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JIAFU XU*, EVREN OZBAYOGLU**, STEFAN Z. MISKA**, MENGJIAO YU**, NICHOLAS TAKACH**

CUTTINGS TRANSPORT WITH FOAM IN HIGHLY INCLINED WELLS AT SIMULATED DOWNHOLE CONDITIONS

TRANSPORT UROBKU WIERTNICZEGO PRZY UŻYCIU PIANY W SILNIE NACHYLONYCH OTWORACH W SYMULOWANYCH WARUNKACH W OTWORZE

Along with the rapidly growing demand and development activities in unconventional resources, is the growth of environmental awareness and concerns among the public. Foam, as an alternative to traditional drilling fluid, is gaining more and more momentum in the drilling industry. Drilling with foam can minimize formation damage, water usage, and drag and torque. Foam also costs less and leaves a much smaller environmental footprint than other commonly used drilling fluids, such as synthetic oil-based fluids, when developing vulnerable formations such as shale gas. As drilling in horizontal and near horizontal sections has become very common, and the need for such sections is increasing, it is very important to understand cuttings transport and hole cleaning issues when drilling with foam in such sections.

A team from University of Tulsa Drilling Research Projects (TUDRP) conducted a series of experiments focused on studying the effects of change in hole inclination angle from 90 degrees to 70 degrees on cuttings transport with foam under Elevated Pressure and Elevated Temperature (EPET) conditions. This experimental and theoretical study also includes other influential parameters such as foam quality, foam flow rate, polymer concentration and drill pipe rotary speed. We have observed that there is no significant difference in cuttings concentration and frictional pressure losses as inclination changes from 70 to 90 degrees. Also, an increase in superficial foam velocity reduces cuttings concentration within the annulus. Pipe rotation influences cuttings concentration and frictional pressure losses for low quality foams, but does not have a significant effect on high quality foams.

A correlation for the cuttings bed area and a computer simulator are developed for practical design and field applications. The predicted results are compared with experimental results from this study and previous studies. The comparison shows good agreement.

We believe that the findings of this paper will help designers with the choice of optimal drilling fluid for drilling horizontal wells in unconventional (shale) gas/oil reservoirs.

Keywords: foam, rheology, cuttings transport, high inclination, horizontal drilling, high pressure high temperature

* THE UNIVERSITY OF TULSA, NOW WITH SR. PRODUCT ARCHITECT, IHS GLOBAL INC., 17177 PRESTON ROAD – SUITE 200, , DALLAS, TX, 75248, USA

** THE UNIVERSITY OF TULSA, MCDOUGALL SCHOOL OF PETROLEUM ENGINEERING, 800 S TUCKER DR. TULSA OK 74104 USA

Równolegle ze stale rosnącym zapotrzebowaniem na prowadzenia prac udostępniających w złożach niekonwencjonalnych notuje się wzrost świadomości społecznej odnośnie zagadnień ochrony środowiska. Piana jako alternatywa dla tradycyjnej płuczki wiertniczej nabiera coraz większego znaczenia w górnictwie otworowym. Wiercenie przy użyciu piany pomogą ograniczać zniszczenia formacji geologicznych, redukuje zużycie wody, pozwala na zminimalizowanie oporów ruchu i momentów obrotowych silników. Ponadto, koszty piany są niższe a jej oddziaływanie na środowisko naturalne jest mniej znaczne niż w przypadku typowych płuczek opartych na olejach syntetycznych używanych w trakcie udostępniania trudnych w eksploatacji złóż, np. gazu łupkowego. Wiercenia odcinków poziomych lub prawie poziomych są już szeroko stosowane a zapotrzebowanie na takie odcinki wrasta, ważnym jest właściwe rozpoznanie problemów związanych z transportem urobku wiertniczego i czyszczeniem otworu w trakcie prowadzenia prac wiertniczych na tych odcinkach przy użyciu piany.

Zespól badaczy z uniwersytetu w Tulsa zaangażowanych w projekt badawczy w dziedzinie wiertnictwa (TUDRP) przeprowadził serię eksperymentów mających na celu zbadanie wpływu zmiany kąta nachylenia otworu z 90 na 70 stopni na przebieg transportu urobku wiertniczego z wykorzystanie piany w warunkach podwyższonego ciśnienia i podwyższonych temperatur. Badania eksperymentalne i teoretyczne obejmowały także analizę pozostałych parametrów procesu: jakość piany, natężenie przepływu piany, stężenie polimerów, prędkość obrotowa przewodu wiertniczego. Nie stwierdzono znacznych różnic w stężeniu zwiercin ani utraty ciśnienia wskutek tarcia w trakcie zmiany kąta nachylenia z 90 na 70 stopni. Ponadto, dodatkowy wzrost prędkości ruchu piany prowadzi do zmniejszenia stężenia zwiercin w pierścieniu. Prędkość obrotowa przewodu wpływa na stężenie zwiercin i straty ciśnienia wskutek tarcia w przypadku stosowania pian niskiej jakości, efektu tego nie notuje się gdy wykorzystywane są wysokiej jakości piany.

