Characterization of Foam Rheology at HPHT for Hydraulics Optimization Whilst Drilling Underbalanced

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ABSTRACT

A discussion about horizontal foam flow behavior in pipes and annular geometry under elevated pressures and temperatures is presented. 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.

INTRODUCTION

The use of lightweight fluids in drilling operations is becoming common practice all over the world. They are normally used to induce underbalanced condition, i.e., to keep the wellbore pressure below the formation's fluid pressure, while drilling in low-pressure reservoirs. This diminishes formation impairment from drilling fluid, enhancing productivity. It is also used to overcome operational difficulties such as stuck pipe and loss of fluid circulation. Other benefits include the reduction of drilling time due to increased rate of penetration, less bit wearing and the ability to handle fluid invasion.

Among the numerous types of lightweight fluids used in drilling operations, foam appears as one of the most widely used. This is mainly because foam generates very low Equivalent Circulating Densities (ECD) while exhibiting good lubrication and hole cleaning capacity, especially in vertical wells. It also offers a better control over the flow behavior of the phases involved within the well.

In order to achieve success in drilling operations under this scenario the understanding and design of properties affecting borehole hydraulics becomes a major issue. Predictive models, chiefly for pressure profile, become even more imperative by the fact that common tools used for logging while drilling do not work properly when lightweight fluids are used, especially in offshore operations. Based on this, it is clear that rheological characteristics of this compressible non-Newtontian fluid must be fully understood.

Several researchers1[1,2,3] have studied foam flow behavior in pipes in the past. However, there is no general agreement on the rheological description of the foam. The analysis of foam flow behavior is rather difficult because of the number of variables involved such as: compressibility, flow geometry, foam generation, quality (ratio of gas phase to foam volume), liquid and gas phase properties, slippage at the conduit's wall, non-Newtonian behavior, etc. It becomes even more challenging when annular flow takes place. Therefore, this study focuses on the experimental investigation of pipe and annular foam flow under elevated pressures and temperatures, with the objective of gaining a better understanding of how different variables affect the flow of this complex fluid.

Capillary Viscometry

When a rheogram for a non-Newtonian fluid is available, it is possible, at least in principle, to predict the laminar flow properties of such a fluid in conduits of simple cross section. The flow curve for a fluid can be rigorously and easily derived from pressure drop and flow rate data obtained with a capillary-tube or pipe viscometer of diameter D and length L.

Metzner and Reed[4] observed experimentally that for most fluids the following relation for the shear stress at the wall is expected:

$$\tau w = \frac{D\Delta P}{4L} = K'\left(\frac{8v}{D}\right)^{n'} . \qquad (1)$$

From the slope of a logarithmic plot of viscometric data in the form $(D\Delta P/4L)$ versus $(8v/D)$, the derivative, n', can be readily evaluated. For Power-Law Fluids, K' and n' are constant over a wide range of shear rates or shear stresses. This graphical evaluation of the parameter n' enables the construction of a flow curve for any kind of fluid (excluding time-dependent fluids) from laminar pipe-flow data

It can be shown that $(-dv_r/dr)_w$ and (8v/D) are identical except for the constant multiplying factor $(3n'+1)/4n'$. In view of these facts, an analytic expression for the shear stress-shear rate behavior of the fluid can be written in the form of a Power-Law relationship with $n = n'$:

$$tw = K\left(\frac{8v}{D}\left(\frac{3n'+1}{4n'}\right)\right)^{n'} , \qquad (2)$$

where v is the average fluid velocity and,

$$K = K'\left(\frac{4n'}{3n'+1}\right)^{n'} . \qquad (3)$$

FOAM FLOW EXPERIMENTS

The Experimental Facility

The Tulsa University's Advanced Cuttings Transport Facility is designed to simulate the flow scenario for regular and underbalanced drilling operations. Its actual capabilities include physical pipe and annular flow simulation of incompressible non-Newtonian drilling fluids up to 2000 psig of pressure and 200°F of temperature. At this point, aerated fluids and foams can be tested up to a maximum pressure of 700 psig and temperatures up to 200°F. It is fully instrumented and all information is managed by a data acquisition system based on a LabView 5.0 environment. In addition, automatic control of the most important variables is available.

During foam flow experiments three insulated pipe sections were used as a capillary-type of viscometer. In addition, an annular section that simulates a 6 inch well casing with a 3,5 inch drillstring was also used. Table 1 shows internal diameters and lengths of the test sections in the flow loop.

