, the information obtained from this study is applicable to any underbalanced drilling operation conducted with gas-liquid mixtures, for optimization of flow rates for liquid and gas phases in order to transport the cuttings in the horizontal, inclined and vertical sections in an effective way with reasonably low pressure losses to prevent undesired drilling incidents.

Acknowledgments

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Nomenclature

D_{wh} : Wellbore diameter, L

D_{dp} : Drill pipe diameter, L

N_{Re_p} : Reynolds Number for solid particle motion in fluid

$N_{Re_{th.mix}}$: Reynolds Number based on the hydraulic diameter of cylinder for liquid, cutting and gas homogenous mixture

V_m : Two phase liquid and gas homogeneous mixture slip velocity, L/t

D_P : Solid particle diameter, L

D_B : Bit diameter, L

C_{Dp} : Drag coefficient

Q_S : Solid phase flow rate, L3/t

Q_L : Liquid phase flow rate, L3/t

Q_G : Gas phase flow rate, L3/t

r_{ei} : Drill pipe radius

r_{eo} : Well bore radius

r_e^* : Radius ratio

V_{stm} : Three phase liquid, gas and cutting mixture slip velocity, L/t

V_{SC} : Solid particle superficial velocity, L/t

$\vec{v}_{sp}$: Slip velocity of solid particle, L/t

V_{sm} : Two phase liquid and gas mixture resultant velocity, L/t

V_{SL} : Liquid superficial velocity, L/t

V_{SG} : Gas superficial velocity, L/t

V_Z : Mixture axial velocity in cutting – liquid two phase flow, L/t

V_θ : Tangential velocity, L/t

Greek Letters

λ : No Slip void fraction of Liquid phase in two phase liquid and gas homogeneous mixture

$\emptyset_{avL}$: Slip void fraction of Liquid phase in two phase liquid and gas homogeneous mixture

$\emptyset_{avG}$: Slip void fraction of Gas phase in two phase liquid and gas homogeneous mixture

$\emptyset_{Lt}$: Slip void fraction of Liquid phase in three phase liquid, gas and cutting homogeneous mixture

$\emptyset_{avp}$: Slip void fraction of Solid phase in three phase liquid, gas and cutting homogeneous mixture

$\emptyset_{Gt}$: Slip void fraction of Gas phase in three phase liquid, gas and cutting homogeneous mixture

ρ_{sm} : Slip mixture density of two phase liquid and, m/L3

ε : Cutting (solid) bed porosity

ϵ : Eccentricity ratio

μ_L : Liquid viscosity, m/ (L t)

μ_G : Gas viscosity, m/ (L t)

ρ_{stm} : Three phase liquid, gas and cutting mixture density, m/L3

μ_{stm} : Three phase liquid, gas and cutting mixture viscosity, m/ (L t)

μ_{sm} : Slip mixture viscosity of two phase liquid and gas, m/ (L t)

ρ_L : Liquid density, m/L3

ρ_C : Cutting density, m/L3

ρ_G : Gas density, m/L3

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Table 1 New Concentric Annulus Geometry Properties

ID	OD	(a+d)	e	r*	ε	ηi	ηo	New ID	New OD
1.850	2.910	4.30	0.300	0.636	0.566	1.379	1.004	2.17	3.15

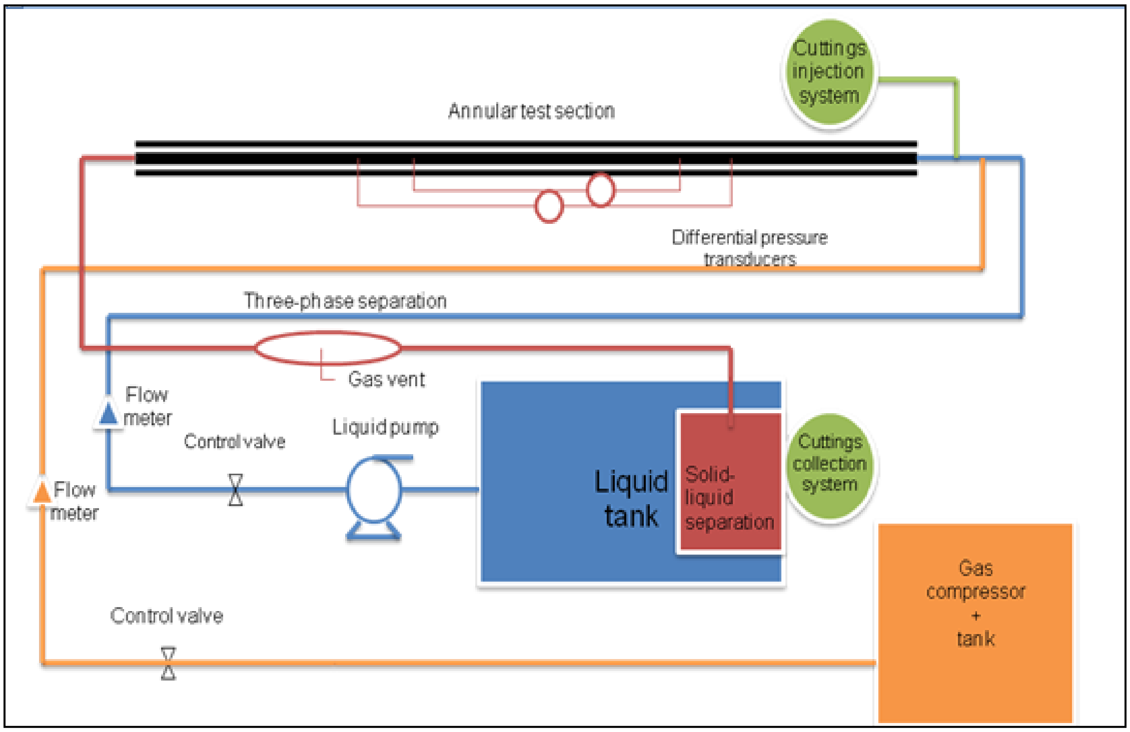

Fig.1 -Schematic of Experimental Setup

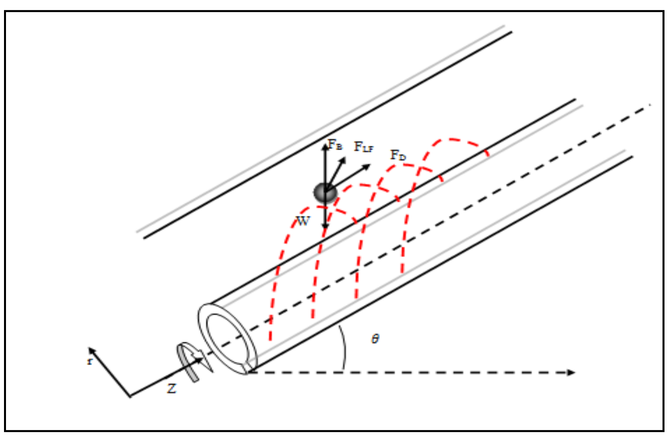

Fig. 2-Free Body Diagram for a Cuttings Particle of Dispersed Phase (Solid Particle)

