Friction Performance of BCG-CO₂ Fracturing Fluid for Shale Gas

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Abstract. BCG-CO₂ 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 friction performance of BCG-CO₂ fracturing fluid in a wide range of experimental conditions for guiding the selection of fracturing parameters. The experimental results showed that the frictional resistance coefficient levels off under the flow velocity greater than 1 m/s. For the impact of the foam quality on the friction resistance coefficient, the completely opposite change rule is showed under foamed and unfoamed conditions.

1. Introduction
Hydraulic fracturing technology is considered to be one of the most effective methods of stimulating oil and gas wells, and today it has been a standard procedure of completion[1-2]. CO₂ foam fracturing has been used to stimulate the reservoirs of low-permeability, including coal seams and shales[3-5]. BCG-CO₂ fracturing fluid system can be used to stimulate shale gas with the advantage of minimizing the actual water consumption and the impact on the environment, reducing the damage to formation, recovering more rapidly and efficiently, etc[6-7]. Studying friction performance of BCG-CO₂ fracturing fluid is critical for predicting the frictional pressure drop of pipe flow in the operation. This study is aimed to find out the friction performance of the CO₂ foam fracturing fluid based on the BCG system, and achieve the correlations of relevant parameters. 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 °C).

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[8].

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. Foam quality impact on the friction properties
As shown in Fig.1, under foamed condition the friction resistance coefficient shows a rising trend with increasing foam quality. This is because under experimental condition, CO₂ in the system exists as the supercritical state and its property is close to the nature of the gas. The BCG fracturing fluid and supercritical CO₂, two fluids of limited miscibility, form emulsion that is closer to the traditional foam system. When the foam quality increases, in the system the bubbles begin to become dense and the mutual interference is also enhanced between them, causing that friction pressure drop gradient has a great change. Thus, the friction resistance coefficient increases slightly.

![Frictional resistance coefficient vs. foam quality](image1)

Fig. 1. Foam quality effect on frictional resistance coefficient under foamed conditions.

3.2. Flow velocity impact on friction characteristics
It can be seen from Fig.2 that under foamed condition the friction resistance coefficient also decreases with increasing flow velocity, which is consistent to that under unfoamed condition. However, the decreasing range of the friction resistance coefficient under foamed condition is smaller than that
under unfoamed condition. This is mainly because the fracturing fluid under foamed condition presents state of foam, in the process of foam flow the slip flow characteristics will appear in the pipe wall due to the interaction between a large number of bubbles, resulting in the friction resistance coefficient of fluid flow decreases.

![Flow velocity effect on frictional resistance coefficient under foamed conditions.](image1)

**3.3. Temperature impact on friction characteristics**

![Temperature effect on frictional resistance coefficient at different flow velocities (P=20MPa).](image2)

Fig. 3 is changing curve of friction resistance coefficient with the temperature at pressure of 20 MPa under different flow rates. It can be seen that under unfoamed and foamed condition the friction resistance coefficient shows a decrease trend with increasing temperature. However, a sudden increase appears near the critical temperature and the biggest increase amplitude is 35%. This phenomenon is consistent to the change trend of the effective viscosity. The specific reasons have been mentioned. The activation energy of foam system, in general, increases with increasing temperature. The previous experimental studies have found that as the temperature is greater than the critical temperature of CO₂, the effective viscosity presents a decrease trend with increasing temperature, resulting in the friction resistance decreases. It is similar to the change of viscosity that friction resistance coefficient shows a sudden increase trend when phase change of CO₂ occurs.
3.4. Mathematical model of frictional resistance coefficient

The calculation correlations of frictional resistance coefficient of laminar flow and turbulent flow region are unified. The calculating is more convenient. The correlations between the frictional resistance coefficient and the generalized Reynolds number are as follows:

(1) unfoamed condition

\[ \lambda = 11.39212 \text{Re}^{0.64625} \]  

The relational coefficient of correlation is 0.91077, and the average errors of calculation are all within 13.21%. The application scope of Eq. 1 is:

\[ 85 \leq \text{Re} \leq 4030, \quad 0 \leq \Gamma \leq 75\%, \quad 15^\circ \leq t \leq 30^\circ \text{C}, \quad 10\text{MPa} \leq P \leq 40\text{MPa}. \]

(2) foamed condition

\[ \lambda = 14.25602 \text{Re}^{0.68987} \]  

The relational coefficient of correlation is 0.93936, and the average calculation errors are all within 9.46%. The application scope of Eq. 2 is:

\[ 74 \leq \text{Re} \leq 3300, \quad 0 \leq \Gamma \leq 75\%, \quad 30^\circ \leq t \leq 100^\circ \text{C}, \quad 10\text{MPa} \leq P \leq 40\text{MPa}. \]

4. Conclusions

Friction performance 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. Under foamed conditions, the frictional resistance coefficient presents an increase trend with increasing foam quality. It is similar to the change of viscosity that friction resistance coefficient presents a sudden increase trend when phase state of CO$_2$ transforms from the liquid into supercritical state. The calculation correlations of the BCG-CO$_2$ fracturing fluid friction resistance coefficient, $\lambda$, have been obtained, and the average calculation errors are less than 14%, which can satisfy the actual engineering needs.

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