Dane z obszaru wiercenia skorelowane zostały z wynikami symulacji komputerowych do wspomagania projektowania i do wykorzystania w terenie. Prognozowane wyniki porównano z wynikami eksperymentów uzyskanymi w tym oraz w poprzednim programie badawczym. Porównanie to wykazuje dużą zgodność wyników.

Mamy nadzieję, że wyniki obecnej pracy pomogą inżynierom projektantom w wyborze optymalnej płuczki wiertniczej do wierceń poziomych odcinków otworów przy eksploatacji niekonwencjonalnych złóż ropy i gazu (np. gazu łupkowego).

Słowa kluczowe: piana, reologia, transport urobku wiertniczego, nachylenie, drążenie odcinków poziomych, wysokie ciśnienie, wysoka temperatura

1. Introduction

Foam has been used as a drilling fluid in many drilling operations, especially in underbalanced drilling applications. In many cases, drilling with foam has shown to provide significant benefits, including increased productivity (by reducing formation damage), increased drilling rate, reduced operational difficulties associated with drilling in low pressure reservoirs (e.g., lost-circulation and differentially stuck pipe), and improved formation evaluation while drilling. One of the other major applications of foam as a drilling fluid is drilling in shales. As known, significant drilling costs attributed to shale instability problems have been reported in the literature. The major causes of shale instability are stress changes compared to shale strength environments, shale / fluid interactions, capillary pressure, osmotic pressure, borehole fluid invasion into shale, etc. In order to minimize shale instability, proper selection and maintenance of mud weight, effective control of equivalent circulating density, and selection of borehole fluid that is compatible with the formation being drilled are very important. Since conventional hydrocarbon sources are depleting fast, unconventional hydrocarbon sources are becoming very important to access in order to in order to compensate the growing energy demand (Patzek, 2010). One of these unconventional energy sources is oil/gas in shales. Because the gas/oil in shale formations is aimed for production, excessive borehole pressures while drilling will cause very significant problems during the production stage. Therefore, at-balance, or preferably, underbalanced conditions should be achieved. Since foam has lower density compared to conventional water-based systems, and has a significant stability when required additives are used, it becomes a good alternative for drilling shale formations with gas. However, shale formations have very low permeability and in order to produce gas/oil from such formations, the contact area of the wellbore with the formation should be maximized. One of the ways of achieving this is drilling horizontal wells. Unfortunately, within the horizontal sections hole cleaning is a challenge and proper circulation conditions must be achieved in order to drill and clean these sections successfully. This paper aims to address this issue.

2. Literature Review

Foams consist of a continuous liquid phase, forming a stable cellular structure that surrounds and entraps a gas phase. Special chemicals, called surfactants, are used to capture the gas phase, at least for a desired period of time. Foams are considered to be dry or wet, depending on the gas content. Wet foams have spherical bubbles with a large amount of liquid between the bubbles, and dry foam bubbles are polyhedral in shape, with contact between the bubbles. In between these two extremes, geometrical structures having both curved and flat faces can exist. Foams are thermodynamically unstable systems because they always contain more than a minimal amount of gas solution interface (Herzhaft et al., 2000). This interface represents surface free energy, the amount of which can be estimated from knowledge of the surface tension and the interfacial area of the foam. Wherever a foam membrane breaks and the liquid coalesces, there is a decrease in surface free energy. Thus the decomposition of foam into its constituent phases is a spontaneous process. Since the solution phase is always denser than the gaseous phase, there is a strong tendency for the liquid to separate or drain from the main body of foam unless it is circulated or agitated in some way. Foams can have extremely high viscosity. In all instances, their viscosity is greater than the viscosities of either the liquid or the gas that they contain (GRI, 1997). At the same time, foram densities are much lower than the density of water. Foams are stable at high temperatures and pressures. So, by using foam as a drilling fluid, its high viscosity allows efficient cuttings transport and its low density allows underbalanced conditions to be established; thus formation damage is minimized. Foams are also preferred when water influx is a problem because they can handle large amounts of water.

Cuttings transport studies in horizontal and high-angle wells were initially focused on developing semi-empirical equations and the effects of drilling parameters such as rate of penetration, flow rate, fluid properties, mud density, inclination, cuttings size, eccentricity, etc. (Tomren, 1979; Iyoho, 1980; Becker, 1987; Larsen, 1990; Jalukar, 1993; Sanchez et al., 1997). Later, researchers attacked the problem by developing mathematical models. Two-layered and three-layered mechanistic models were developed using certain assumptions (Clark & Bickham, 1994; Gavignet & Sobey, 1996; Nguyen & Rahman, 1996).

Cuttings transport using foam in horizontal and inclined wellbores has been investigated in the past both experimentally and theoretically. A brief summary of critical work on cuttings transport with foam in horizontal and highly inclined wellbores is presented below.

Extensive experimental work was conducted that considered foaming-agent selection and optimum concentration, salt/oil contaminants, rheological characterization of foams, development of a flow loop to test the foam-carrying capacity in high-angle wells, definition of the test procedure and matrix, and analysis of the results (Martins & Lourenco, 2001). After 60 bed tests were performed in a cuttings-transport flow loop, correlations were proposed to predict the cuttings-bed erosion capability in horizontal wells as functions of the foam quality and the mixture's Reynolds number.