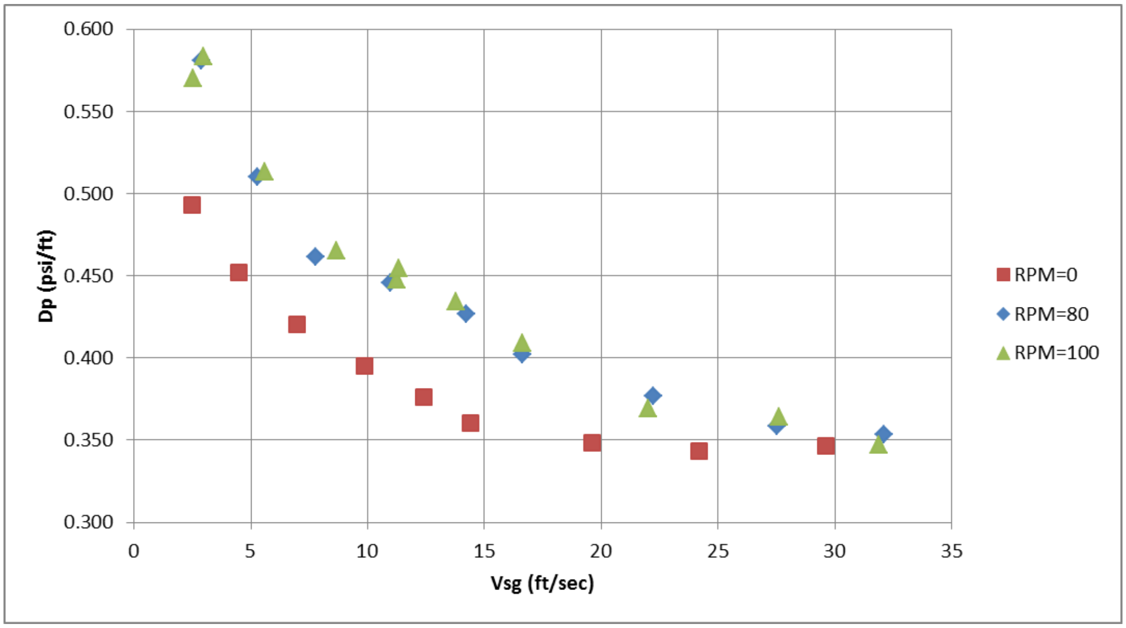

Fig. 3-Measured Pressure Drop vs. Gas Superficial Velocity in Nearly Vertical Test Section (θ=12.5) V_{SL}=3.0 (ft/sec), ROP=80(ft/hrs)

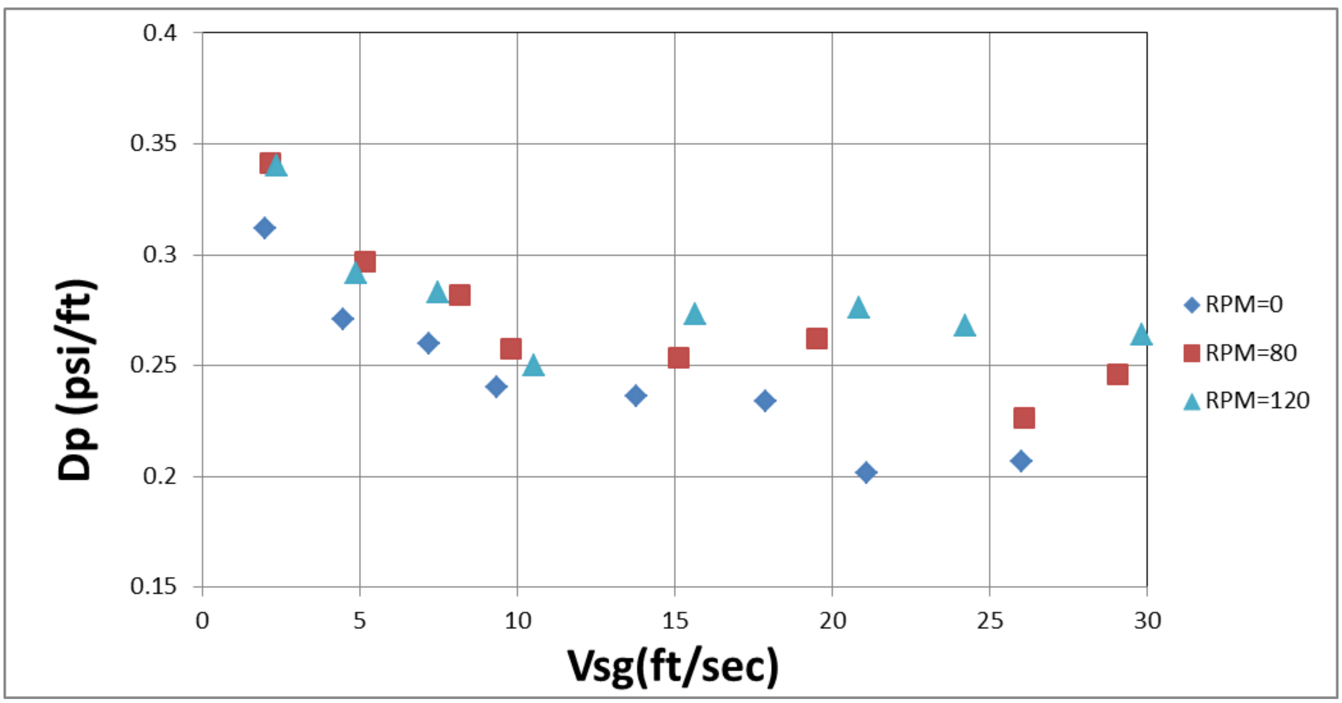

Fig. 4-Measured Pressure Drop vs. Gas Superficial Velocity in Inclined Test Section (θ=45.0), V_{SL}=2.0 (ft/sec), ROP=120(ft/hrs)

