Journal of Natural Gas Science and Engineering 26 (2015) 873–882

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

# Rheological behavior of oil-based drilling foams

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ARTICLE INFO

*Article history:*
Received 3 July 2015
Received in revised form
12 July 2015
Accepted 13 July 2015
Available online 17 July 2015

*Keywords:*
Oil-based foam
Rheology
Hydraulics
Underbalanced drilling
Formation damage
Wall slip

ABSTRACT

The application of foam in the petroleum field has been around since the late sixties. Foam has been successfully used in stimulation as well as drilling. It has desirable properties which make it very suitable for underbalanced drilling (UBD) and other oilfield applications such as cementing, well stimulation and fracturing. Aqueous foams have been in the industry for a long time. As a result, in the past, foam research was more focused on characterization of aqueous foams to optimize their hydraulic and hole cleaning performance (solids carrying capacity). Currently, modern foams such as polymer-based and oil-based foams are becoming more popular due to their superior performance. However, flow behavior of modern foams is complex and not well-understood.

The principal objective of this study is to investigate flow behavior of oil-based foams. In order to achieve the study objective, experiments were performed using a recirculating flow loop that has three pipe viscometers. Tests were conducted at room temperature (25 ± 2 °C) and elevated pressure (0.67 MPa). Base liquid was prepared by mixing diesel (68%), mineral oil (30%) and surfactant (2%). Nitrogen was used as the gas phase. Foam quality (i.e. gas volume fraction) was varied from 34 to 68%. The effect of foam quality on bubble size was also investigated to provide further insight into the behavior of oil-based foams.

Results showed non-Newtonian behavior of oil-based foams which becomes more prominent as foam quality increases. Moreover, like aqueous and polymeric foams, rheology of oil-based foams greatly depends on quality and base-liquid viscosity. Wall-slip effect was observed in the small diameter pipe (13.4 mm). The averaged bubble size of oil-based foams increased with foam quality.

## 1. Introduction

Gas and oil production is being carried out at a pace never seen before. The growing demand from emerging economies as well as the already established demand from developed nations has pushed the need for exploration and production of oil and gas to an all-time high. The traditional way of overbalanced drilling has served the industry for a long-time; however, with ever increasing drilling operations, the need for efficient, environmentally friendly and formation specific drilling fluid becomes more important. Drilling low-pressure and depleted wells needs the use of underbalanced drilling. This type of drilling technique requires low-density (light) drilling fluid which has the desired properties to minimize fluid loss, formation damage, and well control and hole cleaning related issues. Drilling foam fluid exhibits low density, high viscosity and good solids carrying capacity. These properties are the most important in performing underbalanced drilling operations.

UBD has the advantage of being economical as well as practical for low-pressure and depleted formations (Cade et al., 2003). The use of foam in UBD or other oil-field applications also has the added advantage of reducing the liquid needed for the operation. The volume of water needed for drilling and fracturing operations has been a major concern over the years especially in areas where water is scarce. In addition to the inherent benefits, the fact that it can be recovered without substantial loss of its liquid phase gives it an added advantage. High quality foams have been often used as they contain small amount of liquid.

Foam is thermodynamically unstable mixture of gas and liquid, which greatly differs rheologically from its components. Rheological properties of foam change with temperature, pressure, foam quality, and base liquid properties (Hutchins and Miller 2003; Lourenço, 2002; Lourenço et al., 2003; Martins et al., 2001a). This means several factors should be considered in formulating foam

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http://dx.doi.org/10.1016/j.jngse.2015.07.022
1875-5100/

fluid for a specific application. The volumetric gas content which is known as the quality of the foam plays a significant role in the effectiveness of the fluid in performing its desired duties. Normally, higher the quality of foam, higher is its viscosity. This can be attributed to the fact that at higher qualities, the interfacial forces between bubbles restrict the free movement within the bulk fluid, hence higher apparent viscosity. In addition, foam structure becomes more rigid as the quality increases. Structural rigidity of the foam improves its viscosity and stability.

Bubble size is also one of the major characteristics of foams. A number of experimental and theoretical studies (David and Marseden, 1968; Harris, 1989; Eren, 2004; Debrégeas et al., 2001; Gopal and Durian, 1998) have examined the relationship between bubble size and rheological properties of foams. Under dynamic (flowing) condition, one of the main factors that affect the bubble size is the shear rate that is applied. At higher shear rates, large bubbles tend to deform and rupture, forming fine bubbles. However, at low shear rates, bubbles tend to degrade and collapse. This indicates the presence of a delicate balance (optimum shear rate) between high and low shear rates.

Over the years, studies were conducted to develop aqueous and polymer-based foams that have the desired properties for drilling application. These foams are frequently used when conventional drilling fluids become impractical due to severe formation damage and lost circulation (Paknejad et al., 2009). However, when dealing with water sensitive formations such as shale and tight gas reservoirs, their effectiveness decreases considerably. Presently, major operational problems in using aqueous and polymer-based foams are: i) temporary overbalance; ii) drilling water-sensitive formations; and iii) inadequate understanding of drilling foam fluid rheology.