Using the principles of mass and linear momentum conservation, a model consisting of three layers (motionless bed – observed in most experiments, moving foam-cuttings mixture and foam free of cuttings) was presented (Ozbayoglu et al., 2003). As part of this study, cuttings transport experiments were conducted at inclinations of 70-90 degrees for a wide range of foam flow velocities and ROPs. At a given flow rate and rate of penetration, bed thickness increases with an increase in foam quality. There is little effect of inclination angles within the considered range.

In another study, a one-dimensional, unsteady-state, two-phase mechanistic model of cuttings transport with foam in horizontal wells was developed (Li & Kuru, 2003). In this model a new critical deposition velocity correlation for foam-cuttings flow is introduced. The model is solved numerically to predict cuttings bed height as a function of the drilling rate, the gas and the liquid injection rates, the rate of gas and liquid influx from the reservoir and the borehole geometry.

A critical foam velocity correlation has been proposed to predict the minimum foam flow rate required to remove or prevent the formation of stationary cuttings beds on the low-side of highly deviated and horizontal wells (Li & Kuru, 2004). The effects of key drilling parameters (i.e. drilling rate, annular geometry, foam quality, bottomhole pressure and temperature) on the critical foam velocity were investigated.

Horizontal foam-flow behavior in pipes and annular geometry under elevated pressures and temperatures was presented (Lourenco et al., 2004). The study is empirically-based and covers the effects of foam quality, foam texture, pressure, temperature, and geometry of the conduit on the rheological response of foams. This study is important since it is the first experimental work on foam flow under high pressure – high temperature conditions.

An experimental study of cuttings transport with foam at intermediate angles was conducted in the TU-LPAT flow loop using an anionic surfactant to determine the effects of inclination angle, foam quality, foam velocity and rate of penetration (ROP) on cuttings transport (Capo et al., 2006). It is shown in this study that the transport of cuttings (in terms of cuttings concentration) improves when using foams of low quality. Also, inclination and ROP have a direct impact on in-situ cuttings concentration.

Cuttings transport experiments were carried out at elevated pressures (100 to 400 psi) and temperature (80 to 170°F) conditions on the TU-ACTF flow loop using foam and hydroxylethylcellulose polymer (HEC) mixtures with various liquid, gas and cuttings injection rates (Chen et al., 2007). Two flow patterns, stationary cuttings bed and fully suspended flow, were observed during the cuttings transport tests. The flow patterns depend on polymer concentration, foam quality, and annular velocity.

The TU-ACTF was used to investigate the effects of pipe rotation, foam quality and velocity, and downhole pressure and temperature on cuttings transport and pressure losses in a horizontal wellbore (Duan et al., 2010). Experiments were conducted with backpressures from 100 to 400 psi and temperatures from 80 to 160°F. Pipe rotary speeds were varied from 0 to 120 RPM, with foam qualities ranging from 60 to 90% and foam velocities from 2 to 5 ft/sec. It was found that pipe rotation not only significantly decreases cuttings concentration in a horizontal annulus but also results in a considerable reduction in frictional pressure loss.

The present study focuses on cuttings transport with foam enhanced with polymers in highly inclined wells (70-90 degrees) under elevated temperature and pressure conditions, and includes the effects of pipe rotation.

3. Experimental Setup

The experimental work was mostly conducted with the Advanced Cuttings Transport Facility (ACTF). The ACTF (Fig. 1) is a field-scale facility designed and built by TUDRP to carry out experimental research for fluid flow and cuttings transport under simulated downhole conditions. It has the ability to simulate elevated pressure and elevated temperature up to 2000 psi and 200°F. It also has the ability to simulate cuttings transport at hole inclination angles of 60-90 degrees. Cuttings are injected into the system to simulate the drilling process. By controlling and measuring the injection rate of cuttings we can calculate the corresponding ROP.

Fig. 1. Photo of Advanced Cuttings Transport Facility

The rheology of the drilling fluid is widely believed to have an important impact on cuttings transport (Okranji, 1981; Hareland, 1985; Meano, 1987). In our study, 13 rheology tests were conducted on the ACTF for foam with different qualities and polymer concentrations to study their effects on cuttings transport. The rheology tests were conducted using a series of pipes of the ACTF that have different inner diameters . The pressure differences from the upstream to the downstream end of each pipe were measured when the test foam flowed at different flow rates. By analyzing calculated wall shear stress versus Newtonian wall shear rate, a proper rheology model can be chosen and corresponding parameters can be calculated.

In all, 25 cuttings transport experiments were run with test conditions of 200 psi, 115°F, simulated ROP of 30-80 ft/hr and pipe eccentricity of 0.78. The experiments cover the following variables in different levels:

- Polymer concentration: 0.25% and 0.5%;
- Foam quality: 70%, 80% and 90%;
- Hole inclination angle: 70, 80 and 90 degrees;
- Drill pipe rotary speed: 0, 40 and 80 RPM;
- Foam superficial velocity in the annuli: 100, 150 and 200 GPM.

4. Experimental Results Analysis

Previous studies (Duan, 2007; Chen, 2005) suggest that foam under EPET may best be described as a Power Law fluid. They also suggest that foam rheology parameters vary with pressure, temperature, foam generation methods and many other factors. Thus, foam rheology should be obtained under conditions at which it is most likely used.

