

Rheology of Oil-Based Drilling Foams

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Abstract

Formation damage can occur with water-based foams because of chemical interaction as well as spontaneous imbibition of water. This led to the development of oil-based foams. However, rheological properties of oil-based foams are not fully understood.

This paper presents results of an experimental study conducted on rheology of oil-based foams. The study was performed varying foam quality (34 to 68 percent). The base-liquid was a mixture of mineral oil, diesel oil and fluoro-surfactant. Experiments were carried out at 100 psi and ambient temperature ($80 \pm 3^\circ\text{F}$) using a flow loop that has the capability to generate and circulate foam. To identify the existence of wall-slip, tests were conducted using different diameter pipe viscometers (0.53, 0.77 and 1.25 inches ID), which are fully transparent to verify homogeneity of the foam. To minimize foam degradation during the test and maintain the same foam generating conditions at different flow rates, the foam was regenerated by circulating at the maximum flow rate before each flow measurement was made.

Experimental results show expected trends. Mean bubble size of oil-based foams increased with foam quality. Slight wall-slip was observed in 0.53-in. pipe viscometer. However, measurements obtained from 0.77-in. and 1.25-in. pipes did not display wall-slip. The foams exhibited strong non-Newtonian behavior, which increases with foam quality. Rheology of the foams best fit the power law model. Applying regression analysis, new correlations are developed to predict power law parameters of the foams.

1. Introduction

During underbalanced drilling (UBD), foam can be generated at the surface and then injected into the drillpipe; or its components may be injected into the drillpipe separately and foam generation occurs as the mixture flows down the drillpipe, bottomhole assembly (BHA) and drillbit. Perhaps the major advantage of foam, compared with other drilling fluids, is that it allows better control of equivalent circulating density (ECD). It is well known that proper wellbore pressure management is important not only for pore pressure control but also for wellbore stability. Excessive underbalance can lead to wellbore instability and collapse. Accurate wellbore pressure control is achieved by varying gas and liquid injection rates, base fluid rheology, and backpressure at the

surface. In-situ gas fraction (foam quality), which substantially influences foam rheology is a function of pressure and temperature. This creates strong coupling between borehole pressure and friction pressure loss. Hence, understanding flow behavior of foam is very critical for hydraulic and cuttings transport modeling and optimization. A number of studies¹⁻⁵ conducted on aqueous and polymer-based foams show significant increase in relative viscosity of foam (ratio of viscosity of foam to that of base liquid evaluated at the same shear rate) as the foam quality increases. Low quality foams and bubbly liquids (less than 60%) do not exhibit structure; and as a result, their relative viscosity is not high. Drilling is conducted using intermediate and high quality foams. Wet foams are generated in the intermediate quality range (i.e. between 60% and 90%). These foams display strong structure and viscosity to transport rock cuttings to the surface.

Currently, different types of foams (aqueous, polymer-based and oil-based foams) are being used in drilling, completion, and fracturing applications. Liquid component of oil-based drilling foam contains oil phase (mineral oil or diesel oil), surfactant and additives, which are introduced to improve foam stability and control liquid phase rheology. Air and nitrogen are common gases used in foam drilling. Often drilling foams have high quality. As a result, they are highly compressible and exhibit strong non-Newtonian behavior, which is strongly influenced by quality and base liquid rheology. The foam quality, Γ , at a given temperature and pressure is expressed as:

$$\Gamma(P, T) = \frac{V_G}{V_L + V_G} \dots \dots \dots (1)$$

where V_G and V_L are in-situ gas and liquid phase volumes, respectively.

2. Literature Review

UBD provides advantages such as minimizing lost circulation and differential sticking, increase in instantaneous drilling rate and limiting skin damage. However, it does have its own challenges. Major operational problems during foam drilling are: i) drilling water-sensitive formations; ii) temporary overbalance; and iii) foam stability. In water-sensitive formations, water molecules and ions can be transported by chemical potential difference even in

underbalanced condition. This results in formation damage and creates various drilling issues. In addition, in tight-gas reservoirs, formation damage can occur during foam drilling due to spontaneous imbibition.⁶ Efforts to circumvent these issues have resulted in the development of oil-based foams, which is used to great effect in these specific conditions.

2.1 Oil-Based Foams

Studies on oil-based foams are fairly recent and limited in number. Early field experiments⁷ on oil-based foam was conducted on foam fracturing in the Niobrara shale wells (Wyoming). Previous fracturing jobs in the area had been mostly unsuccessful leading to these specific field experiments. It was found that the use of oil-based foam improves the success rate of fracturing in shale formations. The study reactivated the field by significantly improving the production rate. The improvement was attributed to compatibility of the oil-based foam to water-sensitive shales.

Recently, different oil-based drilling and fracturing foams have been developed.⁸⁻¹¹ The foams have been adapted from most common non-aqueous base fluids, including diesel, mineral oil and native crude. Studies on these foams showed better control of fluid loss, preservation of formation permeability and improved drilling performance. Enhancement in drilling performance is achieved through reduction in fluid loss and differential sticking, and high rate of penetration.

Foam is thermodynamically unstable fluid. Stability of foam is critical during UBD operations. Liquid phase rheology and surface tension predominantly control stability and drainage behavior of foams under static condition. Viscosifying agents are added to the liquid phase to improve stability of drilling foam. Increase in liquid phase viscosity reduces foam drainage by hindering flow of liquid phase in the film. For successful drilling operations, it is necessary that foam exhibits high stability under downhole conditions and in presence of large amount of contaminants such as formation water and crude oil.