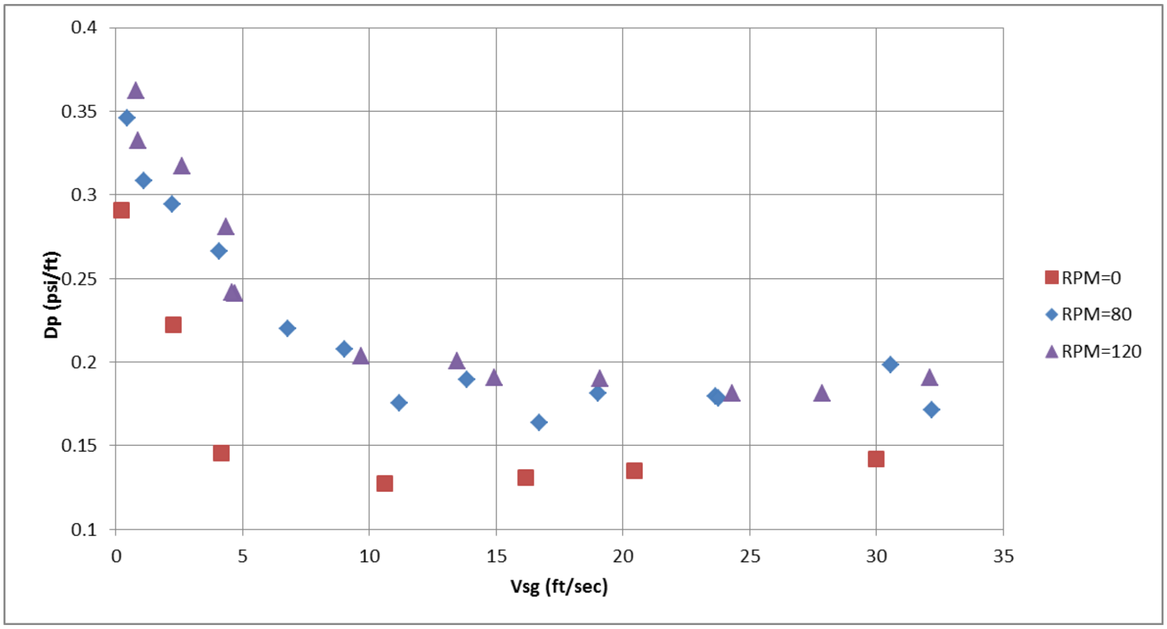

Fig.5-Measured Pressure Drop vs. Gas Superficial Velocity in Incline Test Section (θ=70.0) V_{SL}=2.0 (ft/sec), ROP=80(ft/hrs)

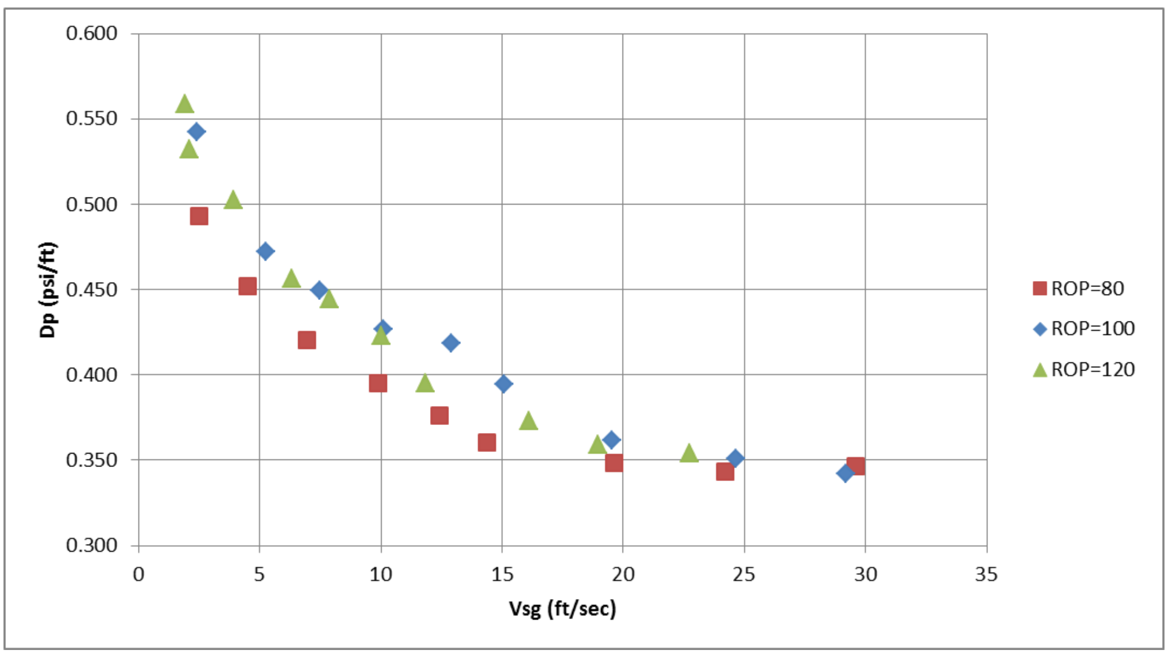

Fig. 6-Measured Pressure Drop vs. Gas Superficial Velocity in Nearly Vertical Test Section (θ=12.5) V_{SL}=3.0 (ft/sec), RPM=0 (1/min)