The wall shear stress and Newtonian wall shear rate are calculated from measured data in the rheology tests from this study. The data were taken using different qualities of foam, different polymer concentrations and different size of pipes. A wall shear stress versus Newtonian wall shear rate is plotted (Fig. 2). From this chart, it appears that the rheological difference of polymeric foam with polymer concentration of 0.25% and 0.5% is insignificant for foam quality from 70% to 90%. After the determination of true shear rates, and curve-fitting, it is observed that the Power Law model can be used for characterizing the rheological behavior of foams of different qualities. It is also observed that for a constant foam quality, polymer does not affected the rheological behavior significantly. This allows the investigator to conclude uniform rheo-

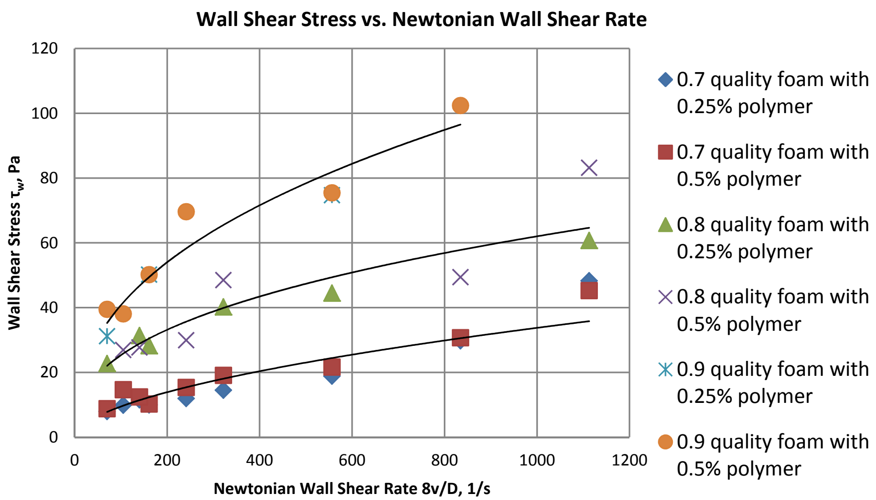

Fig. 2. Wall Shear Stress vs. Newtonian Wall Shear Rate for Different Quality Foam with Different Polymer Concentration

logical parameters for both 0.25% and 0.5% polymer concentration foams. Power Law model parameters for the foam in this study, despite the polymer concentration differences, are obtained as follows (Table 1).

TABLE 1

Rheological Parameters for Foam Used for Cuttings Transport in this Study

Foam Quality (%)	K (Pa.s)	n
70	0.662	0.4
80	4.01	0.388
90	6.058	0.406

The cuttings concentration and frictional pressure loss in the annular test section of the ACTF were measured in each test under elevated pressure and elevated temperature. The primary focus of this study is to investigate the influence of inclination for highly inclined wells. An investigation on the influence of foam quality, foam flow rate and drill pipe rotational speed is also conducted.

Fig. 3 shows the cuttings concentration versus hole inclination angle for 70% quality foam at flow rates from 100 GPM to 200 GPM. It appears that the influence of changing hole inclination angle from 90 to 70 degree on the cuttings concentration is insignificant. Similar results are observed for 80% and 90% quality foams. It can also be observed from Figure 3 that increasing foam flow rate from 100 GPM to 200 GPM reduces the cuttings concentration from 0.61 to 0.38, which suggests that increasing foam flow rate can significantly reduce the cuttings concentration.

Fig. 4 shows how cuttings concentration is influenced by the change of foam quality from 70% to 90% at same volumetric flow rate. It appears that for the same volumetric flow rate, as the foam quality increases, the cuttings concentration decreases.

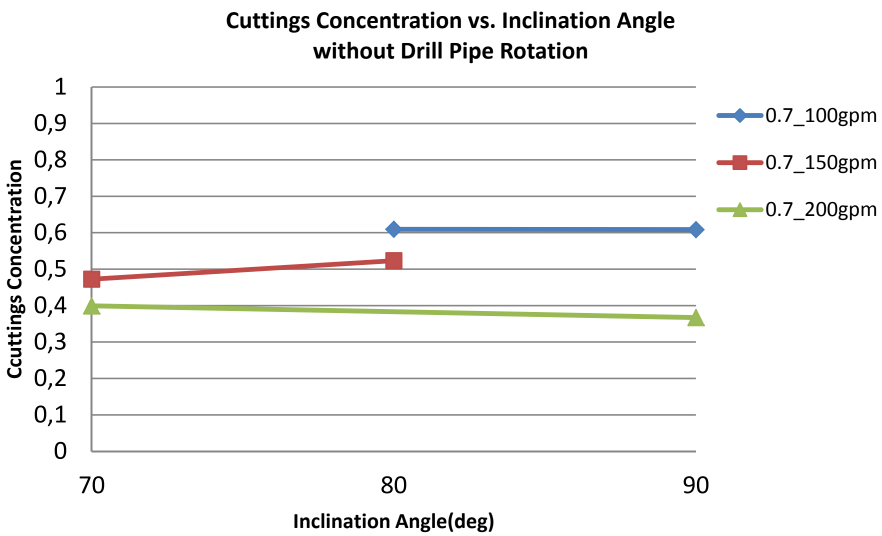

Fig. 3. Cuttings Concentration vs. Inclination Angle for 70% Quality Foam at Different Flow Rate