Table 1 – Dimensions of Test Sections

PIPE NOMINAL DIAMETER (in)	PIPE ID (in)	LENGTH (ft)
2	1.918	52'9''
3	2.9	52'9''
4	3.826	66'6''
Annular (6 x 3.5)	5.761x 3.5	57'4''

Figure 1 shows a scheme of the facility set up for the HPHT foam experiments.

Experimental Procedure

The experiments consisted of measurements of pressure drop in the three pipe sections and the annular section for a particular test condition. The variable parameters were pressure, temperature, foam quality and in situ foam volumetric flow rate. Water was the liquid phase and air was the gaseous phase for all experiments. An Alkyl Ether Sulfate anionic surfactant at 1% v/v concentration in water was used during

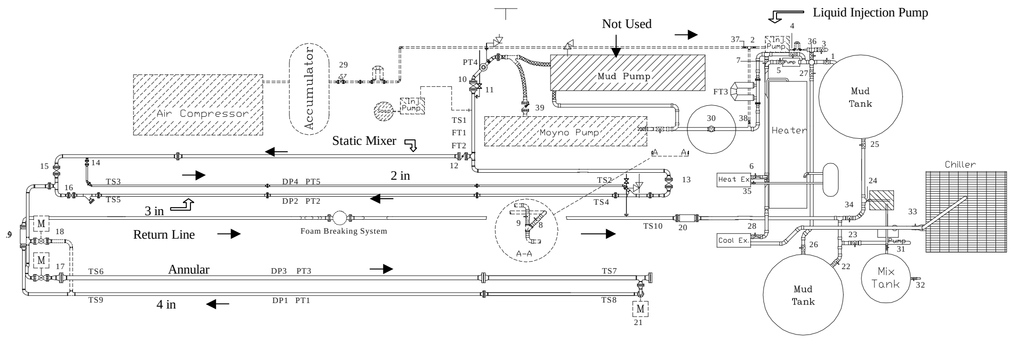

Figure 1. Experimental Facility

these experiments. The experiments were carried out in a single pass throughout the test sections configured in series. Foam was generated in a static mixer, and then flowed through the 2 and 3-inch pipe sections, the annular section and finally through the 4-inch section. Subsequently, a 10 % v/v silicon-based foam breaker chemical was injected in a return line upstream of a vertical two-phase separator where air is vented and liquid is directed to disposal tank.

The following steps summarize the most important actions to set and run a particular test:

- Heat the flow loop up to desired temperature with water.
- Establish values for pressure, foam quality and in situ foam velocity at the static mixer.
- Start air and water injection to achieve desired steady state test conditions.
- Start surfactant injection and the optimum amount of defoamer (10% to 15% v/v of the surfactant injection rate).
- Record data: temperature, static pressure, differential pressure, liquid and air flow rates.

Two different sets of experiments were carried out where the only difference was the foam generation procedure. A ball valve located downstream of the pumps, but upstream of the static mixer, was used to apply an extra 100 psid during foam generation for a second set of tests. In fact, foam texture could not be strictly controlled or evaluated during the tests, but the new procedure allowed the study of the impact of texture on foam rheology by increasing shear rate and mixing energy during foam generation. The first set of experiments will be referred to as the baseline tests and the second set as the “stiffer” foam tests.

With measurements of pressure drop and foam volumetric flow rate from the three pipe sections, the shear stress at a pipe wall and Newtonian shear rate were calculated for all tests. This information formed the basis for the rheological characterization of foams.

Test Matrix

The test matrix covered pressures from 100 up to 650 psig; temperatures from 80 up to 180°F and foam quality ranging from 60% up to 90%.

RESULTS

Foam Generation Effect

Figure 2 shows the significant effect of foam generation method on its rheology.