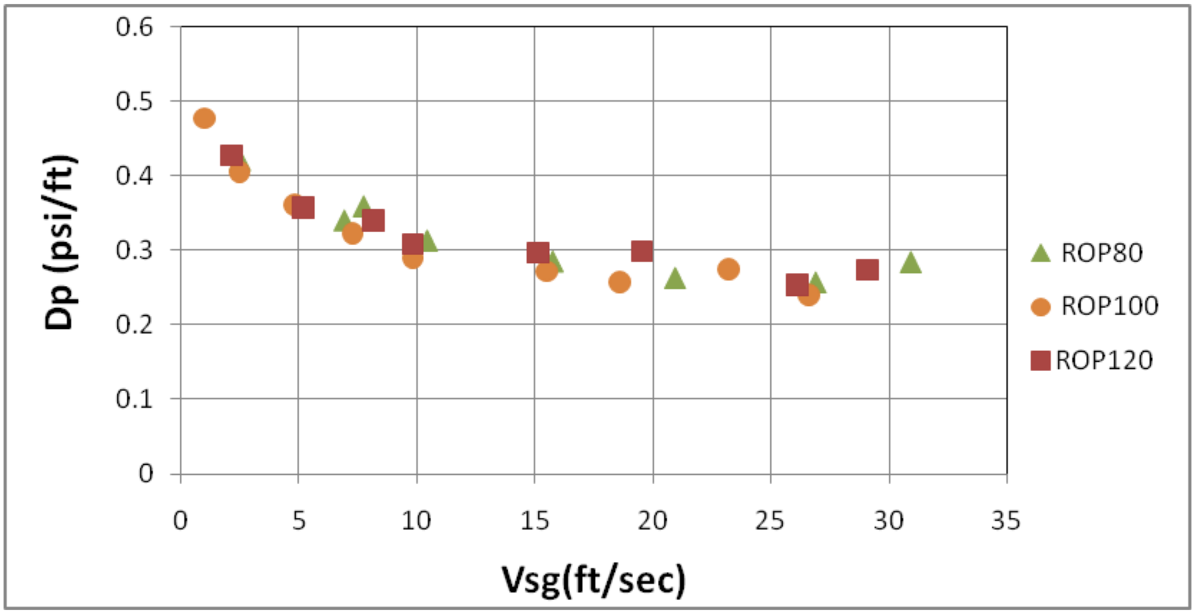

Fig. 7-Measured Pressure Drop vs. Gas Superficial Velocity in Inclined Test Section (θ=45.0) V_{SL}=2.0 (ft/sec), RPM=80 (1/min)

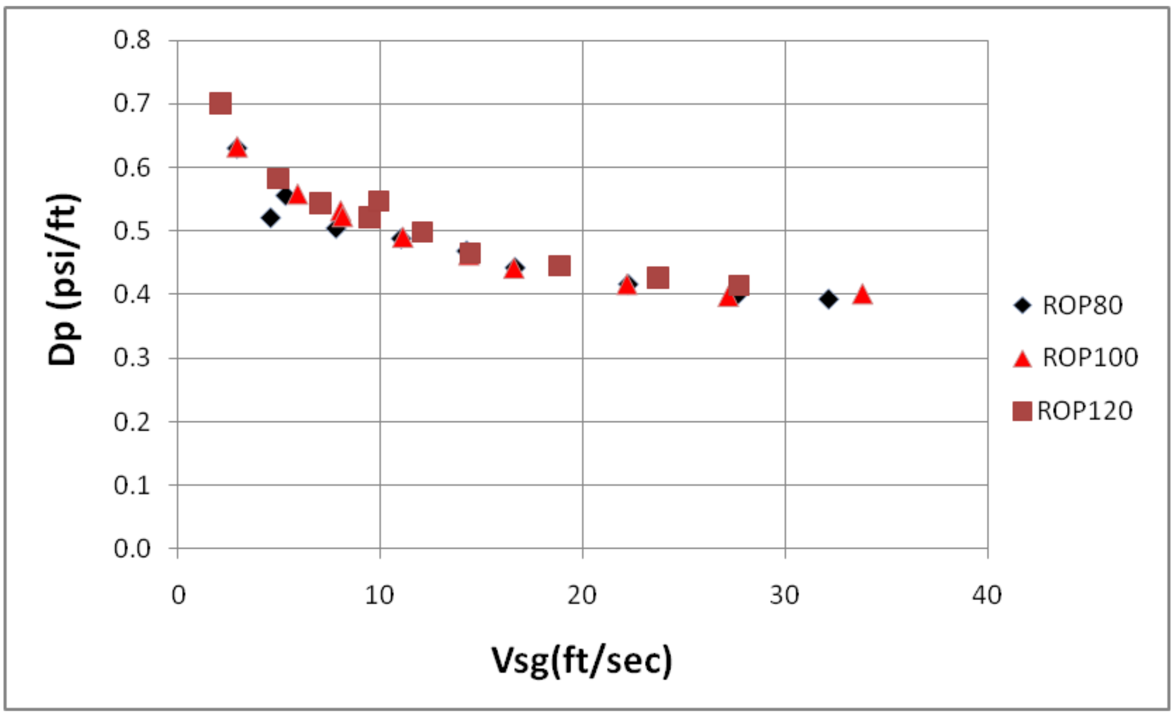

Fig. 8-Measured Pressure Drop vs. Gas Superficial Velocity in Nearly Vertical Test Section (θ=12.5) V_{SL}=3.0 (ft/sec), RPM=80 (1/min)