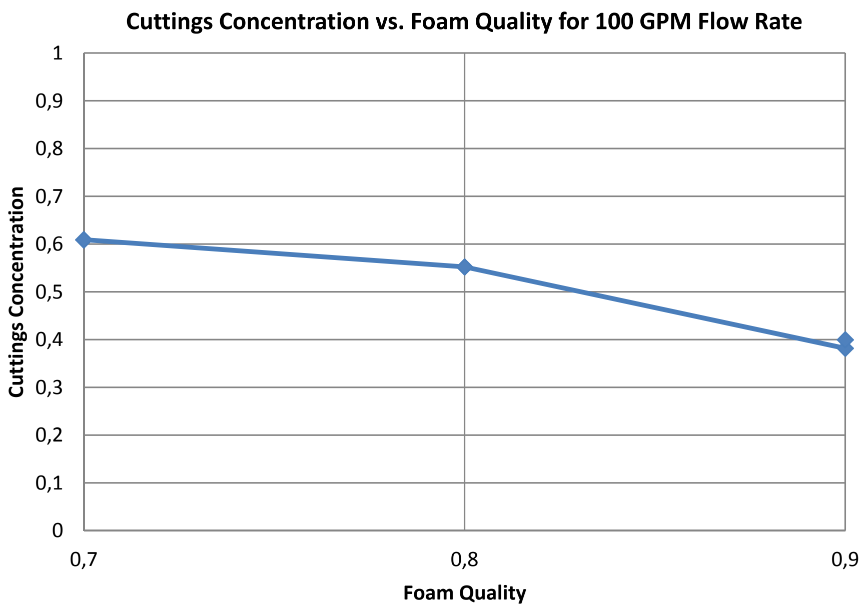

Fig. 4. Cuttings Concentration vs. Foam Quality for 100 GPM Foam Flow Rate

Figs. 5-7 show cuttings concentration versus drill pipe rotational speed for foam qualities of 70%, 80% and 90%, respectively. It appears that drill pipe rotation at different rotary speeds may reduce the cuttings concentration, depending on the foam quality and foam flow rate. The higher the drill pipe rotational speed, the greater the reduction of cuttings concentration.

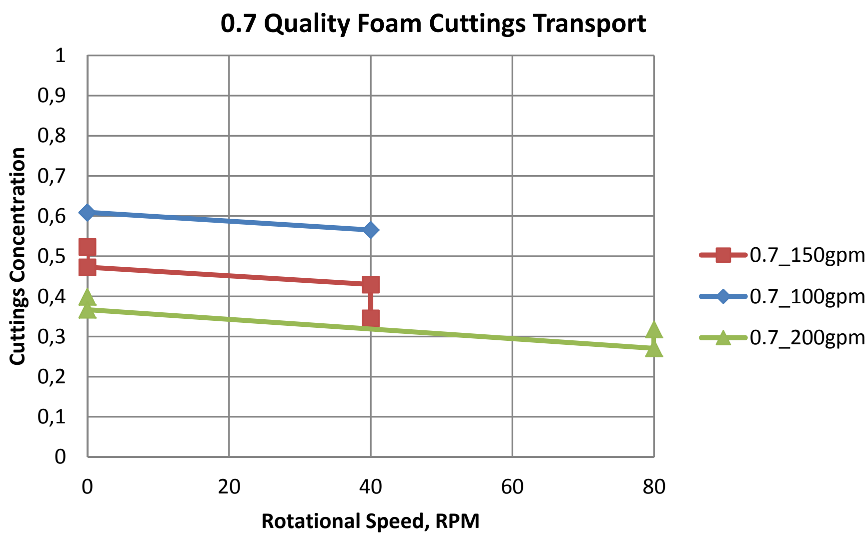

Fig. 5. Cuttings Concentration vs. Drill Pipe Rotational Speed for 70% Quality Foam

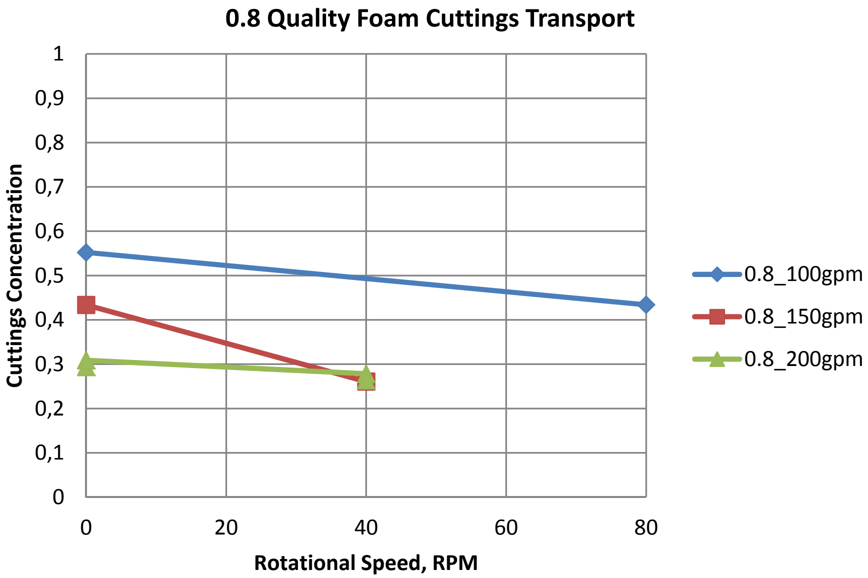

Fig. 6. Cuttings Concentration vs. Drill Pipe Rotational Speed for 80% Quality Foam