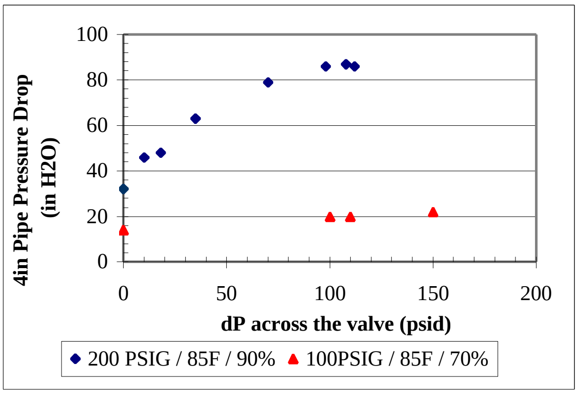

Figure 2. Effect of Foam Generation on Foam Rheology – Stiffer Foam

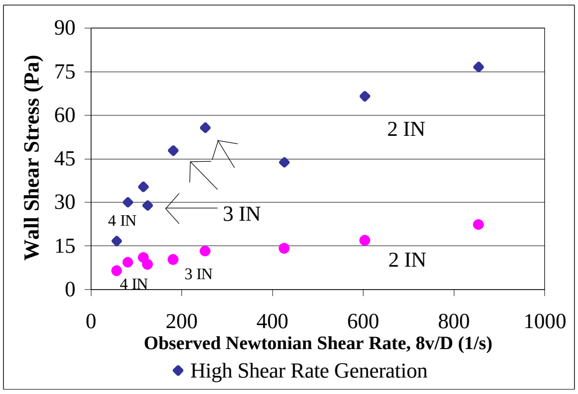

Figure 3. Effect of Foam Generation on Rheology – 90% quality/100 psig/85°F

This Figure presents a the profile of the measured pressure drop in the 4-inch pipe section as a function of differential pressure drop across the ball valve located upstream of the static mixer. The 4-inch line pressure drop almost tripled, for the 90% quality test, with the increase in differential pressure drop and associated shear *during foam generation*. This effect was also observed for the 70% quality test, but to a lesser extent. Results indicate the existence of a range of shear rate and/or hydraulic power where good texture foam is achieved, but completely different rheological responses can occur. After a certain level of shear rate, there was no significant change in pressure drop.

A removable transparent sample port installed at the 4-inch pipe, allowed visual inspections of foam samples at actual pressure and temperature conditions with a microscope. These observations did not provide a good way to properly quantify the bubble size and shape distribution, but did enable qualitative observations. The results indicate a reduction in bubble size and a narrower distribution of bubble size for foam, under the same operational conditions, when generated with higher shear rates. Harris[5] observed that the viscosity of low quality foams were not so susceptible to bubble size effects at high shear rates. Figure 2 confirms these observations. One possible explanation for these phenomenon is related to foam structure. Foams with less than 70% quality normally form spherical bubbles with thicker liquid films between the bubbles. High quality foams exist as polyhedral-type bubbles with thinner liquid lamellas. The structure of polyhedral bubbles is more rigid and more resistant to shearing than the spherical type. Harris[5] also observed a decrease in bubble size and narrower bubble size distribution with increases in shear rate. Pred'homme and Khan[6] also observed an increase in viscosity of emulsions with a decrease in drop size of the dispersed phase. The trend makes sense since the number of bubbles per unit volume of fluid increases with a decrease in bubble size. Consequently, the interaction forces among them increase. Another fact is that for a particular unit volume, the surface area increases with a decrease in bubble size. Therefore, the resistance to flow in a structured fluid like foam should increase as bubble size decreases. The test results demonstrate the importance of bubble size characterization for proper rheological evaluation of foams. Variables of bubble shape and size distribution must be included in the rheological evaluation in order for a hydraulic model to be totally independent of the method of foam generation. Figure 3 confirms the increase of viscosity after the new foam generation procedure.

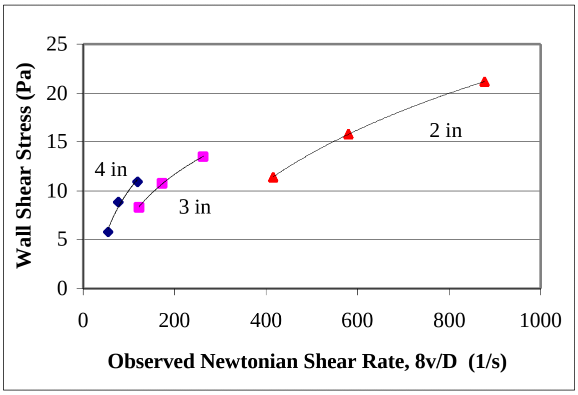

Figure 4. Example of Slippage at Wall in Pipe Flow – 100psig / 150°F / 90% Quality Foam – Baseline Tests