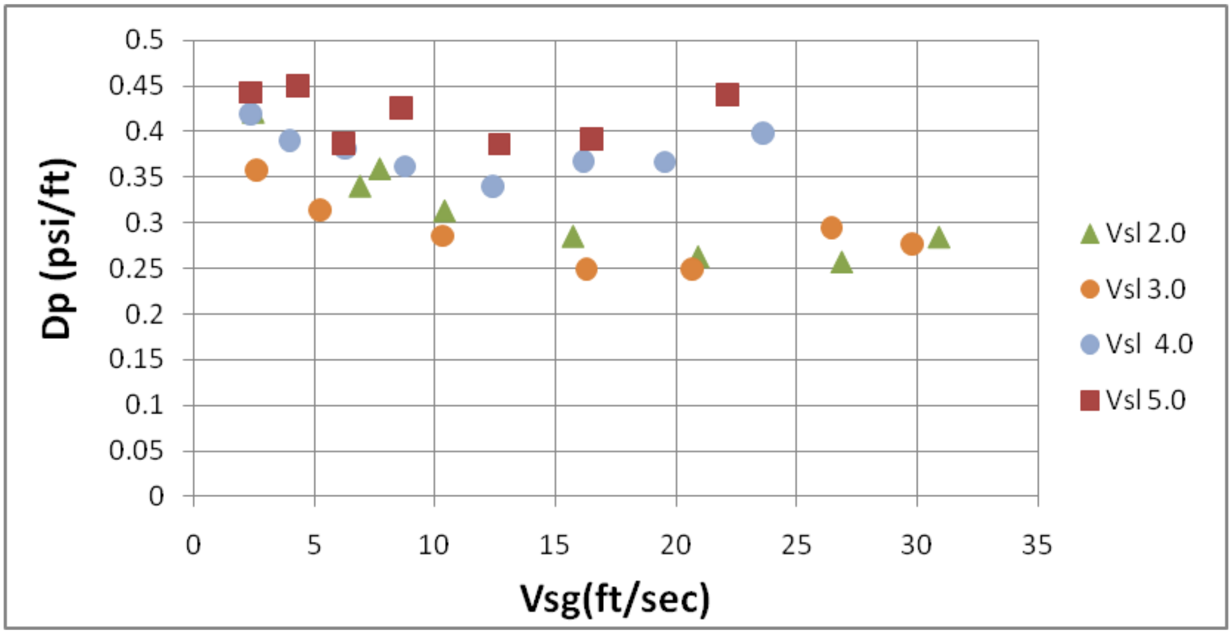

Fig. 9-Measured Pressure Drop vs. Gas Superficial Velocity in Inclined Test Section (θ=45.0), RPM=80 (1/min) and ROP=80 (ft/hrs)

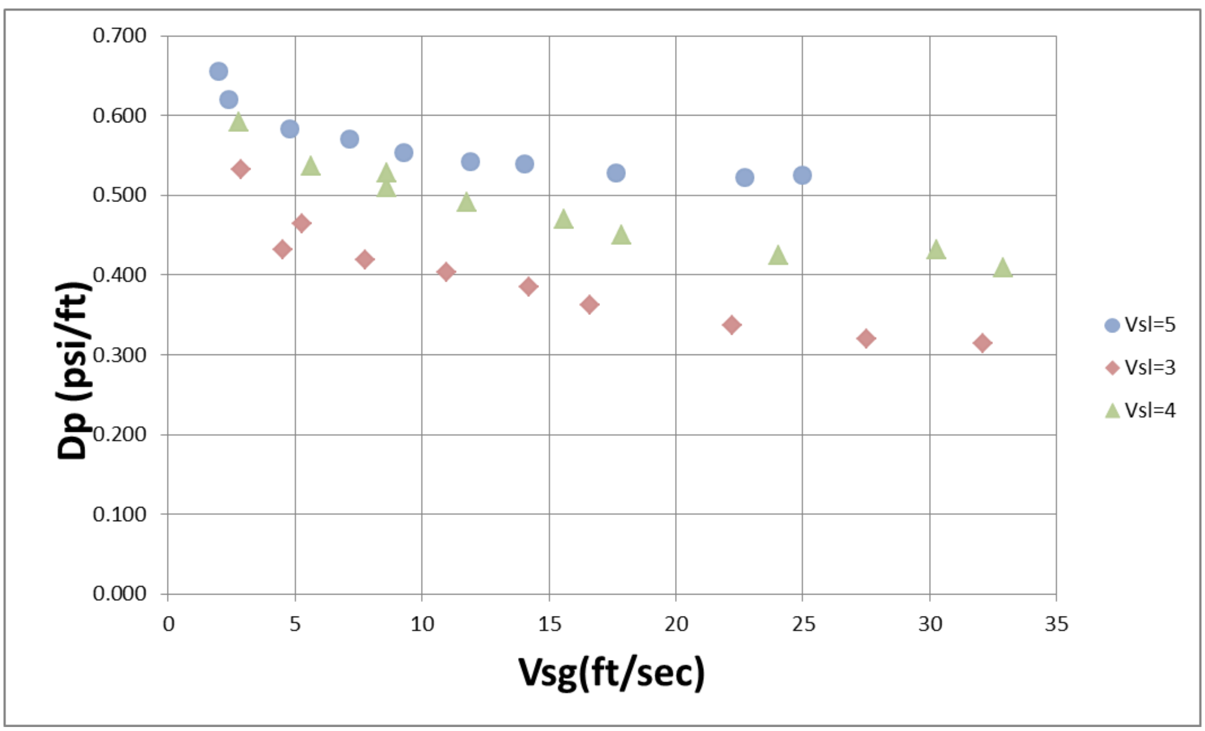

Fig. 10-Measured Pressure Drop vs. Gas Superficial Velocity in Nearly Vertical Test Section (θ=12.5), RPM=80 (1/min) and ROP=80 (ft/hrs)

