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EXPERIMENTAL INVESTIGATION OF THE RHEOLOGY OF WHITE OIL FOR OIL-BASED DRILLING FLUIDS

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Abstract

The rheological properties of white oil used as the base for drilling fluids were investigated at 4, 10, 20, 30, 50 and 100°C, shear rates ranging from 0 s^{-1} to 1000 s^{-1} and at atmospheric pressure and 3.5 MPa. The results revealed the rheological behaviour of white oil followed that of typical Bingham plastic fluids. When the shear rate increased, the apparent viscosity decreased markedly in the lower shear rate range (< 200 s-1), and as the shear rate increased it tended to exhibit Newtonian behaviour. Shear stress was linearly related to shear rate which fit into a Bingham plastic model. The effect of temperature on viscosity was quantified through modelling (Arrhenius equation), while the influence of pressure was examined by comparing the rheological behaviour of white oil at pressures of 0.1 MPa and 3.5 MPa. This study indicated that plastic viscosities at the higher pressure were generally higher than at the lower pressure, and the effect was more noticeable at lower temperatures.

Keywords: Drilling fluids; Rheological properties; White Oil; Bingham Fluids.

1. Introduction

In petroleum engineering, drilling fluid (or drilling mud) is commonly used to aid the drilling of boreholes into the earth (oil and natural gas wells), and is usually pumped down the drill string to the drill bit and back to the surface through the annulus. During the drilling process, circulation of drilling fluid serves to lubricate and cool the drilling bit, suspend and/or flush out the drill cuttings and control subsurface pressures [1-2]. The behaviour of drilling fluid is typically non-Newtonian, which is dominated by shear resulting from the rotating drill bit under drilling conditions such as high down-hole temperatures and pressures. Therefore, the rheology of drilling fluid is of significant importance and necessary to achieve effective and efficient operations by monitoring and controlling the viscosity of the fluid [3-4].

With the recent advances in oil-based drilling fluids, they have become widely used in the petroleum industry owing to their distinct advantages over water-based drilling fluids in terms of fluid-loss control, lubrication of drill bits and cutting carrying ability [5]. White oil, which is a refined petroleum mineral oil mixture consisting of a combination of liquid saturated hydrocarbons with carbon numbers predominantly C_{16}-C_{31}, has good drilling performance and is environmentally-friendly [6-8]. The physical-chemical properties of white oil are well-documented [9-10], however studies on the rheology of white oil, which are essential to understanding and controlling the rheology of white oil-based drilling fluids, are lacking. Therefore, the aim of the present study was to investigate the rheological properties and behaviour of white oil under industrially-relevant conditions, i.e. at a range of shear rates, temperatures and pressures.

2. Materials and Methods

White oil samples (#5 Industrial White Oil) were supplied by the Xinji Jingshan Petrochemical Factory (Hebei Province) and used without further treatment. A Thermo Haake Rheometer (RS-300) was used to characterise the rheological properties of white oil. In the rotational RS-300 Rheometer, an inner cylinder (bob) rotated inside a restrained outer cylinder (cup). By filling the test sample to the marked level, the fluid sample was confined between the bob and cup. The rotation of the bob generated a velocity gradient (i.e. shear rate) across the gap. While rotation of the bob caused the fluid to flow, its resistance to deformation imposed a shear stress on the inner wall of the cup. The rotational RS-300 Rheometer allowed continuous measurements of the shear stress at selected shear rates under various temperature and pressure conditions. Temperature and pressure were constantly monitored and controlled automatically. In this study shear rates ranged from 0 s^{-1} to 1000 s^{-1} at temperatures of 4, 10, 20, 30, 50 and 100°C, and two pressure levels (atmospheric pressure and 3.5 MPa).