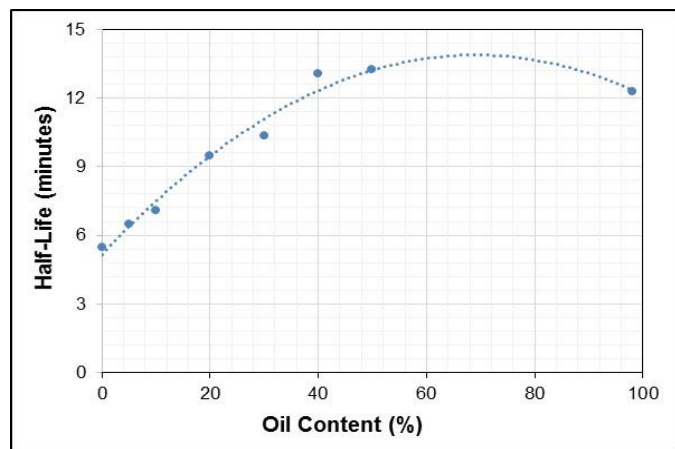


Fig. 1 Effect of mineral oil content on stability of diesel-based foams (redrawn from Ibizugbe⁷)

Stability of foam has great impact on its performance. Ibizugbe¹² investigated the drainage behavior of oil-based foams. The base-liquid considered contained mineral oil, diesel and 2% surfactant (nonionic fluorosurfactant). Addition of mineral oil up to 50% extended foam half-life substantially. However, above 50%, it did not improve the stability of foam (Fig. 1). In addition, results indicated that stability of oil-based foam is strongly affected by foam quality, liquid-phase rheology and surfactant concentration.

2.2 Foam Rheology

Rheological properties of foam are important to perform cuttings transport and hydraulic analysis for drilling and completion operations. Wellbore hydraulic models are based on well-known principles of conservation of mass, momentum, and energy. However, they cannot be solved without the constitutive equation that relates the shear stress with the resulting shear rate.

In the past, foam rheology studies^{2-4,13-16} were conducted, covering wide range of foam quality, liquid phase composition, temperature and pressure. Although there are some differences in the outcome of these investigations, it can be deduced that rheology of foam primarily depends on quality, liquid phase viscosity and texture (method of foam generation). Temperature strongly affects foam rheology by varying liquid phase viscosity.² Pressure effect can be direct (primary) or indirect (secondary). Due to compressibility of the gas phase, pressure has a direct impact on foam quality (i.e. primary effect), and subsequently, on its rheology. Secondary pressure effect accounts for change in foam rheology occurring at constant foam quality because of pressure variation. Experimental results² showed limited secondary pressure effect, which resulted in approximately 10% increase in frictional pressure loss for pressure increase of 650 psi.

2.3 Wall Slip

A number of studies^{2,17-20} indicated presence of wall-slip in foam flows. Wall-slip is believed to occur due to displacement of gas phase away from the pipe wall. It forms a thin liquid film at the wall. The film tends to lubricate the bulk flow.²¹ Because of the wall-slip, a higher shear rate (flow rate) is normally observed compared to if the slip was not present (Fig. 2). Nevertheless, in some foam rheology studies³⁻⁵ wall slip was not considered. This disparity exists because there is no definite method to identify wall slip in foam flows. There are several conditions during flow measurements such as foam instability and foam expansion, degradation and regeneration, which mimic indication of wall slip. A standard procedure for wall-slip determination involves measuring of foam rheology using pipe viscometers that have different internal diameters. For isothermal laminar flow of time-independent incompressible fluids in smooth pipe, it is theoretically shown that without wall-slip, pipe viscometers with different diameters should give a single flow curve (i.e. plot of wall shear stress vs. nominal wall shear rate) for a given fluid. Figure 2 shows typical flow curves (solid

lines), which demonstrate presence of wall-slip. The dotted curve in this plot represents a flow curve of the same fluid that would form without wall-slip. The gap between the solid lines and dotted curve shows the contribution of wall-slip to the nominal-Newtonian shear rate. In order to obtain accurate fluid rheology data, contribution of the wall-slip must be considered.²²

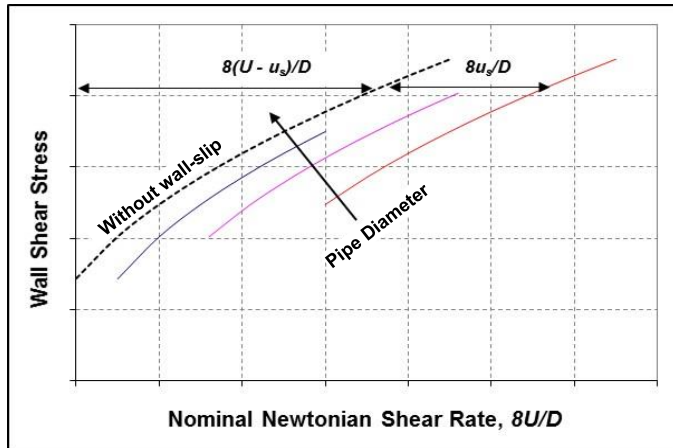


Fig. 2 Typical viscometric data indicating wall slip

2.4 Foam Bubble Size

Foam texture and bubble size vary with quality and method of foam generation. Effectiveness of foam generation method depends on efficacy of mechanical energy transfer to surface energy. An efficient generation method results in creating well equilibrated foam with finer bubbles. Even though there is no direct relation between foam bubble size and rheology, for given foam, increasing foam quality reduces available liquid volume in the foam system causing reduction in lamellae thickness and growth in bubble size. Only a few studies^{9,23-24} have been conducted on drilling foam bubble size. An experimental study²⁴ on aqueous foams indicated strong influence of foam quality on mean bubble diameter and bubble size distribution (Fig. 3). As the quality increased, the average bubble size increased substantially.