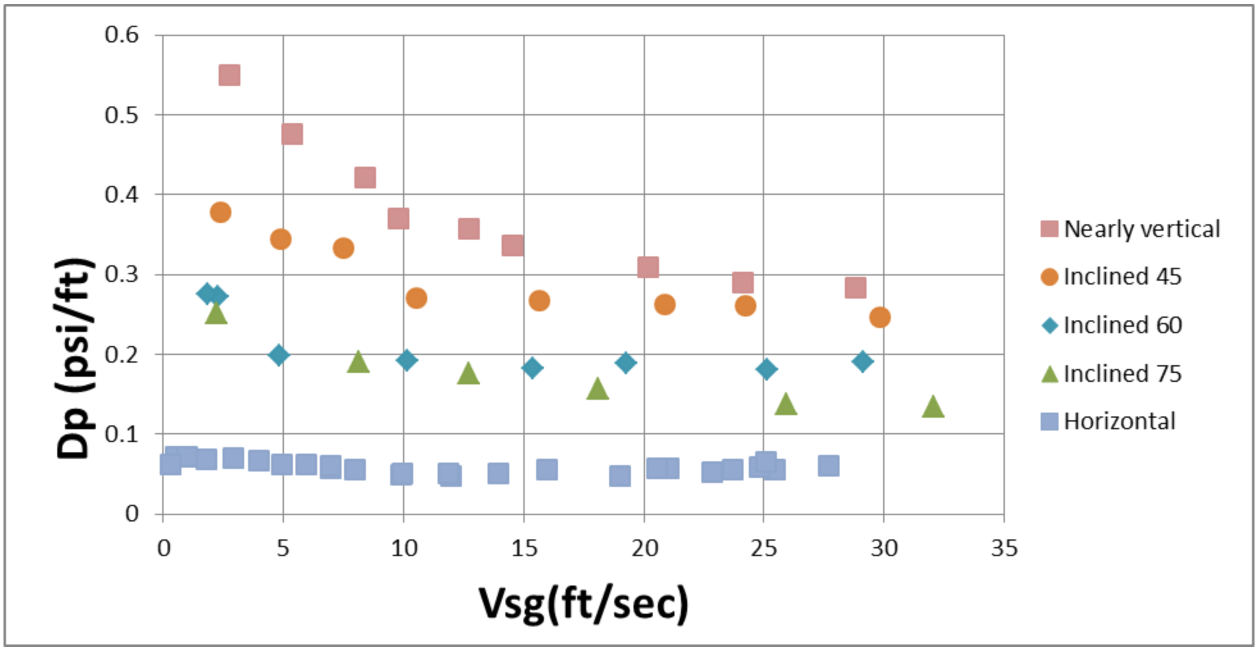

Fig. 11-Measured Pressure Drop vs. Gas Superficial Velocity in Nearly Vertical (θ=12.5) and Inclined (θ=45.0, 60.0&75.0) Test Section for VSL=2.0 (ft/sec), RPM=120 (1/min) and ROP=120 (ft/hrs)

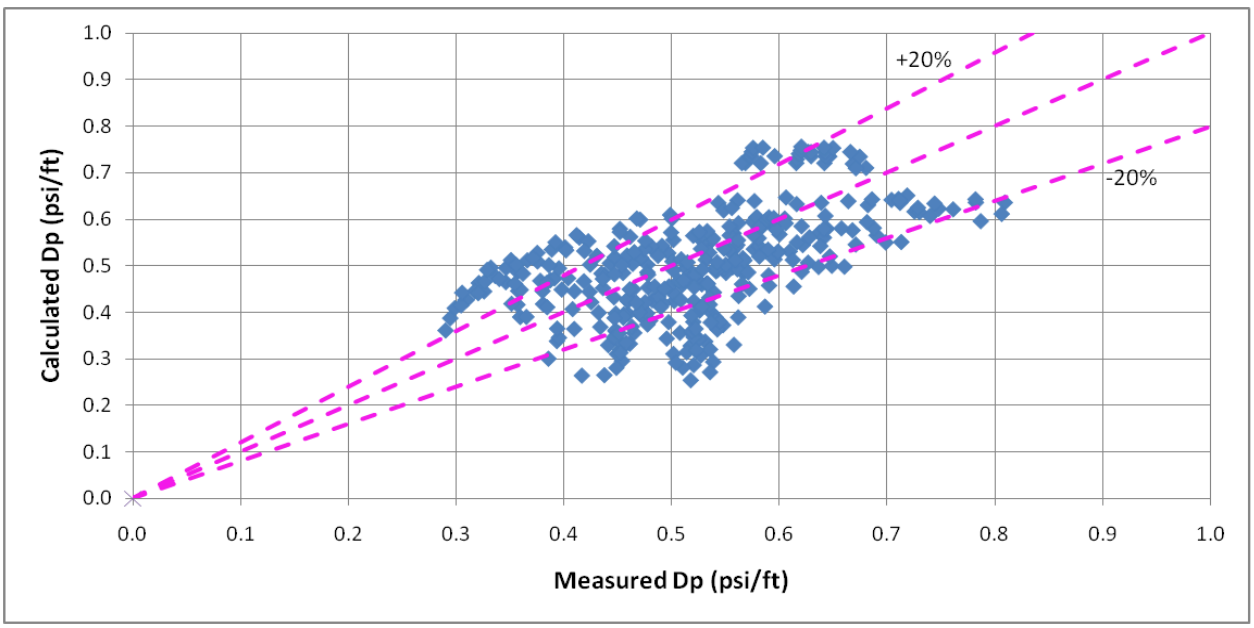

Fig. 12-Measured and Predicted Pressure Drop vs. Gas Superficial Velocity by Mechanistic Model vs. Gas Superficial Velocity for VSL=2.0, 3.0, 4.0,5.0(ft/sec), ROP=80,100,120(ft/hrs), RPM=80,100,120 (1/min) for Nearly Vertical (θ=77.5) Water-Air and Cutting Three Phases Flow in Eccentric Annuli with Inner Pipe Rotation by Using Developed Mechanistic Method

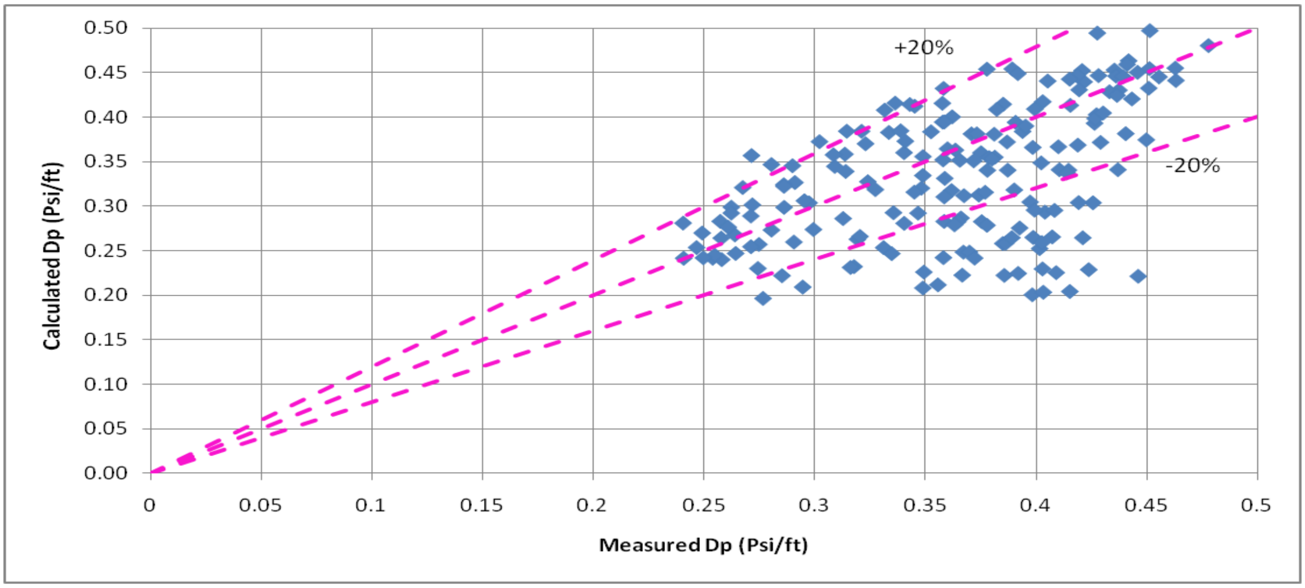

Fig. 13-Measured and Predicted Pressure Drop vs. Gas Superficial Velocity by Mechanistic Model vs. Gas Superficial Velocity for VSL=2.0, 3.0, 4.0,5.0(ft/sec), ROP=80,100,120(ft/hrs), RPM=80,100,120 (1/min) for Inclined (θ=45.0) Water-Air and Cutting Three Phases Flow in Eccentric Annuli with Inner Pipe Rotation by Using Developed Mechanistic Method