3. Results and Discussion

3.1 General rheological measurements

Figure 1 illustrates the measurements of viscosity versus shear rate at 0-1000 s^{-1} at 4, 50 and 100°C and atmospheric pressure. The viscosity was not constant over the given range of shear rates, clearly demonstrating non-Newtonian behaviour, which is also observed for the majority of drilling fluids [11]. When the shear rate increased, the apparent viscosity decreased markedly at the lower shear rate range (< 200 s^{-1}). As the shear rate increased, the fluid exhibited Newtonian behaviour, which may be due to the hydrocarbon chain molecules untangling from each other and aligning themselves in the direction of flow [12]. The overall viscosity as a function of shear rate closely followed that of typical Bingham plastic fluids [1] at the three temperatures.

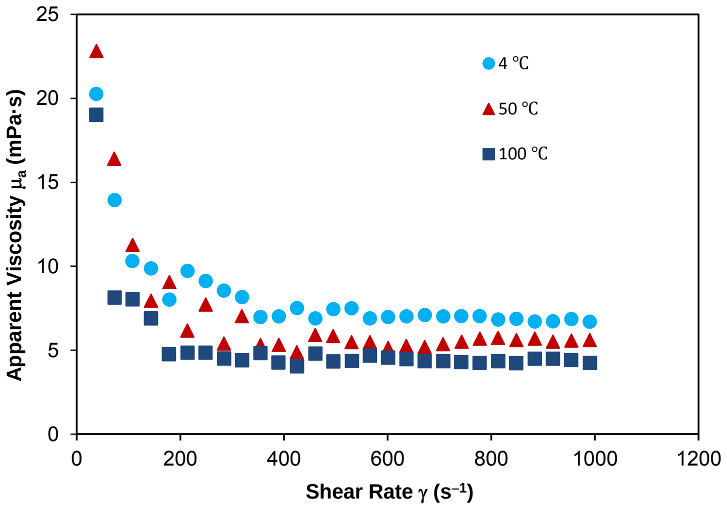

Figure 1. Apparent viscosity as a function of shear rate at different temperatures at atmospheric pressure

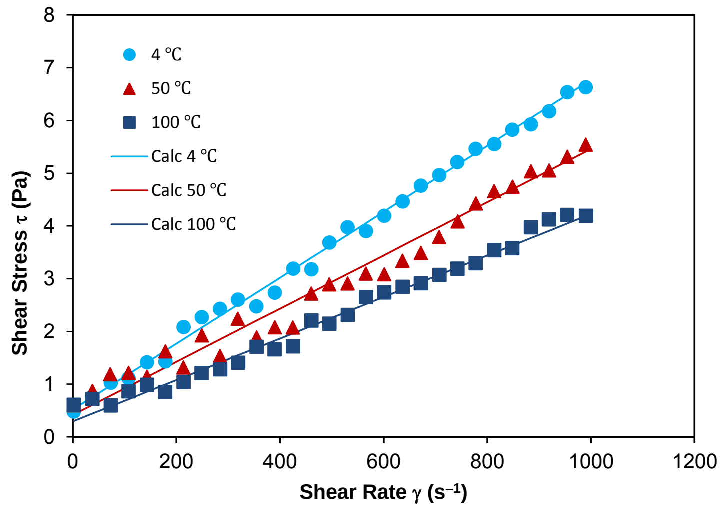

Figure 2. Shear stress vs. shear rate at different temperatures at atmospheric pressure

Figure 2 shows shear stress as a function of shear rate at different temperatures at atmospheric pressure. It shows a linear relationship which can be represented by the Bingham plastic model for viscoelastic non-Newtonian fluids [1,13].

$$\tau = \tau_0 + \mu_P \gamma \quad (1)$$

where τ represents the shear stress (mPa), τ_0 and μ_p are the yield stress (mPa) and the plastic viscosity (mPa s), respectively, and γ is the shear rate (s^{-1}). This model suggests that when shear stress reaches a critical value of τ_0, the white oil starts to flow, and shear stress increases linearly with the increasing shear rate. When shear stress is below τ_0, white oil behaves as an ordinary elastomer [1,13].