Wall Effects

Several authors[7,8,9] have reported the existence of wall effects on foam flowing through pipes. Drainage (syneresis) of liquid from foam produces a thin liquid layer at solid boundaries, which enables wall slip. This phenomenon leads to incorrect computations of shear rates and a wrong evaluation of rheological parameters. Foams may move as nearly pure plug flow due to slippage at the wall. Hence, it is very important to have more than one pipe diameter for experimental measurements whenever capillary-type rheometers are used. The wall effect is identified and corrected based upon the flow behavior in the different pipe sections. The principle is that the rheological behavior of a particular time independent fluid should not change with geometry of the conduit. This is what appears to happen when slippage occurs. During these experiments, the slippage effect was also observed. Figure 4 shows the effect for a particular experiment condition.

Among the many variables involved in the development and behavior of the liquid layer we identify shear stress, pipe diameter, quality, bubble shape and size distribution, liquid phase viscosity, gas phase viscosity and wall roughness. There is currently no theoretical method capable of accounting for all of these variables. Among the available methods, the Oldroyd-Jastrzebski[10] model shows superior performance over the others. The following section lists the most important equations in the subject model.

The form of the slip velocity is assumed as follows:

$$v_{slip} = \frac{\beta_c \tau_w}{D}, \qquad (4)$$

where $ß_c$ is the slip coefficient.

The actual pump rate (also called the "observed" flow rate) incorporates the "true" flow rate associated with shearing of the foam plus the component due to slip. Where the "true" flow rate is,

$$Q_{true} = 2\pi \int_0^R \left(v - v_{slip}\right) r\,dr. \qquad (5)$$

Where R is pipe radius. This flow rate is used to compute the "true" Newtonian shear rate of the foam at the wall. From Eq. 4 and Eq. 5 the following expression can be written in terms of pipe diameter for the observed Newtonian shear rate:

$$\gamma_{obs \cdot newt.} = \gamma_{true.newt} + \frac{8\beta_c \tau_w}{D^2}, \qquad (6)$$

$$\gamma_{obs \cdot newt \cdot} = \frac{8v}{D}, \qquad (7)$$

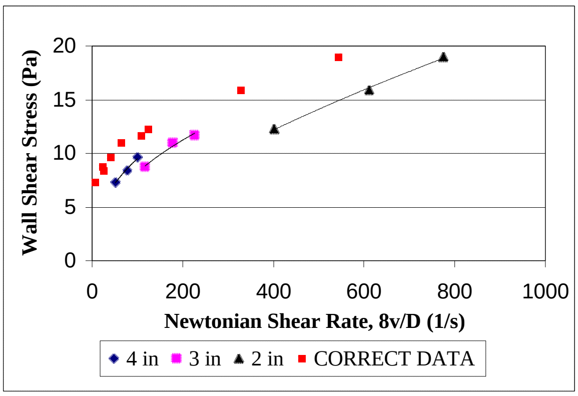

Figure 5 – Slip Correction – 300 psig / 100F / 80% Quality – Baseline Tests

where v is the average velocity of foam inside the pipe, which also includes the slip velocity at the wall. Any flow of liquid at the boundary that allows slip is neglected. The slope of a plot of “observed” shear rate, ?*obs. newt.*, versus 1 / D^2 at a particular shear stress gives the slip coefficient. Hence, it is possible to obtain the relation between slip coefficient and shear stress. When this function is known, the “true” Newtonian shear rate, ?*true. newt.,* can be calculated from Eq. 6. This function was obtained from the experimental method for each test.

Figure 5 shows the ability of the method to eliminate the slip effect. After correction, data from the different pipe diameters tend to lie on a single curve. The Oldroyd-Jastrzebski[10] method is not able to explicitly describe each effect influencing the slip at wall. In spite of this, it assumes that they are implicitly accounted by the wall shear stress.

The effect of wall roughness is not clearly understood either. It is known that a rough surface tends to eliminate or reduce wall slip. Princen[11] claims that it is a function of the ratio of the absolute roughness (ε) and average bubble size. In general, the slippage was more severe in the 2 inches pipe. This makes sense since it was the smoothest pipe, the smallest diameter and had the highest shear stresses for a particular foam flow rate. Another interesting observation was the decrease of the slippage at the wall between the 3 and 4 inches pipes (points with lower shear rates) for the foam generated at high shear rates and having smaller bubbles. One possible explanation is that these smaller bubbles may be sufficiently small to lock into the small bumps of the rough surface, diminishing the slip effect. Another factor is wall roughness. Turbulent water flow tests established that wall roughness was greatest in the 4-inch pipe and least in the 2-inch pipe. This also could have caused progressively less wall slip with increasing pipe diameter.

