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Rheological behavior of aqueous foams at high pressure

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ABSTRACT

Aqueous foams are used in many oil field applications including drilling, fracturing, and enhanced oil recovery operations. The success of all these operations strongly depends on viscosity and stability of foam. Rheology of foams is a function of foam quality (i.e. gas volume fraction), liquid phase viscosity, pressure, and temperature. Besides, foam generation method and stability are factors that influence its rheology.

This article presents results of an experimental study performed to investigate the effects of foam quality, pressure, and wall slip on aqueous-foam rheology. Extensive tests were conducted using a foam recirculating flow loop consisting of three pipe viscometers. Experiments were performed at ambient temperature, and varying pressure (6.89–20.68 MPa), foam quality (40–80%), and pipe diameter (3.06, 6.22 and 12.67 mm). The foam was generated by passing a mixture of water containing 2% surfactant solution and gas phase (nitrogen) through a needle valve. To minimize degradation while testing, the foam was regenerated by circulating at the maximum flow rate (0.55 L/min) before each flow measurement was made.

Results indicate strong non-Newtonian behavior of foam, which closely fits the power law model. For foams with more than 55% quality, measured viscosities were higher than the ones reported in the literature. Noticeable wall slip was not observed. Foam viscosity change because of pressure variation at a constant foam quality was negligible. Foams with quality higher than 70% exhibited yield pseudoplastic behavior. Their rheological behavior can be described better by Herschel–Bulkley model than power law model when the shear rate is below 20 1/s.

1. Introduction

Foam is very light and viscous fluid; as a result, it is suitable for drilling formations that are difficult to drill using the conventional method. Moreover, it is used for fracturing and enhanced oil recovery operations. Due to its low density, wellbore pressure can be maintained below the formation pressure when foam is used in underbalance drilling (UBD). UBD is a drilling technique, which is usually employed to drill low-pressure and partially depleted reservoirs. As a drilling fluid, foam provides many benefits including high cuttings carrying capacity and penetration rate, low formation damage, and reduced risk of differential sticking and lost circulation. The use of foam eases hydrocarbon recovery by eliminating the need for stimulation after drilling. In foam drilling, annular velocities are quite low relative to other UBD methods, thereby minimizing borehole erosion. High-quality foams are often used, which minimize the amount of liquid required for drilling.

Foam is a thermodynamically unstable fluid, and operations that use this fluid must be meticulously monitored to prevent instability related issues such as pressure fluctuation because of slugging flow, which causes temporary overbalance. While circulating, foam degrades due to gravity drainage and bubble coalescence; and thus, liquid phase segregates with time, causing a reduction in viscosity. Consequently, its half-life is measured and monitored at the surface during drilling. Quality is the most critical parameter in determining flow behavior and stability of foams. Quality of foam at a given temperature and pressure is expressed as:

$$\Gamma = \frac{V_G}{V_G + V_L} \tag{1}$$

where V_G and V_L are the in-situ volumes of gas and liquid phases, respectively. Rheological properties of foams are quite different from their constituents and depend on foam quality, base liquid properties, operating temperature and pressure, and degree of foam generation. Fully generated (equilibrated) foam is more homogeneous, stable and viscous than the one not fully generated due to lack of enough mixing

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energy or required amount of surfactant. Moreover, as foam flows down the well, its properties continue to change because of variations in downhole conditions (pressure and temperature). Thus, studying and understanding foam rheology at high pressure such as those encountered downhole is imperative in terms of hydraulic and hole cleaning optimization, improvement of operational safety and cost control. This paper presents a thorough rheological study of aqueous foams at high pressure and compares measurements with those reported in the literature (Harris and Heath, 1998; Cawiezel and Niles, 1987; Bonilla and Shah, 2000).

2. Literature review

Rheology of aqueous foams has been the subject of several experimental studies (Cawiezel and Niles, 1987; Harris, 1989; Harris and Heath, 1998; Martins et al., 2000; Lourenço, 2002; Lourenço et al., 2003; Chen et al., 2007). The tremendous effort is mainly because of conflicting-observations that have been reported in many cases. In addition to experimental studies, a number of theoretical investigations (Hatschek, 1911; Barthes-Biesel and Chhim, 1981; Khan and Armstrong, 1986, 1987) have been conducted on rheology of suspensions, emulsions (suspensions of liquids), and foams. Most of the theoretical studies focused on relating foam viscosity to quality and liquid phase (continuous phase) viscosity. Commonly accepted conclusions are that low-quality aqueous foams exhibit Newtonian flow property while at high qualities, they display non-Newtonian behavior (shear thinning and yielding) due to development of bubble structure. Theoretical studies (Khan and Armstrong, 1986, 1987) have shown the existence of a strong link between non-Newtonian behavior and foam structure.

Foam structure is greatly influenced by its quality. Foam is considered as bubbly-liquid up to a particular quality above which a rigidity transition takes place leading to the formation of bubble structure. For aqueous foams, the rigidity transition is approximately at 63% (Kraynik, 1988; Holt and McDaniel, 2000). Also with increasing quality, bubble shape changes from spherical to polyhedral at around 88% quality. Aqueous foam attains its maximum viscosity at 94.6% quality (Ahmed et al., 2003; Debrégeas et al., 2001; Gopal and Durian, 1998). The viscosity of dry foams (quality greater than 94.6%) significantly reduces with quality. Dry foam becomes unstable when the quality is increased above the inversion point. For aqueous foam, the inversion point quality is approximately 97% (GRI, 1997).