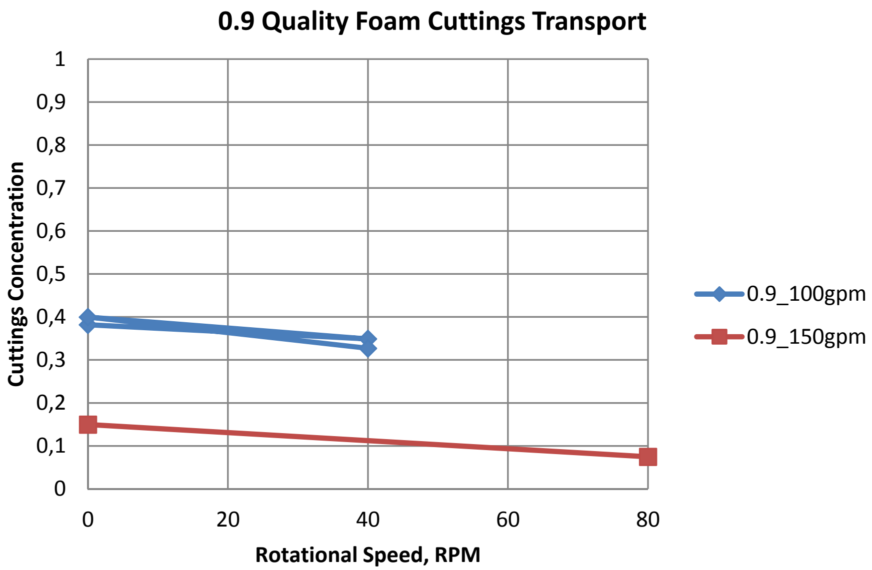

Fig. 7. Cuttings Concentration vs. Drill Pipe Rotational Speed for 90% Quality Foam

However, the total reduction of cuttings concentration is only up to 15% and, thus, not very significant. This observation agrees with the previous study (Duan, 2007) regarding the drill pipe rotation effect on cuttings transport with foam.

The frictional pressure loss in the annular section is influenced by the volumetric flow rate, foam rheology and wellbore geometry. With a given wellbore diameter, drill pipe diameter and drill pipe eccentricity, the cuttings bed thickness is the major parameter that influences the wellbore geometry and foam in-situ velocity. Note that inclination angle change from 90 to 70 degrees has a limited effect on cuttings concentration. Inclination angle also has no significant influence on frictional pressure loss.

Fig. 8 shows the frictional pressure loss gradient versus inclination angle. It can be observed that not only the inclination angle, but the flow rate from 100 GPM to 200 GPM has a limited effect on frictional pressure loss for a given foam quality. One explanation might be that as flow rate increases, there is a reduction in the cuttings concentration and cuttings bed height. The flow area for foam increases with the reduction of cuttings bed. With the particular foam generated in this investigation, in a certain range of the foam flow rates and their corresponding cuttings bed heights, the foam flow appears to generate similar frictional pressure losses.

Figs. 9-11 show the frictional pressure loss gradient versus drill pipe rotary speed for foam qualities of 70%, 80% and 90%, respectively. Similar to the influence of drill pipe rotation on cuttings concentration, applying drill pipe rotation at different rotary speeds may have an influence on reducing the frictional pressure loss due to the decrease of cuttings concentration. The reduction for high quality foams at high flow rates is relatively small.

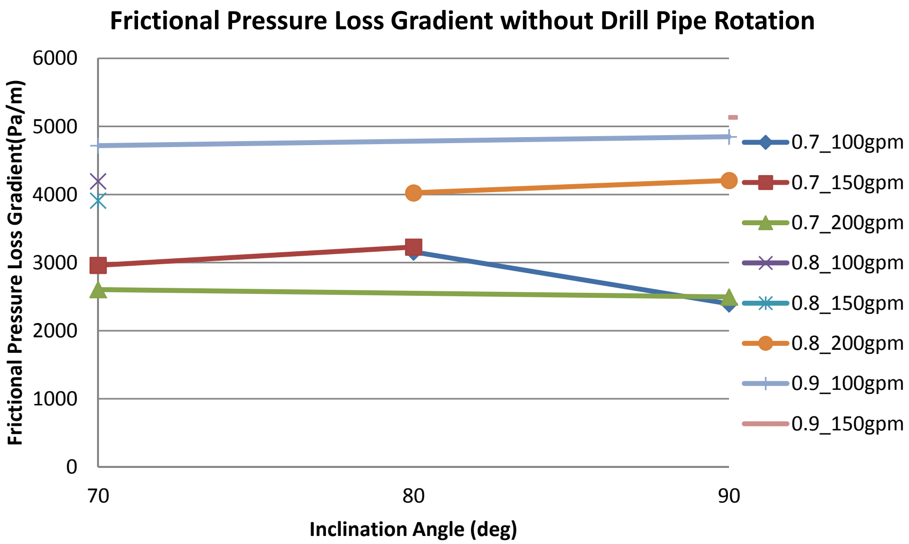

Fig. 8. Frictional Pressure Loss Gradient vs. Inclination Angle

5. Computer Simulation Results Comparison

A Cuttings Transport Simulator was developed based on the experimental results from this study and previous studies, and the modeling approaches are inherited from the work conducted by Duan (2007) and Ozbayoglu (2002). The simulator is capable of predicting cuttings concen-

