Rheological Properties of BCG-CO$_2$ Fracturing Fluid for Shale Gas

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Abstract. BCG-CO$_2$ fracturing fluid system is especially suitable for shale gas stimulation with advantage of minimizing the actual water consumption, reducing the damage to formation, recovering more rapidly and efficiently, etc. A major objective of this article is to ascertain the rheological properties of BCG-CO$_2$ fracturing fluid in a wide range of experimental conditions for guiding the selection of fracturing parameters. The experimental results showed that as the temperature reaches 35 ℃, the effective viscosity of BCG-CO$_2$ fracturing fluid has an obvious increase. Apparently the shear rate change below 1000 s$^{-1}$ is sharper than that above 1000 s$^{-1}$. The effective viscosity presents an increase trend with increasing foam quality under foamed conditions. It has been concluded that the key factors influencing rheological characteristics of BCG-CO$_2$ fracturing fluid are both temperature and foam quality, and the exponential function form can be used to describe the change rule approximately.

1. Introduction

BCG-CO$_2$ fracturing fluid system can be used to stimulate shale gas with advantage of minimizing the actual water consumption and the impact on the environment, reducing the damage to formation, recovering more rapidly and efficiently, etc.$^{[1-2]}$. Aiming at the field application, the rheology analysis of CO$_2$ foam have been research priorities for about thirty years.$^{[3-4]}$. In fact, studying the rheology performance is critical for predicting the proppant settlement situation in the carrier fluid in the operation. This study is aimed to find out the rheology performance of the CO$_2$ foam fracturing fluid based on the BCG system, and achieve the correlations of rheological coefficient, rheological index and so on. Experiments were carried out in 8 mm pipe over a wide range of foam quality (0 to 75%), pressure (10 to 40 MPa) and temperature (0 to 100 ℃).

2. Experimental method

2.1. Materials
A low damage fracturing fluid system (BCG fracturing fluid) and liquid CO₂ were adopted in experiments. The formulation of fracturing fluid used is: 0.5% BCG-1 + 0.3% B-55 + 0.3% B-13 + 0.3% B-14 + 1% KCl + H₂O.

As above, the BCG fracturing fluid are made of BCG-1, thickener, B-55, viscosity synergist, B-13, high-temperature stabilizer, B-14, modifier and so on. In fact, the fracturing fluid formula was determined by the formulation optimization experiment.

2.2. Test system
A high-parameter foam fracturing fluid test system was adopted in this study. The system diagram and the annotations of each part is also given in the published article detailedly[5].

2.3. Experimental procedure
The test system procedure is as follows: 1) By the refrigeration system transforming the gaseous CO₂ in the CO₂ cylinders into a supercooled liquid; 2) mixing BCG fracturing fluid and the CO₂ in the T-branch pipe by using two plunger pumps, thus the BCG-CO₂ fracturing fluid were formed; 3) Regulating the pressure to the test pressure; 4) Heating foam fracturing fluid to the experiment temperature by red copper electrode; 5) Measuring rheological characteristics of the fracturing fluid at the horizontal test section; 6) Collecting the data of friction pressure drop and the flow rates across the one-meter long test pipeline. The measuring data were stored in the computer for post-processing with the required format. In this way, the rheological parameters and effective viscosity can be obtained under some experimental conditions.

3. Results and discussion

3.1. Effect of temperature
It can be seen from Fig.1 that at low temperature the effective viscosity decreases with temperature. This is because CO₂ is in the supercooled liquid state under low temperature condition, and BCG-CO₂ fracturing fluid presents as two kinds of simple mixing liquid. The rise of temperature makes viscosity of the BCG fracturing fluid and the of liquid CO₂ decrease, so the effective viscosity of the system can decrease. As the temperature reaches 35 °C, the effective viscosity of BCG-CO₂ fracturing fluid has an obvious increase. Actually in this process CO₂ phase transition inevitably occurs transforming from a liquid into a supercritical state, the physical property change of CO₂ makes the internal structure of BCG-
CO₂ fracturing fluid change, the mixed system of BCG fracturing fluid and CO₂ changes from the mixture of liquid-liquid into two-phase mixture of gas-liquid. The system's viscosity-enhancing mechanism mutates, transforming from dependence on thickener space mesh structure to CO₂ deformation of foam system. Therefore, the effective viscosity of system appears a certain degree of increase. At the same time, as the temperature is greater than 35 °C, the viscosity-temperature characteristics is consistent with that at the low temperature.