Bubble deformation is a common phenomenon occurring when foam is subjected to continuous deformation. Bubble size is considered as one of the major factors that affects degree of bubble deformation. During foam flows, significant change in bubble shape occurs depending upon the flow capillary number (Ca), which is used to quantify degree of bubble deformation. The capillary number, for Newtonian liquid-based foams flowing at a constant shear rate is given by:

$$Ca = \frac{r_b \mu_L \dot{\gamma}}{\sigma} \dots \dots \dots (2)$$

where r_b , σ and $\dot{\gamma}$ denote average bubble radius, interfacial tension and shear rate, respectively. μ_L is viscosity of the liquid phase, which is strongly affected by temperature. The capillary number compares the viscous forces that tend to

distort the bubble and interfacial tension, which favors sphericity.

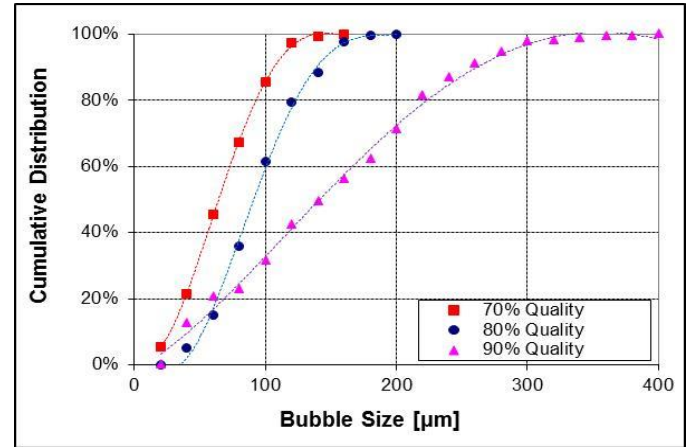


Fig. 3 Bubble size distributions of aqueous foams (redrawn from Chen et al.²⁴)

3. Experimental Setup and Procedure

In this study, rheology experiments were carried out to investigate flow behavior of oil-based foams. The foams were made of base-liquid containing 50% mineral oil, 48% diesel, and 2% surfactant. Base-liquid viscosity was 8.3 cP. A schematic of the loop used is shown in Fig. 4.

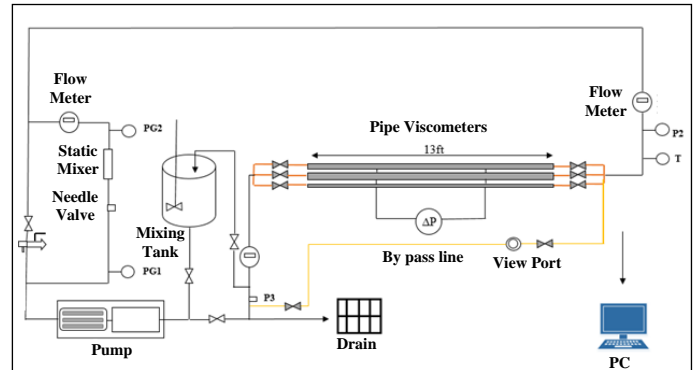


Fig. 4 Schematic of foam flow loop

The loop consists of: i) mixing tank to prepare base liquid for preparing foam; ii) parallel pipe viscometers; iii) foam generation system; iv) circulation pump (Moyno progressive cavity pump); v) visualization port; and vi) measurements and data acquisition system. The loop is equipped with instrumentation including flow meter, pressure and temperature sensors. During the experiments, test parameters were displayed and recorded. Detailed descriptions of the setup and test procedure are presented elsewhere.²⁵⁻²⁶

The foams were generated by circulating mixture of base liquid and gas phase through a foam generation system (Fig. 5) which consisted of: i) partially closed micrometer needle valve; and ii) two static mixers installed upstream and downstream of the valve. The downstream static mixer is fully transparent to monitor and maintain homogeneity of the foam.