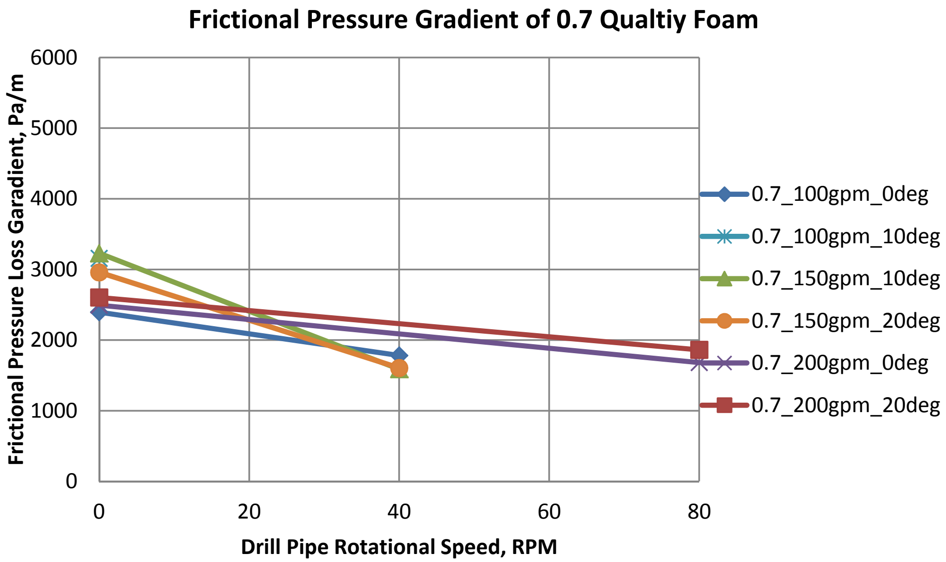

Fig. 9. Frictional Pressure Loss Gradient vs. Drill Pipe Rotational Speed for 70% Quality Foam

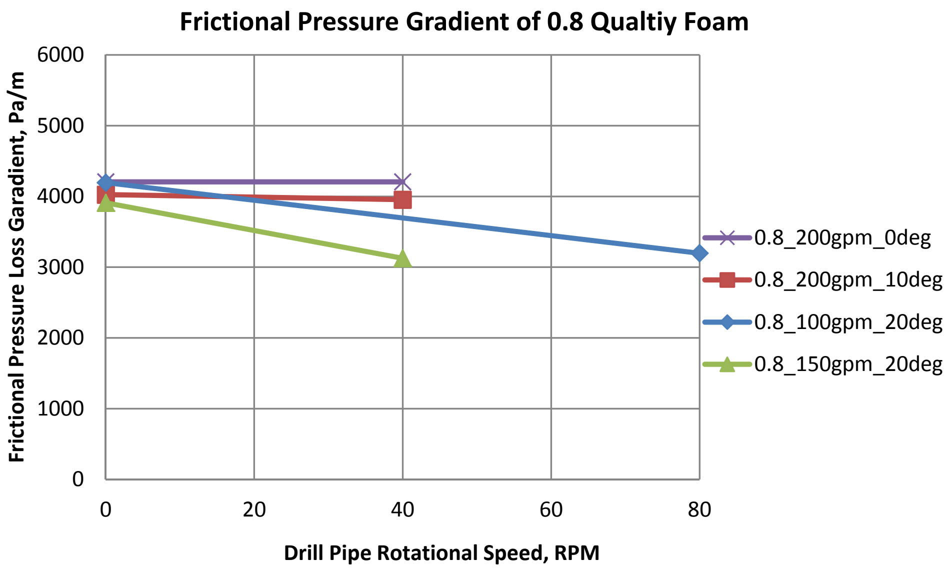

Fig. 10. Frictional Pressure Loss Gradient vs. Drill Pipe Rotational Speed for 80% Quality Foam

tration, cuttings bed height, frictional pressure loss gradient and foam in situ velocity by taking the input of wellbore geometry, gas and liquid flow rate, pressure, temperature, ROP, drill pipe rotation speed and wellbore inclination angle.