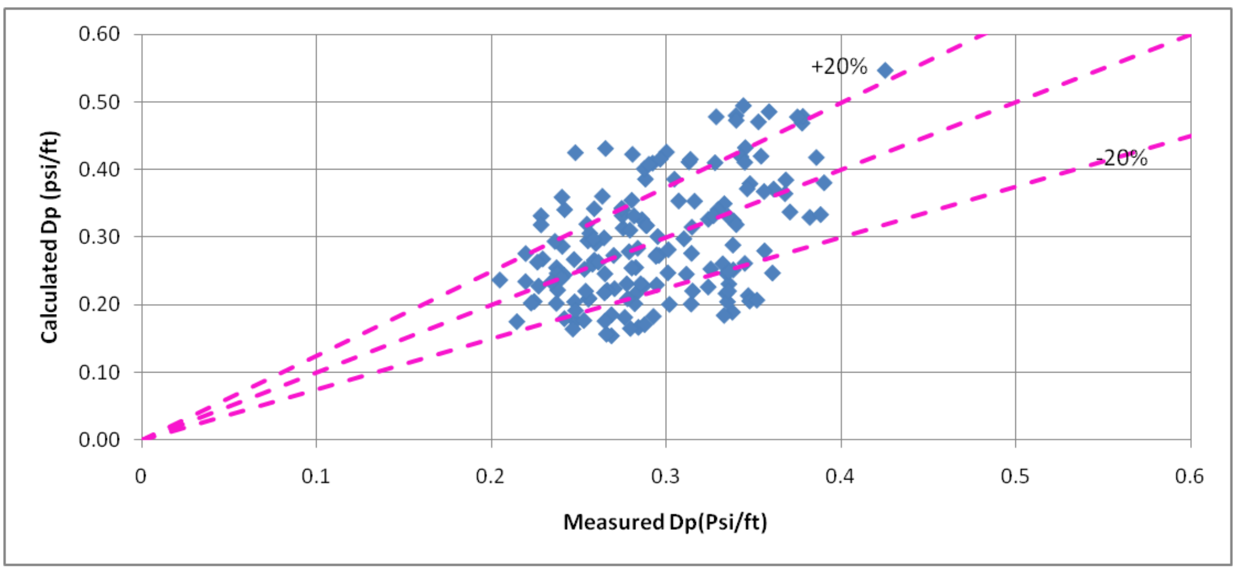

Fig. 14-Measured and Predicted Pressure Drop vs. Gas Superficial Velocity by Mechanistic Model vs. Gas Superficial Velocity for VSL=2.0, 3.0, 4.0,5.0(ft/sec), ROP=80,100,120(ft/hrs), RPM=80,100,120 (1/min) for Inclined (θ=60.0) Water-Air and Cutting Three Phases Flow in Eccentric Annuli with Inner Pipe Rotation by Using Developed Mechanistic Method

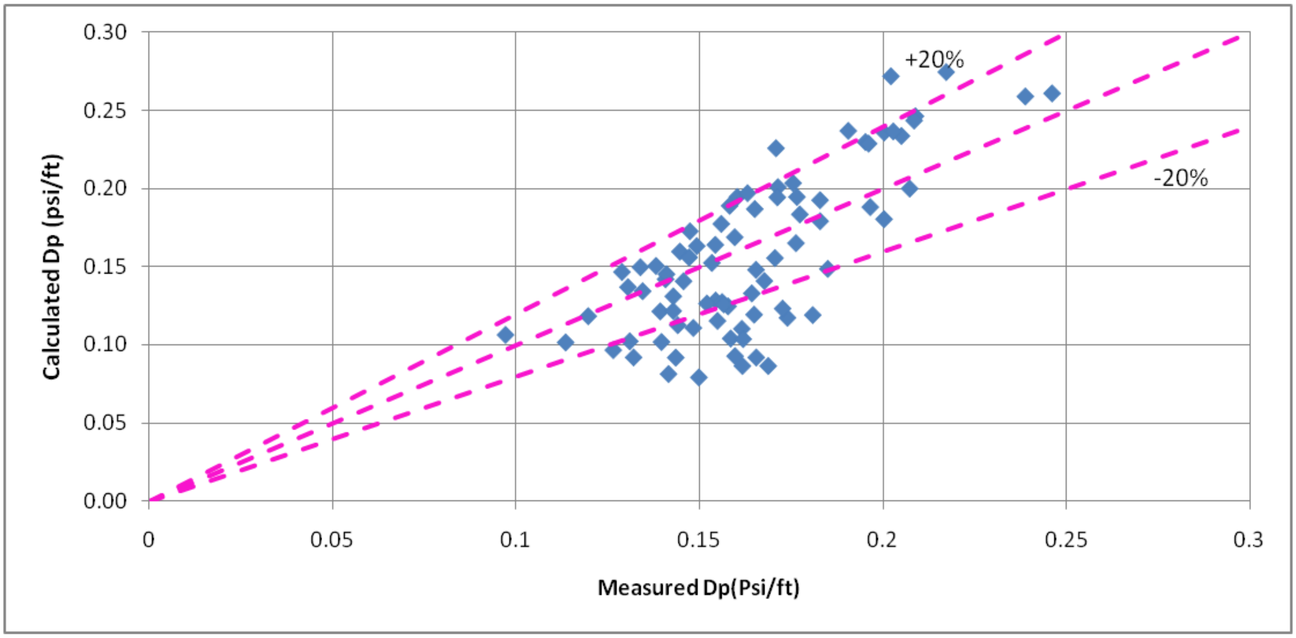

Fig. 15-Measured and Predicted Pressure Drop vs. Gas Superficial Velocity by Mechanistic Model vs. Gas Superficial Velocity for VSL=2.0, 3.0, 4.0,5.0(ft/sec), ROP=80,100,120(ft/hrs), RPM=80,100,120 (1/min) for Nearly Horizontal (θ=75.0) Water-Air and Cutting Three Phases Flow in Eccentric Annuli with Inner Pipe Rotation by Using Developed Mechanistic Method