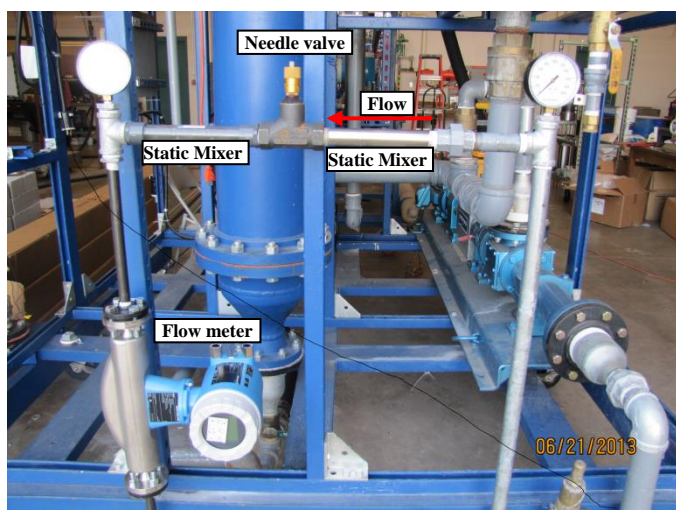


Fig. 5 Foam generation system

After foam generation, a Coriolis flow meter installed downstream of the transparent mixer measures flow rate and density of a homogeneous fluid. Non-homogeneous and unstable foam can easily be identified from flow meter readings. Surfactants play a great role in generating foam and maintaining stability of gas-liquid interface. In this study, 2% surfactant was added to the base-liquid to create relatively stable foam with static half-life of approximately 8 minutes, which is comparable with aqueous foam. To minimize effects of bubble coalescence and foam drainage on rheology measurements, foam was re-generated by circulating the fluid at the maximum flow rate before each measurement was made. Measured foam density was used to compute foam quality. Measurements were adjusted²⁵⁻²⁶ for density change occurring due to pressure variation in the flow loop.

Fully transparent parallel-pipe viscometers shown in Fig. 6 were used to conduct wall-slip investigation. Ball valves are installed at inlet and outlet of the viscometers to isolate the test section. The experiments were performed by circulating foam through a viscometer at a constant flow rate and measuring the corresponding differential pressure across the pressure ports. Other test parameters such as foam density and static pressure were also measured and maintained constant during the test.

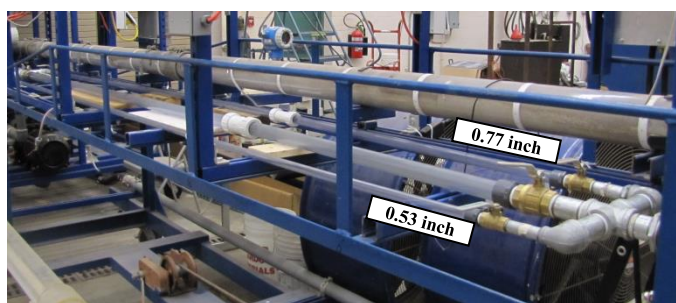


Fig. 6 Viscometers

After completion of the rheology measurements, the foam samples were trapped in the view port and quickly images

were taken (Fig. 7). These images were then processed and analyzed to determine bubble size distribution.

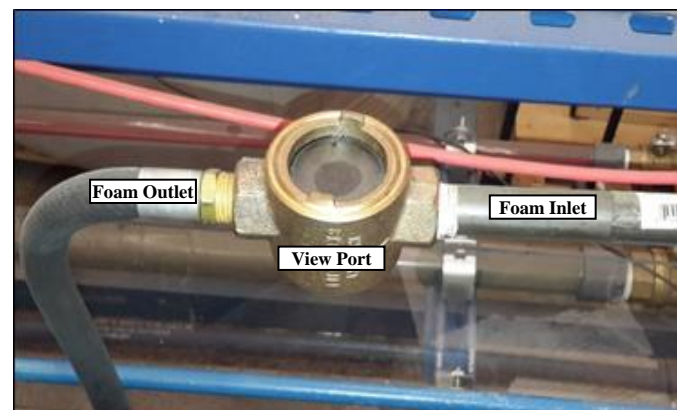


Fig. 7 Foam visualization port

4. Results and Discussion

4.1 Foam Bubble Size Analysis

Figure 8 shows the effect of quality on bubble size distributions of 40 and 60% foams. For other quality foams, the bubble-size distribution was too close to each other to make a definitive and informative distinction. This can be attributed to the coarsening of the foam after entrapment in the view port. Even though every effort was made to take pictures immediately after entrapment, the coarsening effect was somehow affecting the size distribution. In general, the mean bubble size increased with quality for low quality foams (34 to 50%). The trend is similar to that of aqueous foams generated²⁴ using a high-speed mixer.

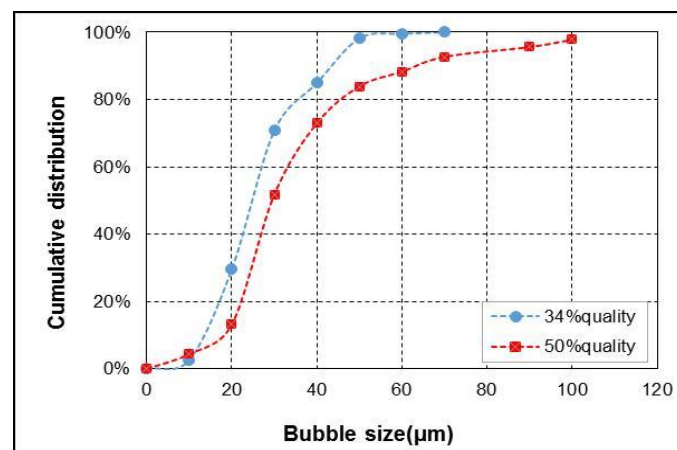


Fig. 8 bubble size distributions of the foams

4.2 Rheological Analysis

At high foam quality (68%), pressure loss measurements show strong shear thinning behavior of the foam (Fig. 9). This observation is consistent with shear thinning often observed in aqueous and polymer-based foams.