As foam circulates in a wellbore, its flow properties change due to temperature and pressure. Increase in temperature at constant pressure lowers the viscosity of the base liquid, thus, affecting the foam viscosity. The effect of pressure on foam rheology can be primary or secondary. Major rheology change due to pressure (i.e. primary effect) occurs when the foam is compressed or expanded due to pressure change. It is known that at a given temperature, significant pressure increase reduces the foam quality and viscosity. The secondary effect is when pressure is increased without affecting foam quality, which can be accomplished by injecting pressurized gas into a constant volume of foam under isothermal condition. The secondary effect of pressure on foam viscosity is considered minor (Harris, 1989; Beyer et al., 1972). However, a study (Cawiezel and Niles, 1987) conducted experiments using single pass pipe viscometers indicated significant secondary effect.

2.1. Foam rheology modeling

Most commonly used foam rheology models relate foam viscosity to quality and base liquid viscosity. Mitchell (1971) developed a classical foam rheology model that predicts foam viscosity based on quality and liquid phase viscosity as:

$$\eta_F = \eta_L(1 + 3.6\Gamma) \text{ for } \Gamma \le 54\% \tag{2a}$$

$$\eta_F = \frac{\eta_L}{1 - \Gamma^{0.49}} \text{ for } \Gamma > 54\% \tag{2b}$$

where η_F and η_L denote viscosity of foam and base liquid, respectively.

Emulsions and foams are rheologically very similar, even though foams exhibit higher instability than emulsion due to gravity drainage. Because of their rheological similarity, most of the theoretical studies conducted on suspensions have been extended to model foams. Hatschek (1911) theoretically related the viscosity of concentrated emulsion to its continuous phase viscosity as: $\eta_F = \eta_L\ (1\text{-}\Gamma^{0.33})^{-1}$. The formula was validated using foams at low capillary numbers. The capillary number of foams with Newtonian base liquid is defined as:

$$Ca = \frac{r_b \eta_L \dot{\gamma}}{\sigma} \tag{3}$$

where r_b, $\dot{\gamma}$ and σ denote mean bubble radius, shear rate and surface tension, respectively. The capillary number compares the viscous forces, which disturbs the bubble structure and interfacial tension that tends to preserve the structural. A recent study (Llewellin et al., 2002) on low quality ($\Gamma \le 0.5$) foams developed a semi-empirical model based on theoretical analysis of Frankel and Acrivos (1970). The model is valid for low capillary number ($Ca \le 0.2$) flows. It has been validated using foam made of Newtonian base liquid (golden syrup) and nitrogen.

For high capillary number ($Ca > 0.2$) flows, Barthes-Biesel and Chhim (1981) developed a theoretical constitutive equation for dilute emulsions. The Barthes-Biesel and Chhim equation is expressed as:

$$\frac{\eta_F}{\eta_L} = 1 + \left(2.5 - \psi Ca^2\right)\Gamma \tag{4}$$

For drilling foams, the reasonable value of the dimensionless parameter ψ is 70 (Ahmed et al., 2003).

Foam rheology experiments (Sanghani and Ikoku, 1983) conducted using a concentric annular viscometer at ambient temperature, and low pressure demonstrated the non-Newtonian behavior of foam, which is best described by the power-law rheology model ($\tau = K\dot{\gamma}^n$), where n and K are flow behavior and consistency indices, respectively. The study showed that fluid parameters, n and K are functions of foam quality. Another study (Ozbayoglu et al., 2002) conducted in large-scale experimental setup indicated the existence of gelling or yielding behavior of high-quality foams (≥90%). Hence, the power law model is used for modeling 70% and 80% quality foams while Bingham plastic model ($\tau = \tau_y + \mu_P\dot{\gamma}$) is applied for 90% quality foam. Other experimental studies (Reidenbach et al., 1983; Harris and Heath, 1998; Bonilla and Shah, 2000; Herzhaft et al., 2000) indicated the non-Newtonian behavior of foam, which best fits, the Herschel–Bulkley model ($\tau = \tau_y + K\dot{\gamma}^n$).

2.2. Method of foam generation

Even though many foam rheology studies have reported similar results, some studies recorded conflicting findings indicating the importance of methods of foam generation and characterization techniques in evaluating flow behavior of foams (Saintpere et al., 1999; Herzhaft, 1999). Often foam is generated by either mixing or shearing of a mixture of base liquid containing surfactant and gas phase. The intensity of mixing or shearing and the foam generation duration determine flow properties of the foam. When foam is generated at a given mixing or shearing condition, its viscosity increases with time and reaches equilibrium or constant viscosity. Hence, foams that are not fully generated due to inadequate mixing and/or insufficient time for generation have a lower viscosity than equilibrated foams.

In pipe viscometer, a foam is commonly generated using static mixers, porous media, or special valves, which are placed in-line with the viscometer. In a valve-type foam generator, the mixing energy is determined by the pressure drop across the valve. Hence, the foam generation can be controlled with valve opening and flow rate, which significantly affect pressure drop across the valve. The amount of energy required to generate foam structure is also a function of foam quality. High-quality