Study of Viscoelastic Properties of Fluids for Hydraulic Fracturing

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Abstract. The study focuses on the rheological behavior of a fluid based on a viscoelastic surfactant (Surfogel grade D, type 70-100, produced by JSC "Polyex") in wide range of strain rates. This fluid is used for hydraulic fracturing technology as a proppant-carrying and proppant-retaining fluid in order to enhance oil recovery, including those with hard-to-recover oil and gas reserves. Quasi-static experiments to determine the values of the dynamic viscosity of the fluids under study were carried out using a falling ball viscometer (according to the Stokes method). The viscoelastic properties of fluids were studied using a Physica MCR501 rheometer with a cone-plane measuring system and an original rheometer with coaxial cylinders measuring system. The rheological properties of the fluid with the addition of proppant were studied using a RheolabQS rheometer with a measuring system of the type of coaxial cylinders. The analysis of the rheological properties of fluids based on a viscoelastic surfactant has been carried out, and it has been established that fluids based on a viscoelastic surfactant have stable rheological properties over the entire range of strain rates, including fluid with proppant concentration up to 20%.

1. Introduction

Currently, in view of the acute issue of developing low-permeability oil reservoirs, the extraction of oil from which is unprofitable by traditional methods, the technology of hydraulic fracturing has become popular [1]. Hydraulic fracturing is a technological process in which cracks are formed in rocks under the influence of excess pressure created by the injection of fracturing fluid into a well, opening highly conductive paths that allow formation fluid to easily pass through dense rocks into the wellbore. To prevent the fracture from closing, a proppant (screening of quartz sand, ceramic balls and other materials with a fraction of 0.5–1.5 mm), is injected into the well together with the fluid, which holds the fracture from closing after the excess pressure is removed and ensures the flow of formation fluid into the well.

A number of requirements apply to fracturing fluids, the main of which is the retention capacity of the proppant. In order to achieve the required parameters of the deposition rate of the proppant material, solutions using high molecular weight polymers like the hydraulic fracturing fluid are usually used. Such fracturing fluids are non-Newtonian [2–4].

In [5, 6], the rheological and sand-holding properties of a fluid for hydraulic fracturing based on a viscoelastic surfactant were studied. This study involved fracturing fluids based on viscoelastic surfactants produced by JSC "Polyex" (Surfogel grade D, type 70-100) which demonstrated their promising use in hydraulic fracturing operations. They are characterized by high conductivity of the proppant packing (on average 2.7 times higher than the standard guar-based hydraulic fracturing fluid), low clogging ability (the ability to penetrate into pores and cracks in rocks) due to the absence of a polymer phase, long-term preservation of the specified properties, ease of dissolution.
Previously, the authors conducted a study and analysis of the viscoelastic properties of fluids based on surfactants and guar [7]. Viscosity measurements were taken using a Physica MCR501 rheometer with a cone-plane measuring system. A fluid based on a viscoelastic surfactant showed a higher stability of rheological properties, which consists in a weak dependence on the amplitude and the frequency of oscillations of the cone, in contrast to a fluid based on guar, which lost its elastic properties at an oscillation frequency of 5.5 Hz. It was shown in [6] that the elastic properties determine the bearing capacity of the propping material. Based on this, it was concluded that usage of a hydraulic fracturing fluid based on a viscoelastic surfactant is more promising than the currently popular guar-based hydraulic fracturing fluids.

The purpose of this work is to study the rheological properties of a hydraulic fracturing fluid based on a viscoelastic surfactant in a wide range of strain rates, including the addition of a proppant, in order to study changes in the rheological behavior of the resulting dispersed system. The conducted researches are of great importance for further practical use and for determining the parameters of the mathematical model for describing the behavior of fluids based on viscoelastic surfactants [8].

2. Experimental part
The study of the viscoelastic properties of the fluid was carried out using a Physica MCR501 rheometer (Anton Paar GmbH, Austria), which has a cone-plane measuring system with a cone diameter $d = 25$ mm, an angle $\alpha = 1$. Rheometers with such measuring system are used to measure the viscosity dependence on the shear strain rate of viscoelastic fluids, i.e. exhibiting a pronounced non-Newtonian nature of the flow [9-11]. This rheometer is capable of operating both in the shear rate control mode and in the shear stress control mode, and allows rheological studies to be carried out in rotational mode (with an angular velocity from $10^9$ rad/s to $314$ rad/s) and in oscillatory mode (with cone oscillation frequency from $10^7$ rad/sec to $628$ rad/sec). The measurement error was no more than 3%.

![Figure 1. External view of the Physica MCR501 rheometer (a); the investigated fluid placed between the movable disk and the stage (b).](image)

The viscosity was also studied using a rheometer of our own manufacture with a system of coaxial cylinders (rotary rheometer) [9-11]. The setup diagram is shown in figure 2. In the design, the driving force is applied to the outer cylinder, the rotation of which causes the fluid to flow in the annular gap. Due to the resistance of the fluid being sheared, the torque is transmitted to the inner cylinder and causes it to rotate. The annular gap between the cylinders of the rheometer has a constant thickness, tests can be carried out with fluid samples containing particles smaller than 1/3 the size of the gap.