In Figure 5 the slip-corrected data suggest the presence of an apparent yield point. In some experiments an apparent yield point appears after the slip correction for low shear rate data, especially in high quality foams. It is called apparent yield point because the foam is flowing nearly as a plug in the conduits with a velocity almost equal to the slip velocity. The difference between the slip velocity and the actual average velocity (based on pump rate and pipe diameter) causes shearing of the foam inside the perimeter of the slip layer. The corresponding velocity profile is determined by the rheology of the foam. As the slip velocity approaches the actual velocity, there is a progressively less shearing of the foam, and the velocity profile tends to become flat and independent of rheology.

<u>Slip Coefficient</u>

An empirical correlation for computing the slip coefficient was developed. The correlation is based on experimental data for slip coefficients over the measured range of shear stress, quality, pressure and temperature. The data showed that the slip coefficient is not only a function of the wall shear stress, but also quality, temperature, pressure, wall roughness and texture. Since the development of an equation accounting for all these effects is extremely difficult, the specific volume expansion ratio, ratio of liquid to foam density, was used in an attempt to eliminate the effects of quality and pressure. Eq. 8 shows the final form of the correlation.

$$b_c = \frac{a t_w^{\,b}}{e_s^{\,c}} . \tag{8}$$

Where the parameters a, b and c were determined by using the least-squares method. Two different sets of parameters were developed, one for the baseline data and another one for the stiffer foam. Table 2 shows the resulting values of parameters a, b and c.

Table 2 – Slip Coefficient Correlation Parameters

PARAMETERS	BASELINE EXPERIMENTS	STIFFER FOAM
a	0.247	0.552
b	-0.559	-0.847
c	-0.173	0.360
Correlation Factor (R)	0.50	0.98

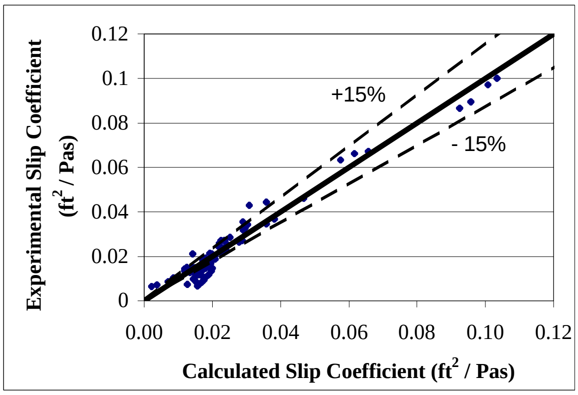

Figure 6. Comparison Between experimental and Calculated Slip Coefficient

Note that the baseline tests and the stiffer foam have an inverse dependence on the specific expansion ratio. See exponent "c" in Table 2. Figure 6 shows the comparison between the experimental and calculated values of slip coefficient for the stiffer foam.

Slippage in Annular Sections

Since no methods are available to predict the slip velocity in annular sections, a model was proposed. The same form of the slip velocity is assumed, but the pipe wall shear stress is replaced with the average wall shear stress in concentric annuli and the pipe diameter is replaced by the hydraulic diameter:

$$V_{slip} = \frac{b c t_{wavg}}{D_h}, \qquad (9)$$

where,

$$t_{wavg} = \frac{\Delta P D_h}{4L}, \qquad (10)$$

where D_h is the outer diameter minus the inner diameter.

Since a single annular geometry was available, the slip coefficient for the annulus was calculated assuming the same functionality with shear stress observed in the pipe sections, but using the average wall shear stress in place of the pipe wall shear stress.

The prediction of frictional pressure losses from the developed hydraulics model is beyond the scope of this paper, but this approach was proposed because it provided the best agreement with experimental data. Different equivalent diameters were tried, but demonstrated less agreement with experimental data than the hydraulic diameter.

Quality Effect

Quality is one of the most important variables affecting foam rheology. The non-Newtonian behavior of foams comes from the presence of bubbles in the fluid. This behavior is usually enhanced with an increase in the percentage of gas in the foam. Usually a shear thinning behavior is observed in the flow of foams.