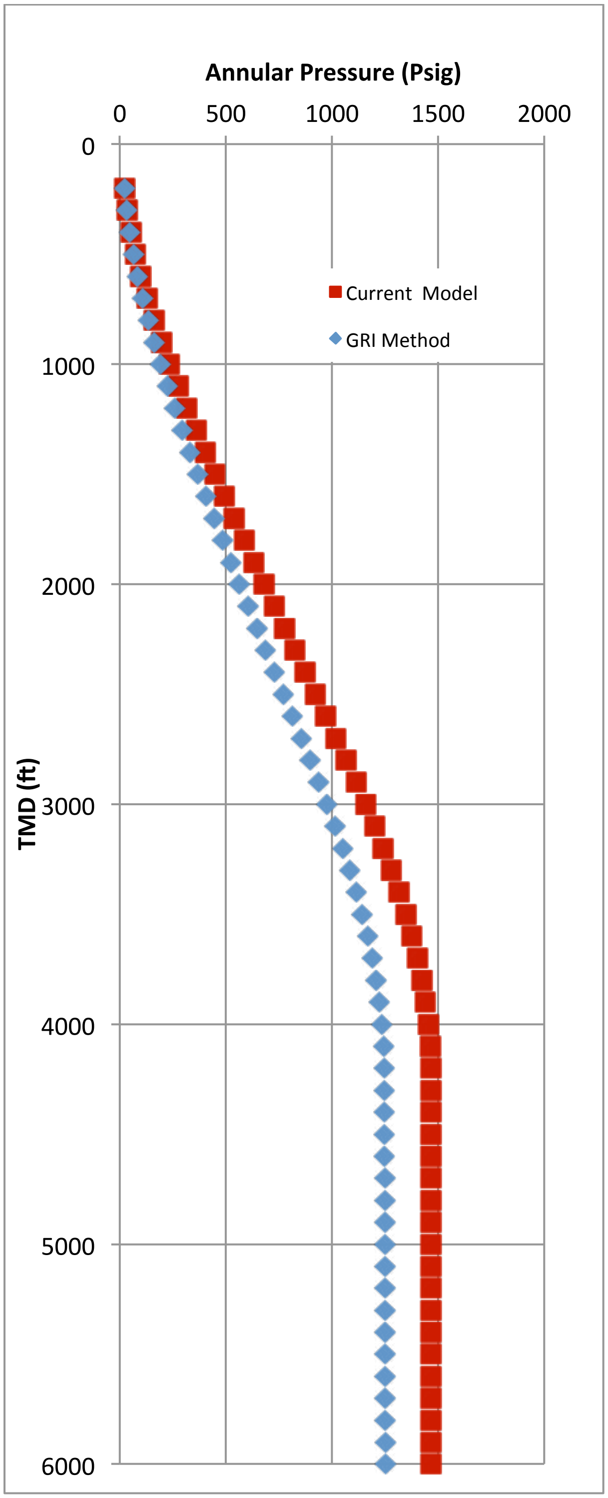

Figure 16- Comparison between the calculated annular pressure distribution by current study model and GRI method for directional well

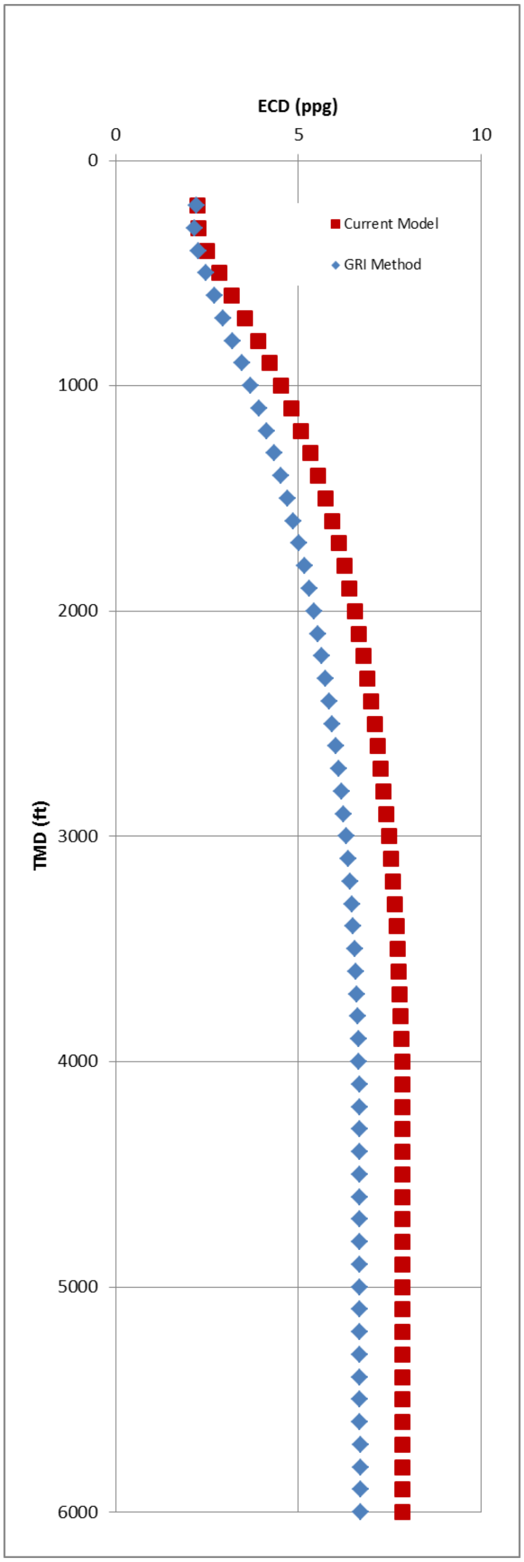

Figure 17- Comparison between the calculated ECD distribution by current study model and GRI method for directional well