Rheological behavior and temperature dependency study of Saraline-based super lightweight completion fluid

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ABSTRACT

This article presents a rheological and statistical evaluation of Saraline-based super lightweight completion fluid (SLWCF) and its effect on operating temperature. In this work, eight rheological models, namely the Bingham plastic, Ostwald–de Waele, Herschel–Bulkley, Casson, Sisko, Robertson–Stiff, Heinz–Casson, and Mizrahi–Berk, were used to describe the rheological behavior of the fluid, and the results were compared with Sarapar-based SLWCF. The results showed that the fluid was best described by both the Sisko and the Mizrahi–Berk models. These two models seem to be able not only to describe the relationship between shear rate and shear stress accurately but also able to accommodate the physical characteristics of the fluids. In the study of fluid viscosity dependency on temperature, the experimental data showed that the viscosity of Sarapar-based SLWCF almost doubled the viscosity of Saraline-based SLWCF. Furthermore, the activation energy seemed to decrease dramatically for both fluids at low shear and tended to remain constant at a higher shear rate. However, Saraline-based SLWCF seemed to be less dependent on temperature, and its behavior could be described by the power equation. Results also showed that the viscosity of the Saraline-based SLWCF was more sensitive to temperature changes at low shear rates.

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1. Introduction

In cased wells, perforation tunnels are the only passages that allow formation fluid flowing toward the wellbore. To create these tunnels, a jet perforation gun is commonly used (Papamichos et al., 1993). However, the pressure impact from a perforating gun impairs and shatters the rock properties (Ibrahim et al., 2009). This often creates a low permeability zone along the perforation tunnels, which leads to reduction of flow potential and well productivity (Bartusiak et al., 1997; Karacan and Halleck, 2003). This rock property impairment is referred to as “perforation-induced formation damage” (Walton, 2000). One of the effective means to minimize this damage is through the application of underbalanced perforation. Underbalanced perforation refers to perforation conducted in a condition in which the wellbore pressure is kept lower than the reservoir pressure (King et al., 1986; Karacan and Halleck, 2003).

Other underbalanced techniques with the use of air, gas, mist, or foam have also been developed to maintain an underbalanced condition before or during detonation of a perforation gun (Al-Riyamy, 2000). The Perforating Ultimate Reservoir Exploitation (PURE) perforating system optimizes the transient underbalance of the well, which occurs instantaneously after the creation of the perforation cavity (Behrmann et al., 2002). The advantages of using these techniques either in the drilling application or completion process include good hole-cleaning capability, the high penetration rate, and the ability to handle considerable formation water (Lorenz, 1980). However, these techniques are not always desirable because they may require additional work, time, special equipment, costs, and safety concerns (Khalil et al., 2010a,b).

In response to the above, an innovative Sarapar-based super lightweight completion fluid (SLWCF) has been successfully formulated to

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Nomenclature

Latin letters

- E_a activation energy ($ML^2T^{-2}M^{-1}$)
- K_{HB} Herschel–Bulkley fluid consistency index (M/LT^{2-n})
- K_{HC} Heinz–Casson fluid consistency index (M/LT^{2-n})
- K_M Mizrahi–Berk fluid consistency index (M/LT^{2-n})
- K_{pl} power law fluid consistency index (M/LT^{2-n})
- K_{RS} Robertson–Stiff fluid consistency index (M/LT^{2-n})
- R gas constant ($ML^2T^{-2}\theta^{-1}M^{-1}$) $= 1.987\times10^{-3}$ kcal/K/mol
- T temperature (θ)

Greek letters

- $\dot{\gamma}$ shear rate (T^{-1})
- $\dot{\gamma}_0$ shear rate correction factor (T^{-1})
- η Heinz–Casson fluid flow behavior index (–)
- η_{HB} Herschel–Bulkley fluid flow behavior index (–)
- η_M Mizrahi–Berk fluid flow behavior index (–)
- η_{pl} power law fluid flow behavior index (–)
- η_{RS} Robertson–Stiff fluid flow behavior index (–)
- η_S Sisko fluid flow behavior index (–)
- k_{0C} square root of Casson fluid yield stress ($M^{1/2}/L^{1/2}T$)
- k_{0M} square root of Mizrahi–Berk fluid yield stress ($M^{1/2}/L^{1/2}T$)
- τ shear stress (M/LT^2)
- τ_B Bingham plastic fluid yield stress (M/LT^2)
- τ_C Casson fluid yield stress (M/LT^2)
- τ_{HB} Herschel–Bulkley fluid yield stress (M/LT^2)
- τ_{HC} Heinz–Casson fluid yield stress (M/LT^2)
- μ viscosity (M/LT)
- μ_0 viscosity under reference condition (M/LT)
- μ_B Bingham plastic fluid plastic viscosity (M/LT)
- μ_C Casson fluid plastic viscosity (M/LT)