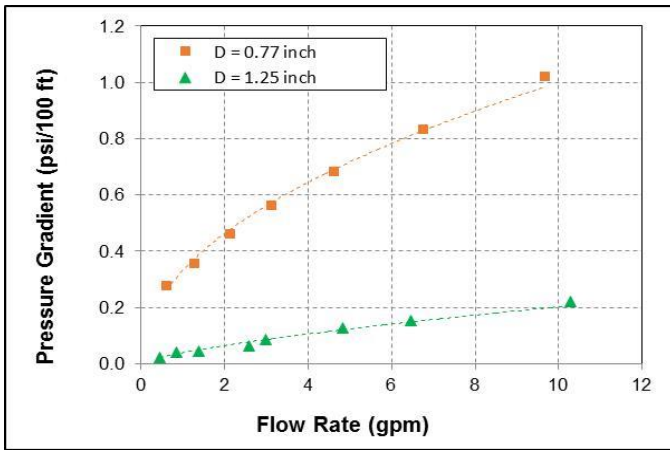


Fig. 9 Pressure loss vs. flow rate (68% quality foam)

Measurements obtained from 1.25-in. ID pipe at low flow rates (less than 3 gpm) display data scattering due to foam degradation while testing. Despite regeneration of foam before every flow test, low flow rate measurements were slightly varying while testing in this pipe.

The pressure loss and flow rate data were converted to wall shear stress and wall shear rate. Then, the flow curves on a logarithmic paper were prepared (Fig. 10). An appropriate rheological model that described the flow behavior of the foams was selected. It was found that the rheology of foams was best described by the power law model. Hence, the power law model parameters (n , K) of the foams were determined. These parameters were then used to calculate the generalized Reynolds number and determine the flow regime (laminar or turbulent). In Fig. 11, Fanning friction factor calculated from the measured pressure loss is presented as a function of Reynolds number. The friction factor is compared with the theoretical friction factor line for laminar flow (i.e. $f = 16/Re_G$). All data points lie on this line, indicating establishment of steady laminar flow in the pipe. The maximum Reynolds number was 1769.

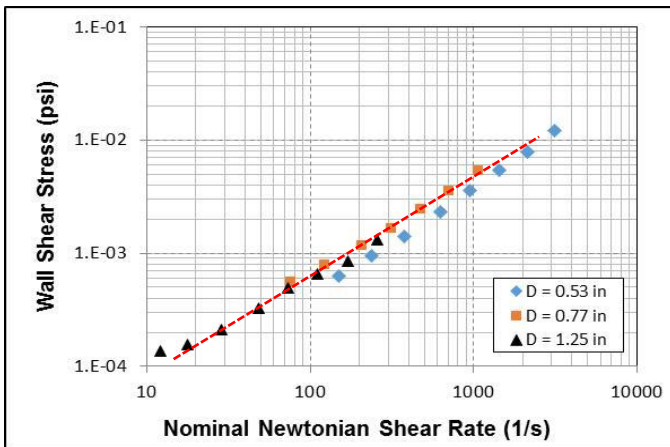


Fig. 10 Wall shear stress vs. shear rate (34% quality foam)

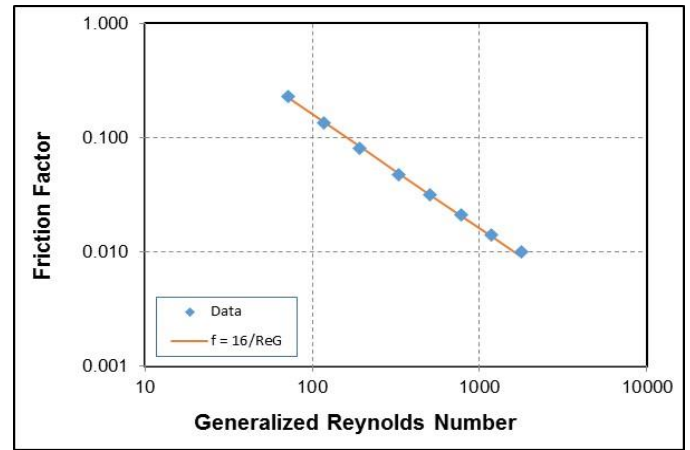


Fig. 11 Fanning friction factor vs. generalized Reynolds number (34% quality foam in 0.53-in. pipe)

Wall slip is observed in foam flow when thin-layer of liquid is formed at the pipe wall. As a result, higher shear rate is observed as compared to the true shear rate of the foam flowing in the pipe. In this study, the existence of wall slip was assessed by performing flow experiments in three different size pipe viscometers. The flow curves prepared from the data are plotted in Figs. 10 and 12 to identify presence of wall slip. The measurements obtained from the 0.77-in. and 1.25-in. pipes do not indicate wall-slip. However, data from the 0.53-in. pipe indicates moderate wall slip as demonstrated by a right shifting of flow curves of low quality foams (34 and 41%). Although a right shifting of a flow curve is often considered as an indication of wall slip, a similar shift can be observed due to other factors such as foam degradation while testing, slight foam quality variation associated with change in pipe size or viscous heating while testing.