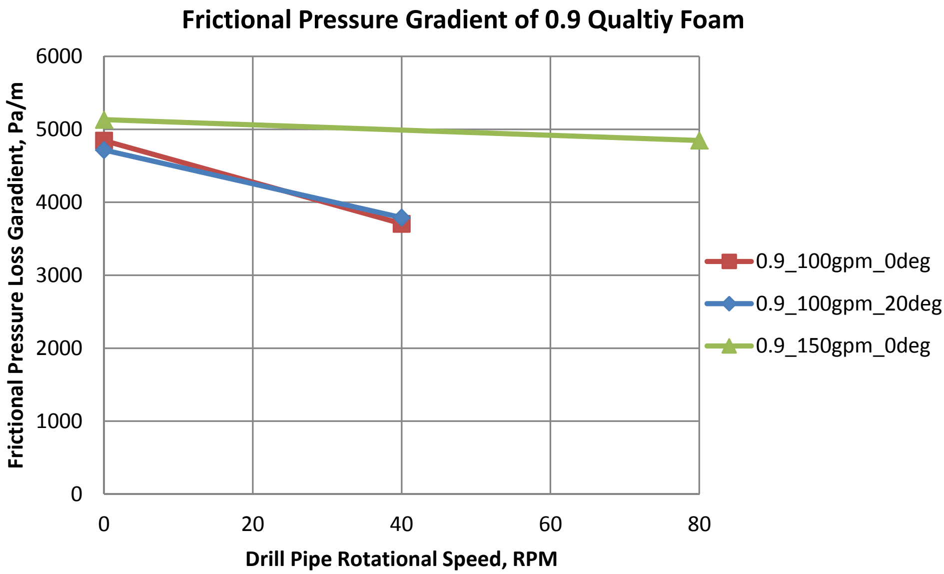

Fig. 11. Frictional Pressure Loss Gradient vs. Drill Pipe Rotational Speed for 90% Quality Foam

Fig. 12 shows the comparison between the simulator prediction and experimental results from this and previous studies (Duan, 2007; Chen, 2005; Ozbayoglu, 2002). The simulator gives reasonable predictions compared to the experimental measurements within the range of these investigations.

6. Summary

The results of this project provide a better understanding of cuttings transport with foam. Based on experimental observations and computer simulations, the following conclusions and recommendations are made.

1) Foam rheology tests on the ACTF support the assumption that foam is best described as a Power-Law model; and the higher the foam quality, the more viscous the foam.
2) The change in inclination angle from 90 to 70 degrees has a minor effect on both cuttings concentration and frictional pressure loss under elevated pressure and elevated temperature conditions.
3) Foam superficial velocity plays the dominant role in cuttings concentration. An increase in foam superficial velocity will reduce the cuttings concentration. Higher foam quality results in slightly lower cuttings concentration under EPET conditions. Drill pipe rotation in low quality foams at low flow rates can reduce cuttings concentration and frictional pressure loss but has a limited effect on high quality foams at high flow rates.

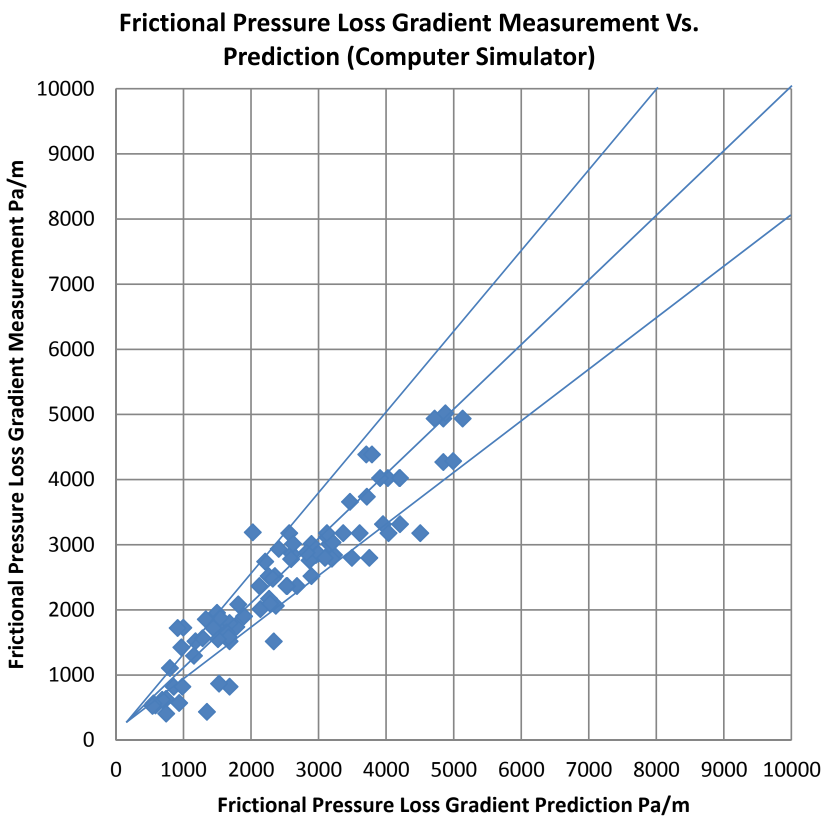

Fig. 12. Measured vs. Predicted Frictional Pressure Loss Using Previous Researcher's Data and Data from this Investigation

4) The computer simulator developed in this study is used for an extensive simulation to compare experimental results from this study and previous investigations. The predictions for the cuttings concentration have an average error of 27.05% and a standard deviation of 19.66%. The predictions for the frictional pressure loss have an average error of 15.91% and a standard deviation of 17.20%.

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