3.2 Effect of temperature on rheological properties

By fitting the Bingham plastic model (Equation 1) to experimental data, the best-fit rheological parameters of white oil were obtained for all temperatures at atmospheric pressure (Table 1).

Table 1. Rheological parameters obtained by best-fitting of the Bingham plastic model

T (℃)	τ_o (Pa)	Plastic viscosity μ_p (mPa.s)
4	0.5176	6.2538
10	0.6170	5.6558
20	0.5461	5.5745
30	0.4432	5.3441
50	0.4169	5.0426
100	0.2938	3.9318

The results revealed the plastic viscosity (μ_p) declined with increasing temperature. The yield stress followed a similar trend, except at 4°C, where it was slighter lower than at 20°C, though the reason for the exception was unclear. In general, the viscosity-temperature relationship was in agreement with that of other drilling fluids, where increasing temperature increased the Brownian motion of molecules in the fluid, resulting in decreased viscosity [14-15].

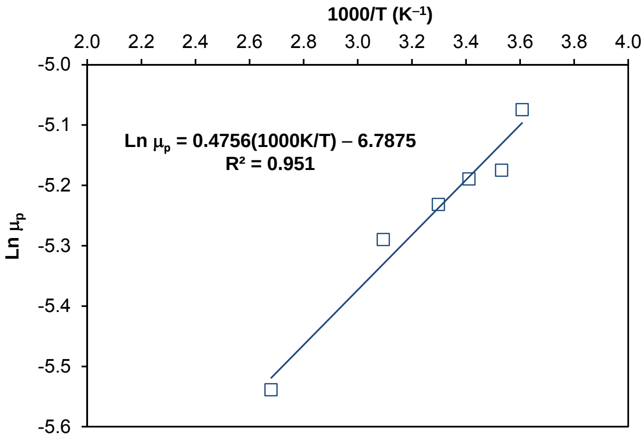

Figure 3. Correlations between plastic viscosity (μ_p) and temperature (*T*) at atmospheric pressure and 3.5 MPa

To quantify the viscosity-temperature relationship, the plastic viscosity was plotted as a function of temperature (Figure 3). It is interesting to note that Ln(μ_p) versus 1/*T* lie on a straight line, and the relationship can be represented by:

$$\mu_p = \frac{1}{A_0} e^{\frac{A}{RT}} \qquad (2) \text{ or}$$

$$\frac{1}{\mu_p} = A_0 e^{-\frac{A}{RT}} \qquad (3)$$

By comparing Equation 3 with the Arrhenius equation [16], $1/\mu_p$ is the fluidity of the fluid, A_0 represents the fluidity factor, and *A* is the activation energy. For this fluid system, A_0 was 886.69 Pa^{-1} s^{-1} and *A* was 3.95 kJ mol^{-1}.

3.3 Influence of pressure on rheological properties

Figures 4a-c show shear stress as a function of shear rate at three temperatures and a pressure of 3.5 MPa (For comparison, data for 0.1 MPa are also shown). As expected, there was a linear relationship between shear stress and shear rate at 3.5 MPa, where the slope of the straight line was slightly higher than at 0.1 MPa and more pronounced at 4°C. This was further confirmed by comparing the plastic viscosities at two pressure levels at different temperatures (Figure 4d), where plastic viscosities at the higher pressure were generally higher than at the lower pressure.

The fluid experienced two opposing effects as both pressure and temperature increased; the increase in pressure tended to increase the viscosity due to its compressibility, while the increased temperature enhanced Brownian motion of the fluid molecules. At 4°C, Brownian motion was relatively low and the effect of increased pressure on compressibility appeared more significant and indicated a more noticeable viscosity increase. With increased temperature, the effect on Brownian motion was more significant, and the viscosity change (as a result of increased pressure) appeared reduced.