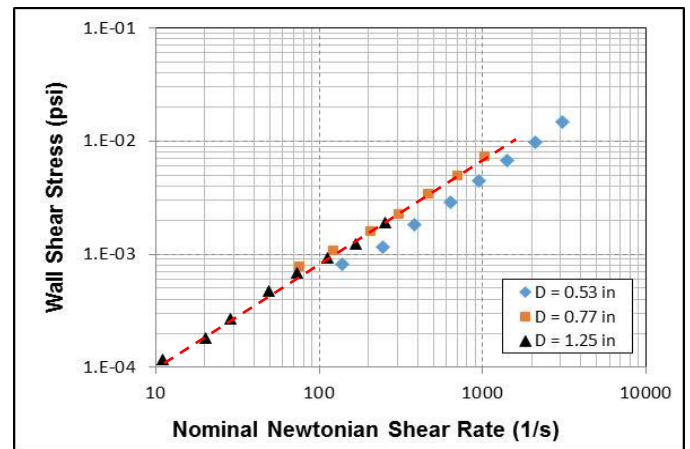


Fig. 12 Wall shear stress vs. shear rate (41% quality foam)

Foam is thermodynamically unstable fluid and as a result, it degrades while testing. This type of degradation (i.e. dynamic degradation) is sensitive to flow rate, pressure and flow geometry. For instance, a small-diameter pipe acts as a foam generator and minimizes the degradation. Therefore, degradation is expected to be more severe in a large-diameter

pipe than a small one. This results in higher drainage, foam quality and wall shear stress than a small-diameter pipe for the same shear rate. This condition causes a left shifting of flow curve of a large diameter pipe. A similar situation can occur, if pressure and foam quality significantly vary in a viscometer (i.e. excessive foam expansion). A small-diameter viscometer has more expansion effect than a large one. In addition, for the same shear rate, it requires a higher inlet pressure, which reduces inlet quality and subsequently wall shear stress. Expansion effect is more pronounced when system pressure is low (i.e. when system pressure is less than 50 times viscometric pressure loss). Hence, wall slip determination based on flow curve shifting is more reliable when foam expansion is minimized and highly stable foam is generated.

For 68% quality foam, results show a slight left shifting of 0.77-in. pipe flow curve (Fig. 13). The shifting is due to minor increase in foam quality during testing. Measurements obtained from other pipe viscometers lie approximately on a straight line.

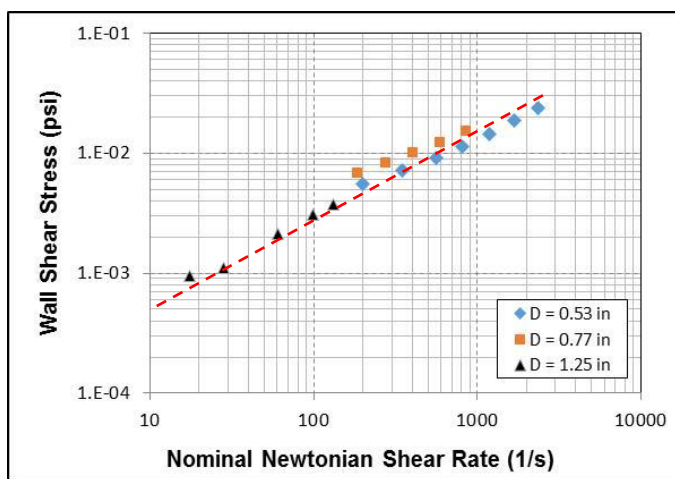


Fig. 13 Wall shear stress vs. shear rate (68% quality foam)

Foams are structured fluids, which are known for exhibiting yield stress at low shear rates. At low shear rate (less than 20 s^{-1}), measurements (Figs. 10 and 13) indicate departure from the power law trend line. Similar low shear rate data point deviation (flow curve turning in log-log plot) was observed with 61% quality foam. These observations can be attributed to change in flow behavior at low shear rate, which is normally displayed by fluids that fit Herschel Buckley model ($\tau = \tau_y + k\dot{\gamma}^n$).

Figure 14 summarizes data obtained during this investigation. Due to wall slip, data points from small pipe viscometer are excluded except for 68% foam. Then, the data is carefully analyzed to develop correlations for fluid rheological parameters. The data form straight line on a log-log plot indicating suitability of the power law model ($\tau = k\dot{\gamma}^n$). Foam quality is the most important factor affecting the fluid parameters (n and k). Applying curve-fitting techniques, correlations have been developed for predicting these parameters as a function of foam quality. To formulate the

correlations, first fluid parameters of the foam is normalized using corresponding base liquid parameters. The normalized foam parameters (n_f/n_L and k_f/k_L) vary significantly with quality.

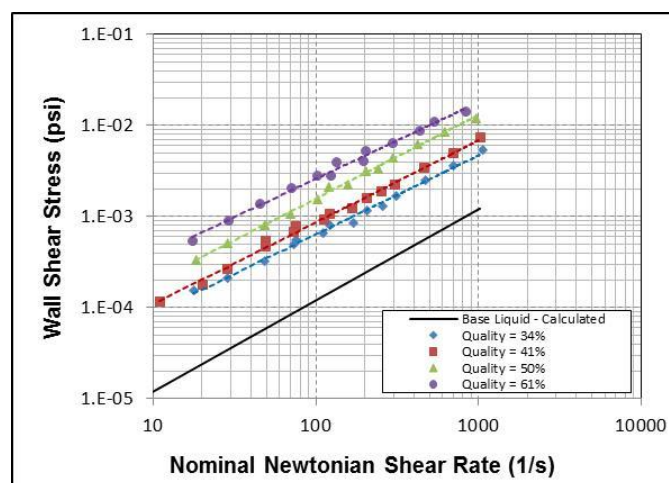


Fig. 14 Wall shear stress vs. shear rate for oil-based foams

Figure 15 shows plots of normalized rheological parameters of the foams. Like other structured fluids, the foams exhibit shear thinning, which improves with structural rigidity. Studies²⁷⁻²⁹ demonstrate enhancement of structural rigidity with foam quality. Even though foams exhibit relatively rigid structure at high quality, their resistance against shearing becomes sensitive to shear rate (deformation rate). As a result, high quality foams exhibit low fluid behavior index. Accordingly, normalized fluid behavior index of the foams decreased with quality (Fig. 15a).