Figure 7 shows the effects of quality

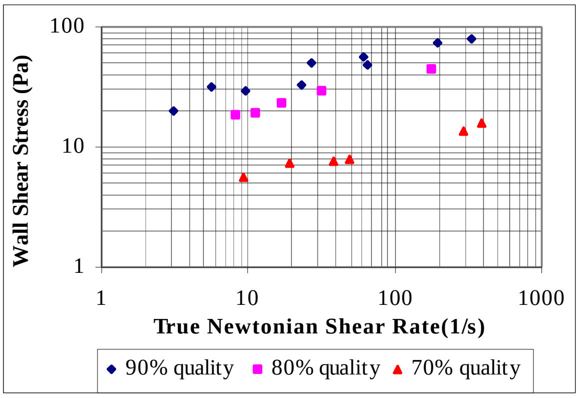

Figure 7. Effect of Quality on Foam Rheology – 300psig / 80°F – Stiffer Foam

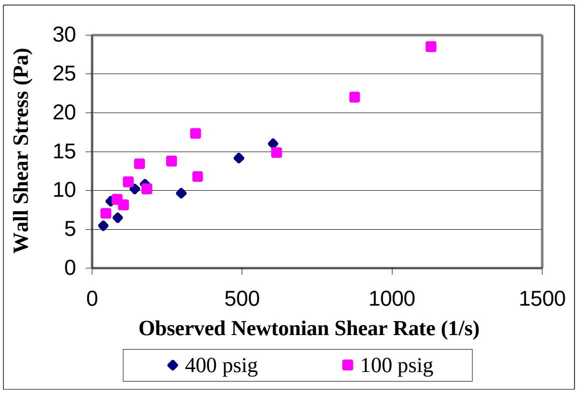

Figure 8. Effect of Pressure on Foam Rheology – 100 °F / 90% quality – Baseline Tests.

over a range of experimental conditions. For a particular true Newtonian shear rate the high quality foams present higher shear stresses, meaning a higher effective viscosity. Newtonian shear rate is used here because the intention at this point is only to highlight the effect of quality and not evaluate the true rheological parameters.

Pressure Effect

Results from experiments, conducted at pressures up to 650 psig, did not reveal a significant effect of pressure on foam rheology. This was observed for both the baseline tests and experiments with the stiffer foam. See figure 8.

Some authors[5,12] have reported a more pronounced effect of pressure on foam rheology, but over a wider range of pressure. In spite of this, the same authors found different trends for the effect of pressure on foam rheology. Harris[5] found an increase of shear stress at the same shear rate with a decrease in pressure. Whereas, Cawizel, et al.[12] found the opposite. It is expected that a greater mechanical and chemical interaction occurs between the bubbles as pressure increases. If true, this should result in an increase of the viscosity of a foam. Apparently, this effect is not significant enough to modify the rheological responses found in this study.

Temperature Effects

Figures 9 shows the effect of temperature on the rheological behavior of foams based on the experimental data.

Figure 9 does not indicate a significant influence of temperature on the rheological response. A thinning of foam was expected at higher temperatures as a result of a decrease in viscosity of the liquid phase, but this could not be clearly observed in the data from these tests.

MASTER FLOW CURVES FOR FOAMS

Volume Equalized Principle

Valko and Economides[13] introduced the concept of the Volume Equalized Principle. The Authors observed that a master flow curve for foam is obtained for different qualities and pressures when the following constitutive equation is used.

$$\frac{\tau_w}{\varepsilon_s} = f_{VE}\left(\frac{\gamma_w}{\varepsilon_s}\right), \qquad (11)$$

where e_s is called specific expansion ratio.

$$\varepsilon_s = \frac{\rho_l}{\rho_f}, \qquad (12)$$

where, ρ_l is the density of the liquid phase; ρ_f is the density of foam; τ_w is the wall shear stress, and γ_w is the shear rate at the wall.