The space between the two coaxial cylinders (1) and (3) was filled with the investigated fluid (2). The stepper motor (4) rotated the outer cylinder with an adjustable linear velocity from 0.005 to 40 cm/s, the inner cylinder was fixed through an elastic element (5) to the base. When the outer cylinder was set in motion, due to viscous stresses in the fluid, the inner cylinder was deflected, deforming the
elastic element. The degree of deformation of the elastic element was previously calibrated by applying a known force $F_{\text{cal}}$ applied to the inner cylinder. The angle of deflection of the inner cylinder was recorded using a SIKC laser rangefinder (7) with a resolution of 2 μm, the error in measuring the viscosity using this rheometer is 7-8%.

Figure. 2. Schematic view of an experimental setup for studying the rheological properties of fluids. 1 - inner stationary cylinder; 2 - investigated fluid; 3 - outer movable cylinder; 4 - electric drive of the outer cylinder; 5 - elastic element; 6 - curtain; 7 - high-precision laser rangefinder.

Figure. 3. Curves of viscosity for the fluid based on a viscoelastic surfactant (● - Physica MCR501 rheometer; ● - original production rheometer; X - Stokes method) depending on the strain rate (vertical axis is logarithmic).

Among other things, the viscosity of the investigated fluid was determined by the Stokes method [9-11], which makes it possible to determine the values of dynamic viscosity at practically zero speed, since a rotary rheometer in the range of low shear rates can give a significant error.

The results of measuring the dynamic viscosity $\eta$ of the fluid based on a viscoelastic surfactant, obtained using a Physica MCR501 rheometer, an original rheometer and determined by the Stokes method at strain rates close to zero, are shown in figure 3 depending on the strain rate.

Figure 4 shows the flow curve (shear stress $\sigma$ vs strain rate $\dot{\varepsilon}$), which illustrates the unstable behavior at a strain rate of more than 380 s$^{-1}$, possibly related to the stratification of the investigated fluid or turbulization of the flow.
Figure 4. Flow curve for the fluid based on a viscoelastic surfactant.

Rheological studies of a fracturing fluid based on a viscoelastic surfactant, with the addition of a proppant in the form of aluminosilicate balls with an average diameter of 1.041 mm “Proppant 16/20” at a concentration of 10 and 20% by weight, were carried out on a RheolabQS rheometer manufactured by Anton Paar, Austria with a measuring geometry in the form of coaxial cylinders with a movable inner cylinder, the measurement error was 3-4% [9-11]. The external view of the rheometer and the measuring geometry is shown in figure 5. The results of measuring the dynamic viscosity of the fluid are shown in figure 6, figure 7 shows the flow curves (shear stress $\sigma$, strain rate $\dot{\varepsilon}$) of the investigated fluid.

Figure 5. a) appearance of the RheolabQS rheometer manufactured by Anton Paar; b) measuring geometry in the form of coaxial cylinders.
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**Figure 6.** Curves of the viscosity for the fluid based on a viscoelastic surfactant, depending on strain rate (● - without proppant, RheolabQS rheometer; ● - with the addition of proppant at a concentration of 10% RheolabQS rheometer; ● - with the addition of proppant at a concentration of 20% RheolabQS rheometer; ● - with the addition of proppant at a concentration of 20%, rheometer of the original setup).

**Figure 7.** Flow curves for the fluid based on a viscoelastic surfactant depending on the strain rate (● - without proppant, RheolabQS rheometer; ● - with the addition of proppant at a concentration of 10% RheolabQS rheometer; ● - with the addition of proppant at a concentration of 20% RheolabQS rheometer; ● - with the addition of proppant at a concentration of 20%, rheometer of the original setup).

### 3. Discussion of results

As a result of the work, the rheological properties of hydraulic fracturing fluid based on a viscoelastic surfactant were studied, including with the addition of proppant, using rheometers of various designs.

The investigated fluid based on a viscoelastic surfactant has stable rheological properties at a wide range of strain rates, including with the addition of proppant at a concentration of 10 and 20% by weight. However, it should be noted that when proppant is added to the investigated fluid, a “yield drop”, similar to the flow curves characteristic of crystalline solids [9,12]. At a proppant concentration of 20%, the beginning of the flow curve sharply rises, which indicates the increasing of ultimate stress, probably caused by sedimentation and coagulation of the proppant [13].

It should be noted that a dispersed solution of proppant in a surfogel is prone to sedimentation (sedimentation of solid particles in a fluid under the effect of gravity) within several tens of minutes [13].

The conducted studies of the rheological properties of fluids based on a viscoelastic surfactant are of great practical and theoretical importance in improving the fracturing technology for oil and gas production from hard-to-recover sources. The rheological properties of fluids based on viscoelastic surfactants under quasi-static and dynamic loading can be used to simulate the behavior of such fluids in hydraulic fracturing processes.
4. Conclusion

A fluid based on a viscoelastic surfactant in earlier works [5,6] showed the main advantages over popular hydraulic fracturing fluids, which include: high residual conductivity of the proppant pack; ease of preparation; high viscosity, which practically does not decrease over time and with increasing temperature; instant recovery of viscosity characteristics after shear.

Together with previous studies [7], which showed stable elastic properties of a fluid based on a viscoelastic surfactant, in comparison with the usually popular guar, which lost its elastic properties at a vibration frequency of 5.5 Hz. It was shown in [6] that the elastic properties determine the bearing capacity of the proppant. And also, on the basis of research data that showed good retention capacity of the propping material while maintaining the specified rheological properties of the fluid, it can be concluded that the use of fluids based on viscoelastic surfactants as fluids for hydraulic fracturing technology is promising.

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