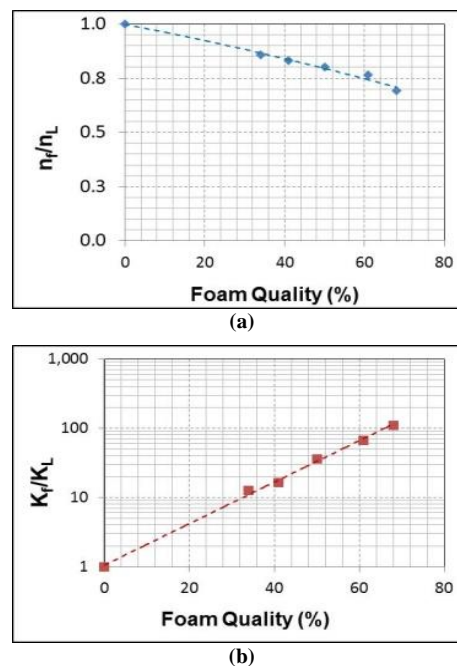


Fig. 15 Normalized power law fluid parameters: a) flow behavior index; and b) consistency index

The normalized consistency index shows an increasing trend with quality. At low qualities (approximately less than 45%), it increased gradually; however, as the quality increased above 45%, it displayed a sharp increase indicating the development of foam structure. Both fluid parameters have strong impact on foam hydraulics under laminar flow condition.

Applying non-linear regression technique, the following empirical correlations have been developed for predicting power-law model parameters of oil-based foams.

$$\frac{n_F}{n_L} = (C_1 e^{C_2 \Gamma} + 1)^{-1} \dots \dots \dots (3)$$

$$\frac{k_F}{k_L} = (C_3 e^{C_4 \Gamma} + 1) \dots \dots \dots (4)$$

where C_1 , C_2 , C_3 and C_4 are dimensionless empirical constants, which vary with properties of base liquid used to generate the foam. The values of these coefficients are presented in **Table 1**.

Table 1 Dimensionless empirical constants

C_1	C_2	C_3	C_4
0.0448	3.3577	1.0900	6.7769

5. Conclusions

Rheological investigation on oil-based foam is essential for wellbore pressure management and hydraulic optimization. Analysis of the data obtained over the course of this study supports the following conclusions:

- Like aqueous foams, quality and base liquid viscosity are the most important factors that define the rheological properties of oil-based foams.
- Oil-based foams exhibit wall-slip in 0.53-in. pipe. However, our study suggests that other conditions may lead to similar phenomenon.
- Foams tested in this study show strong non-Newtonian behavior, which predominately fits, the power-law fluid model. However, high-quality foam measurements at low shear rate (less than 20 s^{-1}) slightly deviate from the model line indicating presence of yield stress.
- Mean bubble size of oil-based foams increased with foam quality, the trend is similar to those of aqueous and polymer foams.

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Nomenclature

Acronyms

- BHA Bottom hole assembly,
 UBD Underbalanced drilling,
 ECD Equivalent circulating density.

Symbols

- C_a Flow capillary number,
 C_i dimensionless constants for $i = 1, 2, 3$, and 4 ,
 f Fanning friction factor
 n Fluid behavior index,
 n_f Foam behavior index,
 n_f/n_L normalized foam behavior index,
 n_L Base liquid behavior index,
 k Fluid consistency index
 k_f Foam consistency index
 k_f/k_L normalized foam consistency index,
 k_L Base liquid consistency index,
 r_b Bubble radius,
 Re_G Generalized Reynolds number,
 V_G In-situ gas volume,
 V_L Liquid phase volume.

Greek Letters

- $\dot{\gamma}$ Shear rate,
 Γ Foam quality,
 μ_L viscosity of the liquid phase,
 σ Interfacial tension,
 τ Shear stress,
 τ_y Yield stress.

References

1. Blauer, R. E. and Kohlhaas, C. A. 1974. Formation Fracturing with Foams. Paper SPE 5003 presented at the 49th Annual Fall Meeting of SPE, Houston, TX, 6-9 October.
2. Beyer, A.H., Millhone, R.S. and Foote, R.W. 1972. Flow Behavior of Foam as a Well Circulating Fluid. Paper SPE 3986, presented at the SPE Annual Fall Meeting, San Antonio, Texas, 8-11 October.
3. Mitchell, B.J. 1971. Test Data Fill Theory Gap on Using Foam as a Drilling Fluid. Oil and Gas Journal vol. 69, September, 96–100.
4. Sanghani, V. and Ikoku, C.U. 1983. Rheology of Foam and ITS Implications in Drilling and Cleanout Operations. J. Energy Resour. Technol 105(3), 362-371.
5. Harris, P.C. and Reidenbach, V.G. 1987. High-Temperature Rheological Study of Foam Fracturing Fluids. Journal of Petroleum Technology, 613-619.
6. Ding, Y., Herzhaft, B. and Renard, G.: 2006. Near-Wellbore Formation Damage Effects on Well Performance: A Comparison Between Underbalanced and Overbalanced Drilling, Journal SPE Production & Operations, Vol 21, Number 1, February, Pages pp. 51-57.
7. Driscoll, P.L., Bowen, J.G. and Roberst, M.A. 1980. Oil base fracturing applied to the Niobrara Shale Formation. Paper SPE 9335, presented 55th Annual Fall Technical Conference and Exhibition of the SPE of AIME, Texas, 21-24 September.
8. Sepulveda, J.J., Falana, O.M., Kakadjian, S., Morales, J.D.,