The unique function f_{VE} relates the

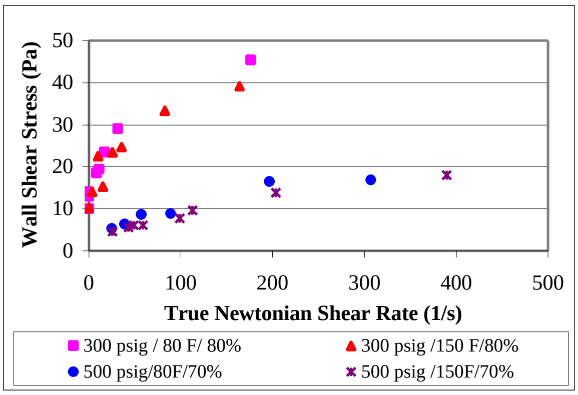

Figure 9. Influence of Temperature on Foam Rheology – Stiffer Foam

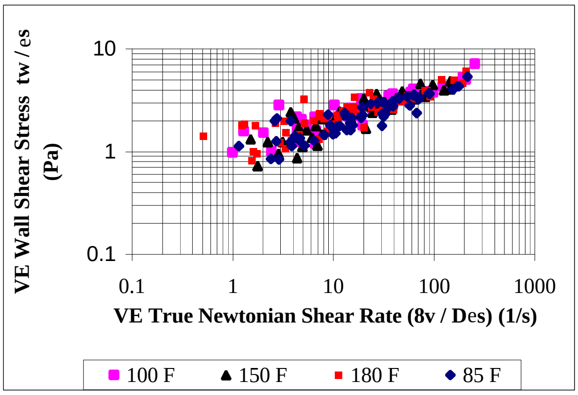

Figure 10. VE Foam Master Flow Curve –60% to 90% Quality – 100 to 650 psig Baseline Tests

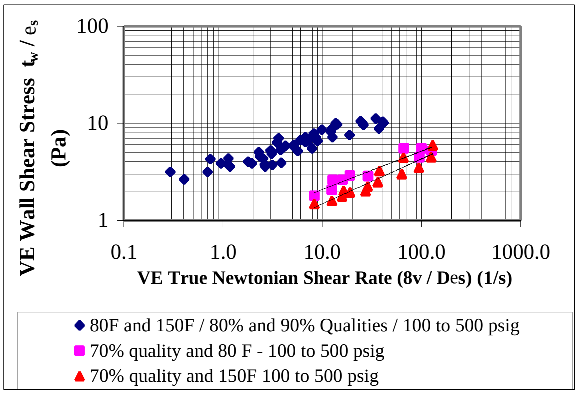

Figure 11. VE Foam Master Flow Curve – Stiffer Foam

volume equalized (VE) shear stress and the volume equalized shear rate. The volume equalized power law is a particular case of Eq. 11:

$$\frac{\tau_w}{\varepsilon_s} = K_{VE}\left(\frac{\gamma_w}{\varepsilon_s}\right)^n . \qquad (13)$$

The experimental results indicate that the rheological behavior of water-air based foams can be characterized by a Power-Law Model. Table 3 shows the VE rheological parameters after regression analyses. Note that these are wall parameters despite the fact Figure 10 and Figure 11 show the true Newtonian shear rate.

Table 3 – VE Rheological Parameters

PARAMETER	BASELINE TESTS	STIFFER FOAM		
		HIGH QUALITY	LOW QUALITY (80 °F)	LOW QUALITY (150 °F)
K_{VE} (Pa s^n)	0.879	3.193	0.808	0.409
n	0.303	0.294	0.373	0.494
(R)	0.91	0.93	0.94	0.94

CONCLUSIONS

1. In addition to foam quality, the experimental results indicate a strong influence of texture on foam rheology. The effects of temperature and pressure on foam rheology are secondary.
2. Foams generated at high shear rate conditions have smaller bubbles and higher effective viscosities.
3. The slippage at the wall is one of the most important phenomena to be considered in foam flow. Empirical correlations for slippage coefficient, independent of quality, were developed. In addition, it is proposed that the average wall shear stress and hydraulic diameter be used for calculating slip velocity in annuli.
4. The Volume Equalized Principle demonstrated good results in generating a master flow curve for foams. However, two master curves were obtained for the stiffer foam, one for high quality and another for low quality foams. These results suggest the need for incorporating texture effects into the model.
5. The effect of shear rate during foam generation on foam rheology was more significant for high quality foams. Consequently, the lower the quality of foam downhole, the less will be the effect of flow through the bit nozzles. Hydraulic models for foam drilling should have texture linked with a rheological model in order to properly estimate flow properties inside the drillstring and annular sections.

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