achieve the desired well pressure for underbalanced application (Badrul et al., 2009; Khalil et al., 2010a,b, 2011, 2012, 2013). It was expected that the formulated SLWCF is able to create a cleaner perforation tunnel during gun detonation. It is also believed that the formation damage and rock debris from a perforation job were minimized by the surge of fluid flow from the reservoir to the wellbore due to the pressure differential (Bartusiak et al., 1997). Hence, postperforation wellbore treatment, such as acidizing and skin fracturing, may not be necessary (Al-Riyamy, 2000).

The formulated nontraditional SLWCF consists of Sarapar 147 synthetic oil, glass bubbles as a density-reducing agent, with an appropriate stabilizing and homogenizing agent. From laboratory tests, a density value as low as 0.60 g/cm^3 (5.0 lbm/gal) could be achieved. A field test was also conducted by preparing 11,448 L (72 bbl) of similar SLWCF. The mixture was then used in perforation operations of the BKC-18 well of the Bunga Raya field. This real field test reported that the well, completed by using SLWCF, significantly improved the daily oil production rate. The well perforated by using SLWCF showed an additional daily oil production of approximately 1000 barrels compared with a well perforated with conventional completion fluid (Badrul et al., 2009). The use of SLWCF has been considered as one the most attractive ways to achieve an underbalance condition because it does not require additional work, equipment, or special treatment. SLWCF is able to provide an underbalanced condition in the wellbore. SLWCF is also applicable in various reservoirs, including a pressure-depleted reservoir or matured well, in which the wellbore is always in an overbalance or balance condition.

Teow et al. (2001) reported that Saraline and Sarapar are suitable to be used as base oils for Oil Base Mud (OBM) in deep-water exploration activities. They also analyzed the physical properties of Sarapar and Saraline and found that Saraline has a flash point higher than 29.4 °C (85 °F), whereas the flash point of Sarapar is 50 °C (122 °F). Furthermore, Saraline also has a pour point that is lower than −16 °C (3 °F), whereas the pour point of Sarapar is higher than −11 °C (12 °F). It also shows that the benzene content for both Saraline and Sarapar is less than 1 ppm. Aromatics contents of Saraline and Sarapar are less than 0.05 wt% and 0.01 wt%, respectively. The physical and chemical properties of the Saraline and Sarapar base oil are shown in Table 1.

In the upstream oil and gas industry, an accurate understanding of the fluid rheological behavior as a function of formation transient temperature and pressure during, before, and after the operations is important (Davison et al., 1999; Santoyo et al., 2001; Tehrani, 2007; Khalil and Mohamed Jan, 2012). Information on fluid rheology could be used not only to ensure that the fluid meets the requirement of the operation but also to select the correct operational practice. A pioneer study on the formulation of Saraline-based SLWCF was conducted by Muhammad and Raman, 2011. Based on the results, SLWCF with a density value of 0.50 g/cm^3 (4.17 lbm/gal) was formulated with a Saraline to glass bubbles ratio of 60:40, and homogenizing and stabilizing agent content of 3 and 9% w/w, respectively (Muhammad and Raman, 2011). However, no work has been carried out on the investigation of flow behavior of Saraline-based SLWCF. Therefore, as a continuation of previous work, the rheological behavior of Saraline-based SLWCF is presented in this study. The summary of optimized conditions for both Sarapar- and Saraline-based SLWCF are shown in Table 2 (Khalil et al., 2011; Muhammad and Raman, 2011).

Rheological behavior can be described as the relationship between an applied shear stress and the resultant shear rate in a laminar flow condition. This usually can be obtained by curve fitting of experimental

Table 1
Physical and chemical properties of Saraline and Sarapar oil (Teow et al., 2001).

	Units	Saraline	Sarapar
Density	g/cm^3	0.778	0.774
Flash point	°C (°F)	> 29 (> 85)	50 (122)
Pour point	°C (°F)	−16 (3)	> −11 (> 12)
Benzene	PPM	< 1	< 1
Aromatics	wt%	< 0.05	< 0.01
Aniline point	°C (°F)	74 (165)	76 (165)
Specific gravity	60/60 °C (°F)	−17 (0.79)	−17 (0.76)
Plastic viscosity	cP	9	6
Yield point	kg/m^2 (lb/100 sqft)	0.98 (20)	1.22 (25)
Gel strength	(10 s/10 m)	5/15	6/15
Electric stability	V	850	850

Table 2
The optimized conditions for both Saraline- and Sarapar-based SLWCF (Khalil et al., 2011; Muhammad and Raman, 2011).

