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Rheological Characteristics and Engineering Predictive Modeling of Liquid CO_2/Guar Foam Fracturing Fluids

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Abstract

Although CO_2 foam fracturing fluids are partially heated by the formation during injection, the majority of the CO_2 phase remains in a liquid state along the wellbore. Therefore, investigating the rheological behavior of liquid CO_2 foam fracturing fluids is essential for accurate friction prediction and hydraulic parameter optimization. In this study, a high-precision rotational rheometer was employed to characterize the rheological properties of liquid CO_2/guar-based foam fracturing fluids under controlled temperature and pressure conditions. Compared with conventional large-scale pipe rheometers, the present method provides improved measurement accuracy, repeatability, lower experimental cost, and better variable control. Experimental results indicate that under high shear rate conditions (>30 s^{-1}), the power-law model adequately describes the flow behavior of the liquid CO_2/guar foam system, with a coefficient of determination (R^2) greater than 0.996. The effects of CO_2 volume fraction, temperature, and pressure on the flow behavior index (n) and consistency coefficient (K) were systematically analyzed. An exponential temperature-dependent correlation model for rheological parameters was established, yielding an average prediction error of only 0.658%. The obtained constitutive relationship provides a reliable theoretical basis for generalized Reynolds number calculation and wellbore friction prediction, offering significant engineering guidance for CO_2 foam fracturing design.

Keywords

Liquid CO_2; Foam fracturing fluid; Rotational rheometry; Non-Newtonian fluid; Rheological modeling.

1. INTRODUCTION

Since the introduction of foam fracturing technology in 1968, various foam-based fracturing systems have been developed, including N_2 foam, CO_2 foam, and mixed-gas foam systems. [1] Among them, CO_2 foam fracturing fluids have been widely applied in low-permeability reservoirs due to their superior proppant-carrying capacity, reduced water consumption, rapid flowback, minimized formation damage, and low fluid loss [2-4].

In field operations, CO_2 foam fracturing fluids are typically injected under low-temperature, high-pressure, and high-rate conditions. Under such circumstances, CO_2 bubbles are compressed to micrometer-scale sizes comparable to the liquid phase. Although formation heating occurs during injection, most CO_2 remains in the liquid state along the wellbore rather than reaching supercritical conditions.High friction resistance remains a critical limitation for pump efficiency in field applications. Accurate friction prediction requires reliable viscosity characterization. However, CO_2 foam fracturing fluids are non-Newtonian and thermodynamically unstable systems. Their rheological behavior is influenced by standing time, transport conditions, foaming degree, base fluid preparation quality, and mechanical disturbances, which may lead to bubble coalescence, collapse, or structural rearrangement [5].

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Traditional rheological measurements often rely on pipe-loop systems, falling-ball viscometers, or capillary viscometers. These methods suffer from poor repeatability, limited shear rate range, low precision, and high operational cost. To overcome these limitations, a high-pressure visualized foam preparation system combined with a modular rotational rheometer was developed in this study. The accurate constitutive equations obtained provide theoretical support for wellbore flow and friction modeling.

2. EXPERIMENTAL METHODOLOGY

2.1. Materials

The experimental system consisted of a guar-based crosslinked fracturing fluid widely used in the Changqing oilfield and liquid CO_2. The base fluid formulation was:0.5 wt% hydroxypropyl guar+0.8 wt% foaming agent+0.3 wt% crosslinker.

2.2. Experimental Apparatus

The experimental procedure for rheological properties of CO_2/guar foam fracturing fluids is illustrated in Fig. 1, consisting of three main components: the Foam preparation and delivery system, the temperature control system, and the Rheological measurement system.

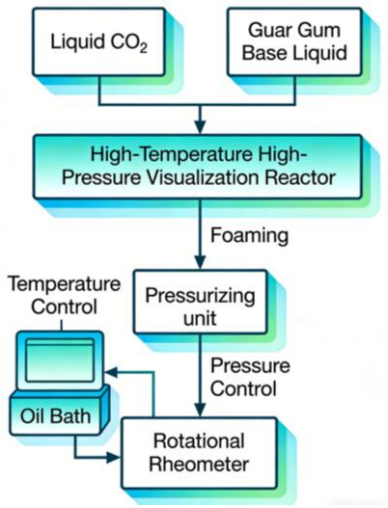


Figure 1. Flowchart of the Experimental System for Rheological Characteristics of Liquid CO_2/guar Foam Fracturing Fluid

A high-temperature, high-pressure visualized reactor was used for precise foam generation. Liquid CO_2 was pressurized using a constant-flow pump and cooled prior to injection into the reactor. After mixing and foam formation under controlled temperature conditions, the foam was transferred to a rotational rheometer using a manual pressurization system. The rheometer temperature was regulated via an oil bath to achieve target testing conditions.