Using a similar approach to fit the Bingham plastic model (Equation 1) to experimental data at 3.5 MPa, the correlation between plastic viscosity and temperature was quantified. A_0 was found to be 1021.16 $Pa^{-1}\ s^{-1}$ and A was 4.45 kJ mol^{-1}. Both values obtained at 3.5 MPa were higher than at 0.1 MPa.

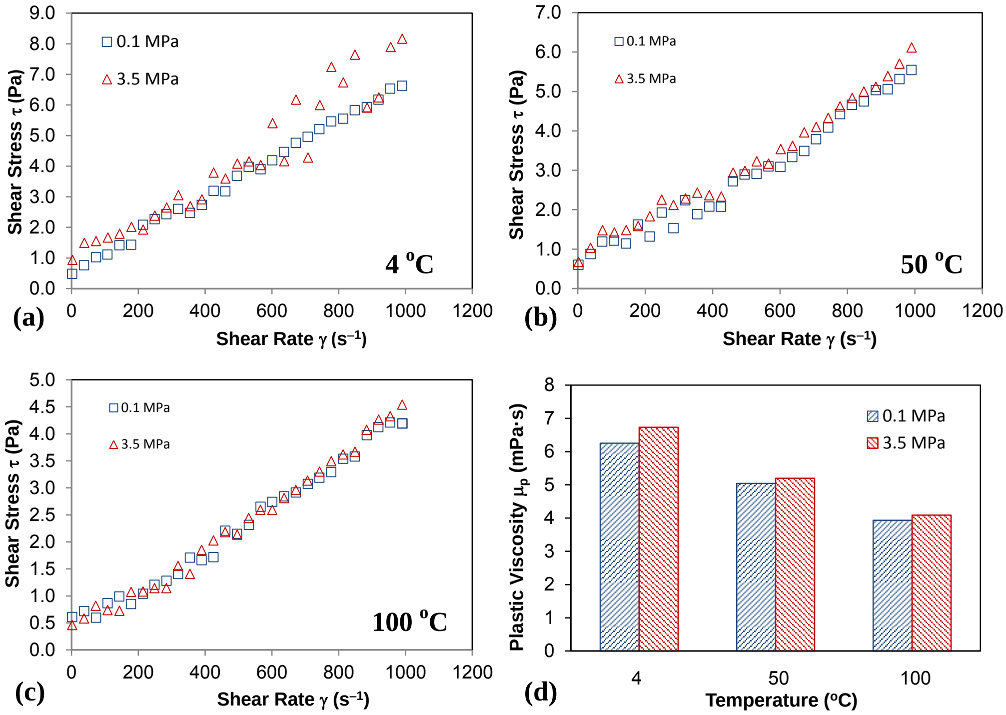

Figure 4. Shear stress as a function of shear rate at 4°C (a), 50°C (b) and 100°C (c). Comparison of plastic viscosity at pressures of 0.1 MPa and 3.5 MPa at different temperatures (d).

4. Conclusions

The rheological properties of white oil were investigated at 4, 10, 20, 30, 50 and 100°C at shear rates ranging from 0 s^{-1} to 1000 s^{-1}, and atmospheric pressure and 3.5 MPa, where the rheological behaviour of white oil was that of typical Bingham plastic fluids. When the shear rate increased, the apparent viscosity decreased at the lower shear rate range (< 200 s^{-1}), and as the shear rate increased, it exhibited Newtonian behaviour. Shear stress had a linear relationship to shear rate which fit into a Bingham plastic model. The effect of temperature on viscosity was quantified through modelling by the Arrhenius equation. The influence of pressure was examined by comparing the rheological behaviour of white oil at 0.1 MPa and 3.5 MPa, which revealed the plastic viscosities at the higher pressure were generally higher than at the lower pressure, and the effect was more noticeable at lower temperatures. The understanding of the rheological behaviour of white oil could be applied to the formulation of oil-based drilling fluids and optimisation of operational conditions.

Acknowledgments

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