3.2. Effect of foam quality
As you can see from the Fig.2, the increase of foam quality makes the effective viscosity present the increasing trend. Previous studies showed that the foam quality is one of the most important factors that influence the foam fluid viscosity in the process of studying the rheological properties of the foam. It is because that the foam fluid is complex gas-liquid two phase fluid and the foam structure and form are the most important factors determining the micro structure of the foam fluid, and foam quality is an important factor determining structure and form. The previous study suggests that as the foam quality is lower than 52%, the bubble in two phase flow of foam is mainly round and able to flow freely. As the foam quality is between 52%~73%, the number of bubbles increases in foam two-phase flow, the bubbles will start to contact to each other and rub, and mutual interference between bubbles will cause bubble deformation, break and generation in shear flow process, thus the effective viscosity increase. As the foam quality is between 74%~90%, in the system the bubbles begin to become dense, and the mutual interference will be enhanced. Within this range, the maximum of viscosity will arise. As the foam quality continues to increase, the internal phase and external phase of the foam fluid are reversed. The thickener, BCG fracturing fluid, is dispersed inside CO₂ emulsion droplets. Based on the theory of gas-liquid two phase flow, the flow state, liquid wrapping gas, is destroyed and the flow pattern begins to turn into mist flow, thus resulting in solution viscoelasticity decrease sharply.

![Graph showing foam quality effect on effective viscosity](image)

Fig. 2. Foam quality effect on effective viscosity ($P=20$MPa).

3.3. Correlations of the rheological parameter
The purpose of rheological experimental study is to guide the fracturing treatment, therefore, it is necessary for us to get rheological parameter calculation correlations used by fracturing simulators to estimate treatment operating parameters and fracture geometry. It can be concluded from the experiment results that the key factors influencing rheological characteristics of BCG-fracturing fluid are both temperature and foam quality, and the exponential function form can be used to describe the change rule approximately. Based on the above, the following correlation equations for calculating the rheological parameters can
be obtained and the calculated and measured values of rheological parameters were compared in detail\[^{[8-9]}\].

\[
\begin{align*}
n' &= -4.37497 + 4.99999 \times e^{0.00778/\nu} \times e^{-0.04656\Gamma + 0.03868\Gamma^2} \\
\gamma &= -4.41346 + 4.60047 \times e^{-0.01316/\nu} \times e^{-0.03233\Gamma - 0.03819\Gamma^2}
\end{align*}
\]

(1) \( (2) \)

where, \( t_c = 31.2 ^\circ C \), the application scope of Eq. 1 and 2: \( 10\% \leq \Gamma \leq 75\% \), \( 5\degree C \leq t \leq 80\degree C \), \( 10\text{MPa} \leq P \leq 40\text{MPa} \). The average calculation errors of the above correlations are all within 10%.

4. Conclusion

Rheological properties of the BCG-CO\(_2\) fracturing fluid were studied in depth in the temperature range of 0–100 \(^\circ\)C and the pressure range of 10–40 MPa by using a high-parameter foam fracturing fluid test system. In various influencing factors, the impact of temperature and foam quality on the rheological properties are larger. Under foamed and unfoamed conditions, the influence rule of the foam quality on rheological properties is complete different. The calculation correlations of the BCG-CO\(_2\) fracturing fluid rheological index and rheological coefficient have been obtained, and all average calculation errors are less than 10%, which can satisfy the actual engineering needs.

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