2.3. Rheological Models

Different types of fracturing fluids exhibit different rheological behaviors. Some behave as Newtonian fluids, whereas others exhibit non-Newtonian characteristics. CO_2 foam fracturing fluid belongs to the category of non-Newtonian fluids, and its flow behavior is commonly described using the power-law model, the Bingham model, and the Herschel-Bulkley (H-B) model [6, 7].

(1) Power-law model

The constitutive equation of a power-law fluid is expressed as:

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$$\tau_w = K\dot{\gamma}^n \quad (1)$$

Where τ is the shear stress (Pa); K is the consistency coefficient (Pa·s^n); n is the flow behavior index, which characterizes the deviation from Newtonian behavior; and γ is the shear rate (s^{-1}).

When n = 1, Eq. (1) reduces to the Newtonian fluid equation. When n > 1, the fluid exhibits shear-thickening behavior, whereas when n < 1, the fluid exhibits shear-thinning behavior. For fracturing fluids, a smaller value of n is generally preferable.

Due to experimental limitations, the shear rate cannot be reduced to sufficiently low values. Under high shear rate conditions, the fluid behavior follows the power-law pattern. Therefore, most experimental studies on CO_2 foam fracturing fluids adopt the power-law model for rheological characterization.

(2) Bingham model

The constitutive equation of a Bingham fluid is expressed as:

$$\tau_w = \tau_0 + \eta_p\dot{\gamma} \quad (2)$$

Where τy is the yield stress (Pa), and μp is the plastic viscosity (Pa·s).

A Bingham fluid does not flow when the applied shear stress is lower than a certain threshold value. Flow occurs only when the applied shear stress exceeds this critical value. At low shear rates, the viscous shear stress shows a nonlinear relationship with shear rate, whereas at high shear rates, it exhibits an approximately linear relationship.

(3) Herschel-Bulkley (H-B) model

The constitutive equation of the Herschel-Bulkley model is expressed as:

$$\tau_w = \tau_0 + K\dot{\gamma}^n \quad (3)$$

The H-B model can be regarded as a combination of the Bingham model and the power-law model. Therefore, the physical meanings of the parameters in this equation are consistent with those in the respective models.

Although the H-B model simultaneously accounts for yield stress and pseudoplastic behavior, the yield stress parameter is difficult to determine accurately. [8] As shown in Table 1,based on the measured data, it was found that under high shear rate conditions (>30 s^{-1}), both the power-law model and the H-B model provide comparable fitting accuracy for liquid CO_2/guar fracturing fluids, with coefficients of determination (R^2) greater than 0.99609. Both models perform significantly better than the Bingham model. Therefore, considering model simplicity, the power-law model was adopted in this study to process the flow data of liquid CO_2 foam.

Table 1. Average Coefficients of Determination (R^2) for Different Rheological Models

Model	Minimum R^2	Average R^2
Power-law	0.99609	0.9977
Herschel–Bulkley	0.99618	0.9981
Bingham	0.89664	0.9332

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3. RESULTS AND DISCUSSION

3.1. Effect of CO_2 Volume Fraction

Foam quality is closely related to the flow performance of foam fracturing fluids and serves as a prerequisite for preparing an ideal liquid CO_2 foam system. [9] However, foam quality is a function of temperature and pressure, resulting in significant variations under different experimental conditions.

Under high-pressure conditions, the foam density approaches the mixed density of liquid CO_2 and the guar-based base fluid. Therefore, with the base fluid formulation kept constant, the volume fraction ratio of liquid CO_2 to guar base fluid was used as the primary parameter to characterize variations in foam composition. This section focuses on the influence of volume fraction on apparent viscosity and rheological parameters. Fig. 2 presents the variation of apparent viscosity with shear rate at different volume fractions. The foam exhibits typical non-Newtonian behavior, with apparent viscosity decreasing as shear rate increases. The relationship between apparent viscosity and volume fraction is non-monotonic. Within the shear rate range of 30 s^{-1} to 1000 s^{-1}, the foam system with a volume fraction of 0.5 exhibits the highest viscosity, whereas the viscosities at volume fractions of 0.4 and 0.6 are similar. When the shear rate exceeds 300 s^{-1} and the volume fraction is greater than 0.5, the apparent viscosity decreases with increasing CO_2 content. This phenomenon can be attributed to the reduction in foam stability at higher CO_2 fractions. Increased CO_2 content leads to thinner liquid films and enhanced structural sensitivity, making the foam more susceptible to disturbance and rupture. In addition, under high volume fraction conditions, the flow regime gradually transitions from liquid-continuous to gas-continuous flow, approaching a mist-like flow pattern. Since the gas-phase viscosity is much lower than that of the liquid phase, the overall foam viscosity decreases with increasing CO_2 proportion.