Accurate estimation of frictional pressure loss and equivalent circulation density is useful for oil well planning. For incompressible fluids, frictional pressure loss and hydrostatic pressure are determined independently and added to compute the overall pressure drop. This approach is not valid for a compressible fluid such as foam because of strong coupling between frictional pressure loss and hydrostatic pressure. Moreover, frictional and hydrostatic pressure gradients can be comparable for foam fluids (Chen et al., 2006). As a result, using low-density drilling foam alone does not always guarantee underbalanced conditions. Excessive frictional pressure loss can result in a downhole pressure that exceeds the pore pressure even with low-density foam. Often extreme frictional pressure losses occur for a short period of time and may result in temporary overbalance (Lyons et al., 2001). In some cases, excessive temporary overbalance results in more severe formation damage than a conventional drilling operation.

Formation damage during foam drilling is still a major issue in water-sensitive rock formations. Water molecules and ions in these formations can be transported by the chemical potential difference even in underbalanced condition. This results in formation damage and creates various drilling problems. Another possible cause of formation damage during foam drilling is related to spontaneous imbibition that occurs while drilling tight gas reservoirs (Ding et al., 2006). Recently, new types of drilling foams have been introduced to drill water sensitive formations. These types of foams contain oil (mineral oil or other light oils) as the base fluid instead of water or water-based fluid. Oil-based foams have very low formation damage potential and good tolerance for temporary overbalance. Although field tests (Seulveda et al., 2008; Kakadjian et al., 2012) demonstrate the benefits of oil based foams, rheology and hydraulics of these fluids are not well understood. Accurate rheology predictions improve hole cleaning and ensure the safety of foam drilling operation (Martins et al., 2001b). Hence, this study is focused on rheological characterization of oil-based foams.

## 2. Literature review

In the past, a number of studies (Sanghani and Ikoku, 1983; Gardiner et al., 1998) were performed to investigate rheology of aqueous foam. Pipe viscometers were used in most of these studies to characterize flow behavior of foams. Other studies (Ozbayoglu et al., 2000; Ahmed et al., 2003b) focused on topics like hydraulic performance of foam under different conditions. In addition, rheological properties of foams with different viscosifying additives were investigated (Harris, P.S. 1989; Reidenbach et al., 1983; Khade and Shah, 2003; Sherif et al., 2015). Some studies (Herzhaft 1999; David and Marseden, 1968; Harris, 1989) investigated the effects of bubble size and foam texture on rheology of foams.

The viscous properties of foam are influenced primarily by its quality and liquid-phase properties. Foam quality, Γ, is the ratio of the gas volume to foam volume at a given temperature and pressure. Mathematically, it can be expressed as:

$$\Gamma(\mathrm{T},\mathrm{P}) = \frac{V_{Gas}}{V_{Gas} + V_{liquid}} \tag{1}$$

where $V_{\mathrm{Gas}}$ and $V_{\mathrm{liquid}}$ are gas and liquid volumes in the foam, respectively. The liquid phase is assumed as incompressible. The compressibility of the gas phase causes the quality to change when there is a change in pressure and temperature. The quality is the major characterizing property of foam; it affects not only the rheology but also the structure of foam. As the quality increases it reaches a critical point where it attains maximum structural rigidity and viscosity. This specific (critical) point depends up on the liquid phase composition and its rheological properties.

### 2.1. Rheology models and wall-slip

Ozbayoglu et al. (2000) investigated different foam hydraulic models (Beyer et al., 1972; Blauer and Kohlhaas 1974; Sanghani and Ikoku 1983; Gardiner et al., 1998; and Valko and Economides 1992) developed over the years to assess their accuracy. Model predictions were compared with their experimental results. The study indicated that there is no generalized rheology model to predict the pressure losses in foam flows. Moreover, they pointed out that the rheology of intermediate quality (70 and 80%) foams can be best described using power law model while high-quality foam (90%) can be best represented by Bingham plastic model.

Some studies (David and Marseden, 1968; Ahmed et al., 2003a; and Ozbayoglu et al., 2000) considered wall slip in rheology characterization and hydraulic model formulation. The formation of a thin liquid layer at the pipe wall is expected to act as lubricant during the foam fluid flow. This would lead to the reduction of the apparent viscosity near the wall. It has been suggested that if wall slip is observed, flow rate values need to be corrected before the development the rheological model. The analysis performed by Ahmed et al. (2003a) was in agreement with the results of prior investigations made by Beyer et al. (1972) and David and Marsden (1968) in concluding that the slip velocity increases with the wall shear stress.

In the classical sense, foam quality is a major defining characteristic of foam. Foam bubble size and its distribution have been shown to have minor effect on its rheological property. Harris (1989) studied bubble size distribution of different quality foams. Foams exhibited shear-history dependency, which means that the bubble size and its distribution adjust to an equilibrium state that depends on time at a given shear rate. However, foam viscosity was predominantly affected by quality and liquid-phase properties. The effects of bubble size and texture were negligible. Moreover, with increasing quality, the average bubble size of the foam increased