- Zamora, F., Dibiasio, M.A., Marshall, E. and Shirley, G., Benoit D.J. and Tkach, S.A.: 2008. Oil-Based Foam and Proper Underbalanced-Drilling, paper SPE 115536 presented at the SPE Annual Conference, 21-24 September 2008, Denver, Colorado.
9. Kakadjian, S., Falana, O.M., Marshall, E., Dibiasio, M.A., and Zamora, F. 2012. Enhanced Oil-Based Foam Drilling Fluid Composition and Method for Making and Using SAME. US Patent No. 8,141,661.
10. Reynolds, S., and Fournier, L.B. 1984. Hydrocarbon Foams. US Patent No. 4,432,882.
11. Blázquez, C., Emond, E., Schneider, S., Dalmazzone, C., and Bergeron, V. 2014. Non-Aqueous and Crude Oil Foams. Oil and Gas Science and Technology, Institute Francais du Petrole, pp. 467-479.
12. Ibizugube, N.O., 2012. Drainage Behavior of Oil-Based Drilling Foam under Ambient Conditions. M.S. Thesis, the University of Oklahoma, Norman, OK, U.S.A.
13. Martins, A. L., Lourenço, A. M. F., Sá, C. H. M. and Silva Jr., V. 2001. Foam Rheology Characterization as a Tool for Predicting Pressures while Drilling Offshore Wells in UBD Conditions. Paper SPE 67691, presented at the SPE/IADC Drilling Conference, Amsterdam, 27 February-1 March.
14. Khade, S.D. and Shah, S.N. 2003. New Rheological Correlations for Guar Foam Fluids. Paper SPE 80895, presented at the SPE Production and Operations Symposium, Oklahoma City, Oklahoma, 22-25 March.
15. Reidenbach, V. G., Harris, P. C., Lee, Y. N. and Lord, D. L. 1986. Rheological study of foam fracturing fluids using nitrogen and carbon dioxide. Paper SPE 12026 presented at the 58th Annual Technical Conference and Exhibition, San Francisco, 5-8 October.
16. Cawiezal, K.E. and Niles, T.D. 1987. Rheological Properties of Foam Fracturing Fluids under Downhole Conditions. Paper SPE 16191, presented at the SPE Hydrocarbon Economics and Evaluation Symposium, Dallas, Texas, 2-3 March.
17. Enzendorfer, C., Harris, R. A., Valkó, P., Economides, M. J., Fokker, P. A. and Davies, D. D. 1995. Pipe viscometry of foams. *J. Rheol.*, 39(2), 345-358.
18. Gardiner, B.S., Dlugogorski, B.Z., Jameson, G.J. 1998. Rheology of fire-fighting foams. *Fire Safety Journal*, pp 61-75.
19. David, A. and Marsden, S.S. 1969. The Rheology of Foam. Paper SPE 2544, presented at SPE of AIME, Denver, Colorado, 28 September- 1 October.
20. Patton, J.T., Holbrook, S.T. and Hsu, W. 1983. Rheology of Mobility-Control Foams, *SPEJ*, 456.
21. Heller and Kuntamukkula 1987. Critical review of the foam rheology literature, *Industrial & Engineering Chemistry Research* 26 (2): 318-325.
22. Jastrzebski Z. 1967. Entrance Effect and Wall Effect in Rheometer during the Flow of Concentrated Suspension. *Ind. Eng. Chem. Res.*, 6, 445-454.
23. Harris, P.C. 1985. Effects of Texture on Rheology of Foam Fracturing Fluids. SPE no. 14257, 60th Annual Technical Conference and Exhibition of SPE, Las Vegas.
24. Chen, Z., Ahmed, R.M., Miska, S.Z., Takach, N.E., Yu, M., Pickell, M.B., and Hallman, J.H. 2005. Rheology of Aqueous Drilling Foam using Flow-Through Rotational Viscometer. Paper SPE 93431, presented at SPE International symposium on oil field Chemistry, Texas, 2-4 February.
25. Sherif, T., Ahmed, R., Shah, S. and Amani, M. 2015. Rheological behavior of oil-based drilling foams, *Journal of Natural Gas Science and Engineering*, Volume 26, September, Pages 873-882.
26. Sherif, T., Ahmed, R., Shah, S. and Amani, M. 2015. Rheological and Wall-Slip Behaviors of Polymer Based Drilling Foams. Paper 41552, presented at the Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering (OMAE2015), May 31-June 5, 2015, St. John's, Newfoundland, Canada.
27. Khan, S.A. and Armstrong, R.C. 1986. Rheology of Foams: I Theory of dry foams. *J. Non-Newtonian Fluid Mech.*, 22, pp. 1-22.
28. Khan, S.A. and Armstrong, R.C. 1987. Rheology of Foams: II Effect of polydispersity and liquid viscosity for foams having gas fraction approaching unity *J. Non-Newtonian Fluid Mech.* 25, pp. 61-92.
29. Kraynik A.M. 1988. Foam Flows, *Ann. Rev. Fluid Mech.*, 20, 325-57.