SLWCF	Saraline	Sarapar
Base oil (%)	60	65
Glass bubbles (%)	40	35
Clay (%)	3	4
Emulsifier (%)	9	10
Density (g/cm^3)	0.50	0.60

Table 3
Rheological models and equations (Kelessidis and Maglione, 2006).

	Models	Equations
1	Bingham plastic	$\tau = \tau_B + \mu_B \dot{\gamma}$
2	Ostwald–de Waele	$\tau = K_{pl} \dot{\gamma}^{n_{pl}}$
3	Herschel–Bulkley	$\tau = \tau_{HB} + K_{HB} (\dot{\gamma})^{n_{HB}}$
4	Casson	$\tau^{0.5} = \tau_C{}^{0.5} + \mu_C \dot{\gamma}^{0.5}$ $(\tau_C{}^{0.5} = k_{0C})$
5	Sisko	$\tau = a\dot{\gamma} + b\dot{\gamma}^{n_S}$
6	Robertson–Stiff	$\tau = K_{RS} (\dot{\gamma}_0 + \dot{\gamma})^{n_{RS}}$
7	Heinz–Casson	$\tau^n = \tau_{HC}{}^n + K_{HC} (\dot{\gamma})^n$
8	Mizrahi–Berk	$\tau^{0.5} = k_{0M} + K_M (\dot{\gamma})^{n_M}$

viscometric data (Livescu, 2012). Flow properties of Sarapar-based SLWCF and its dependence on temperature has been reported by Khalil et al. (2011). Analysis of the results show that Sarapar-based SLWCF is best described by both the Sisko and the Mizrahi–Berk models. It was also found that these two models are able to satisfy the fluid's behavior, which both behaves as Newtonian and non-Newtonian. In this article, similar investigations were carried out for Saraline-based SLWCF. Eight different rheological models, namely the Bingham plastic, Ostwald–de Waele, Herschel–Bulkley, Casson, Sisko, Robertson–Stiff, Heinz–Casson, and Mizrahi–Berk, were used to fit the experimental data. These models were used to predict the rheological behavior of Saraline-based SLWCF. These rheological models are shown in Table 3. Furthermore, the viscosity-temperature relationship was also studied, in which the Arrhenius equation was used to evaluate the fluid viscosity dependency on temperature (Bartlett, 1967; Alderman et al., 1988).

2. Materials and method

2.1. Materials

To formulate Saraline-based SLWCF, Shell Saraline 185 V synthetic oil (Shell Middle Distillate Synthesis, Kuala Lumpur) was used as the continuous phase. Saraline oil is prepared from natural gas, thus it does not contain aromatic hydrocarbons, sulfur compounds, or amines. The density of Saraline oil is 0.778 g/cm^3 (6.49 lbm/gal) (Shell MDS (M) Sdn. Bhd., 2014). 3 M glass bubbles (HGS4000) (3M, St. Paul, Minnesota, USA) were used as a density-reducing agent. To improve fluid stability, clay and suitable emulsifier were used.

2.2. Saraline-based SLWCF formulation

In this study, Saraline-based SLWCF was prepared based on our previous works (Muhammad and Raman, 2011). The fluid was prepared by mixing 60 wt% of Saraline and 40 wt% of glass bubbles. To improve the stability of the fluid, 3 wt% of clay and 9 wt% of emulsifier were added. The mixture was then agitated by using IKA T25 digital ultra-turrax disperser at 6000 rpm for an hour. The readily prepared fluids then were placed in a sealed-cap container for further tests.

2.3. Rheological and temperature dependency measurement

Shear rate and shear stress of the SLWCF were measured by using a rotational Haake Viscometer model VT 550 equipped with MV2P spindle (repeatability and accuracy, $\pm$1%; comparability, $\pm$2). Measurements were carried out by measuring the shear stress at various applied shear rate, which ranged from 2.639 s^{-1} to 264 s^{-1}. To investigate fluid dependency on temperature, fluid viscosity was measured at different temperatures by using a rotational viscometer. The temperature was controlled by a thermostatic water bath (Haake CH bath reservoir with Haake F3 temperature controller) connected to the viscometer. The volume of the sample was approximately 100 mL, and the volume of the water bath was approximately 3500 mL. In addition, the sample was always stirred by the viscometer spindle in the sample cup. These two conditions ensured that the temperature throughout the sample was the same.

2.4. Statistical evaluation

In the investigation of the rheological behavior of the Saraline-based SLWCF, experimental data of SLWCF shear rate and shear stress were fitted to eight different rheological models. The eight rheological models were the Bingham plastic, Ostwald–de Waele or Power Law, Herschel–Bulkley, Casson, Heinz–Casson, Robertson–Stiff, Sisko and Mizrahi–Berk. The fitting was carried out by using a commercial statistical toolbox on Matlab R2013A. Furthermore, to determine the effect of temperature on the viscosity of SLWCF, the Arrhenius equation was used. The relationship between viscosity and temperature according to the Arrhenius law was expressed as the following:

$$\mu = \mu_0 \exp\left(\frac{E_a}{RT}\right) \quad (1)$$

A linear relationship plot of $\ln(\mu)$ against $1/T$ was plotted to evaluate the relationship between viscosity and temperature. The measured viscosities data over the interest temperature range were fitted to the Arrhenius equation. The meaning of symbols for all models and equations can be referred to the nomenclature section.

3. Results and discussion

3.1. Rheological behavior of SLWCF

To study the fluid rheological behavior, shear stress as a function of the applied shear rates of Saraline-based SLWCF were measured and compared with the Sarapar-based fluid. The measured shear stress of the fluids at different shear rates is shown in Table 4 and shows that the measured shear stress of Saraline was lower than that of Sarapar. This may be because Saraline-based SLWCF has a lower concentration of clay than Sarapar-based SLWCF. Clay in the SLWCF formulation acts as viscosifier additive (Shahwan et al., 2006). From Table 2, the optimized percentage of clay in Saraline-based SLWCF is 3%, whereas, in Sarapar-based SLWCF, it is 4%. A lower clay concentration causes the fluid to be less viscous and thus leads to the low shear stress. Low shear stress fluid may lead to reduction of formation damage during perforation.

To assess the rheological behavior of SLWCF, the experimental data were fitted to the eight proposed rheological models mentioned previously. The results of the data fitting along with the

Table 4
The measured shear stress of Saraline- and Sarapar-based SLWCF at different applied shear rates.

Shear rate	Shear stress (Pa)	
(s^{-1})	Saraline	Sarapar (Khalil et al., 2011)
2.639	0.998	3.179
5.279	1.446	4.699
26.4	4.659	11.962
52.71	8.627	17.508
79.28	12.563	22.972
88.17	13.873	23.756
158.3	23.01	38.148
176	25.16	41.532
264	37.983	57.258

corresponding calculated model and statistical parameters, such as *R*-squared, sum of square error (SSE), and root mean square error (RMSE) are summarized in Table 5. The range of *R*-squared in this article is on a 0–1.0 scale. The rheogram of the Bingham-plastic and Ostwald–de Waele models for both Sarapar- and Saraline-based SLWCF are shown in Fig. 1. Based on the results, the Bingham-plastic and Ostwald–de Waele models gave a good prediction for Saraline-based fluids. In our previous work, the SSE and RMSE of Sarapar-based fluid were very high (20.044 and 9.76, respectively) (Khalil et al., 2011), whereas, for Saraline, it was considerably very low (1.03 and 1.33, respectively). However, these two models also gave a considerably high value of *R*-squared values. Based on SSE and RMSE values of all the models, these two models seemed to give less accurate rheological predictions for Saraline-based SLWCF. The magnitude of the SSE and RMSE values of these two models are considerably higher than other models. Low SSE and RMSE values indicate better prediction.

This result can be further observed in Fig. 1, which shows the rheogram of the Bingham-plastic and Ostwald–de Waele predictions. In the case of Bingham-plastic, the prediction seems good at both high and low shear rates. The model seems to perform satisfactorily and is able to estimate the experimental data accurately because the shear stress is directly proportional to shear rate. However, in the case of the Ostwald–de Waele model, this model seems to give a less satisfactory prediction than the Bingham-plastic model. Shown in Table 5, the prediction with the Ostwald–de Waele model gave a greater error (SSE and RMSE) than that of Bingham-plastic model. There are two possible reasons for this phenomenon. First, the shear rate versus shear stress behaves linearly at a lower shear rate, and, second, it is due to the absence of a yield point parameter in the model; this explains the poor prediction of the Ostwald–de Waele model in describing the fluid flow properties (Nasiri and Ashrafizadeh, 2010).

The Herschel–Bulkley, Casson, Robertson–Stiff, and Heinz–Casson models have been proven to be appropriate in describing the behavior of fluid, especially with dispersing particles. In a number of studies (Beirute and Flumerfelt, 1977; Khataniar et al., 1994; Güçüyener and Mehmetoğlu, 1996; Al-Zahrani, 1997; Bailey and Weir, 1998 Kelessidis and Maglione, 2006; Park and Song, 2010), these four models have widely been used in the upstream oil and gas application, such as in the prediction of completion fluids, drilling fluids, and cement slurries. From the results, shown in Table 5, it is apparent that these four models gave a good reliable prediction for Saraline-based fluids. These four models gave almost similar high values of *R*-squared and low magnitudes of SSE and RMSE values compared with the Sarapar-based SLWCF. This result, shown in Figs. 2–5, shows the rheogram of the predictions of these four models. This good prediction could be due to the ability of these four models to satisfactorily accommodate the existence of equation parameters. Hamed and Belhadri (2009) reported that the increment of solid suspension increases the consistency index and decreases the flow behavior index (Hamed and Belhadri, 2009). Saraline-based SLWCF seems to follow this behavior. For Saraline-based SLWCF, a higher concentration of glass bubbles led to a low value for the consistency index and a high value for the flow behavior index. In addition, the power relationship between shear stress and shear rate, and yield point parameters demonstrated good performance. Thus, the four models are appropriate for the prediction of fluid behavior of Saraline-based SLWCF.

Among the eight models proposed in this study, Saraline-based SLWCF could be satisfactorily represented by two models, the Sisko and Mizrahi–Berk models. The rheogram of the Sisko model and the Mizrahi–Berk model are shown in Fig. 6 and 7, respectively. From the results as shown in Table 5, these two models gave the reliable performance in quantitative and qualitative evaluation of the Saraline-based SLWCF.

Table 5
Rheological models of Saraline-based Super Lightweight Completion Fluid with their calculated model's parameters and statistical parameters.

Flow models	Parameters	*R*-squared	SSE	RMSE
Bingham-plastic	$\tau_B=0.9966$ $\mu_B=0.14$	0.99916	1.0351	0.3845
Ostwald–de Waele	$K_{pl}=0.2218$ $n_{pl}=0.9199$	0.99891	1.3324	0.4363
Herschel–Bulkley	$\tau_{HB}=0.6461$ $K_{HB}=0.1747$ $n_{HB}=0.9605$	0.99943	0.6927	0.3398
Casson	$k_{0C}=0.349$ $\mu_C=0.3559$	0.99946	0.6663	0.3085
Sisko	$a=0.1333$ $b=0.4901$ $n_S=0.2904$	0.99952	0.588	0.313
Robertson–Stiff	$K_{RS}=0.178$ $\dot{\gamma}_0=4.041$ $n_{RS}=0.9577$	0.99942	0.7051	0.3428
Heinz–Casson	$\tau_{HC}=0.3533$ $K_{HC}=0.268$ $n=0.6511$	0.99951	0.5972	0.3155
Mizrahi–Berk	$k_{0M}=0.5225$ $K_M=0.2987$ $n_M=0.5263$	0.99955	0.5476	0.3021

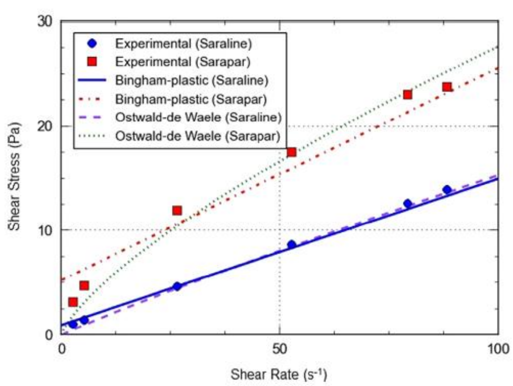

Fig. 1. Shear stress versus shear rate experimental data and fitting plots for Saraline- and Sarapar-based SLWCF based on Bingham-plastic and Ostwald–de Waele model.

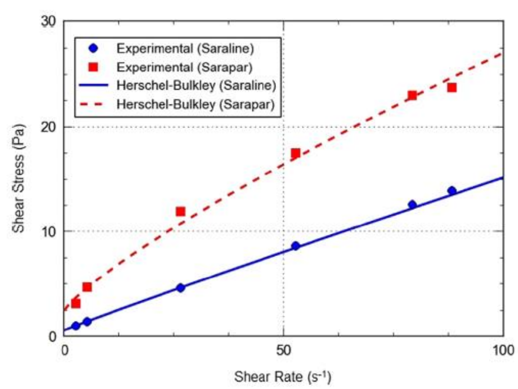

Fig. 2. Shear stress versus shear rate experimental data and fitting plots for Saraline- and Sarapar-based SLWCF based on Herschel–Bulkley model.

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