In summary, the effect of volume fraction on the viscosity of liquid CO_2 foam is nonlinear, and the maximum viscosity is obtained at a volume fraction of 0.5. Based on this result, subsequent experiments investigating the effects of temperature and pressure on rheological behavior were conducted using a fixed volume fraction of 0.5.

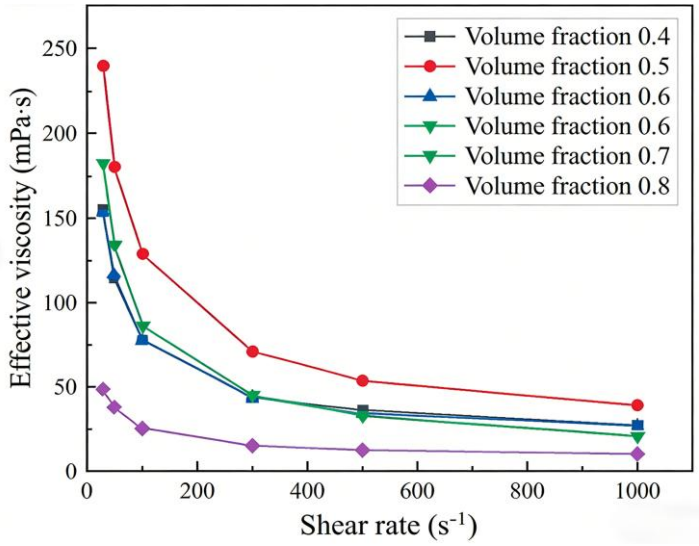


Figure 2. Apparent viscosity of liquid CO_2/guar fracturing fluid as a function of shear rate at different volume fractions (20 °C, 20 MPa)

3.2. Effect of Temperature on Rheological Properties

During field injection of CO_2 fracturing fluids, the fluid is heated by the formation. Temperature variations alter several key factors influencing foam rheology, including gas-liquid

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interfacial tension, liquid-phase viscosity, gas-liquid ratio, and bubble structure. Fig. 3 shows the relationship between shear stress and shear rate at different temperatures. Within the shear rate range of 30 s^{-1} to 1000 s^{-1}, shear stress decreases significantly with increasing temperature, and the corresponding viscosity also decreases. This behavior is primarily attributed to the decrease in liquid CO_2 viscosity as temperature increases. In addition, partial vaporization of liquid CO_2 further reduces the overall foam viscosity. Meanwhile, the reduction in interfacial dilatational viscoelastic modulus weakens bubble interactions, thereby decreasing the macroscopic viscosity.

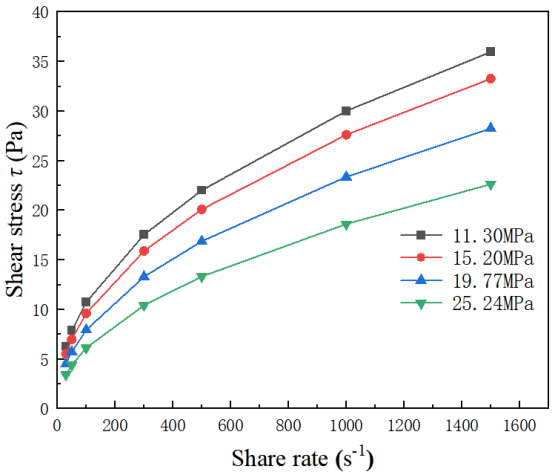


Figure 3. Relationship between shear stress and shear rate of liquid CO_2/guar fracturing fluid at different temperatures (volume fraction 0.5, 25 MPa)

3.3. Effect of Pressure on Rheological Properties

During the fracturing process, the pressure of liquid CO_2 increases from approximately 1–2 MPa in storage tanks to about 50 MPa to overcome formation pressure. Therefore, pressure is also an important variable. To simulate field conditions as closely as possible, system pressure was adjusted by continuously injecting fluid. Due to equipment limitations, the maximum experimental pressure was approximately 25 MPa. Fig. 4 presents the variation of shear stress with shear rate under different pressure conditions. Under liquid-phase conditions, pressure changes do not significantly alter the flow characteristics of the foam. The shear curves at different pressures largely overlap and all conform to power-law fluid behavior. As shown in Fig. 5, fitting analysis of the shear curves indicates that both the consistency coefficient (K) and flow behavior index (n) vary only slightly with pressure. This phenomenon can be explained as follows: under liquid conditions, the viscosity of the base fluid (approximately 98.7% water) decreases slightly with increasing pressure, whereas the viscosity of liquid CO2 increases slightly. However, the magnitude of viscosity variation for both phases is small, resulting in a negligible influence on the overall rheological parameters. Therefore, the rheological properties of the liquid CO_2/guar fracturing fluid are not sensitive to pressure variations under liquid-phase conditions.

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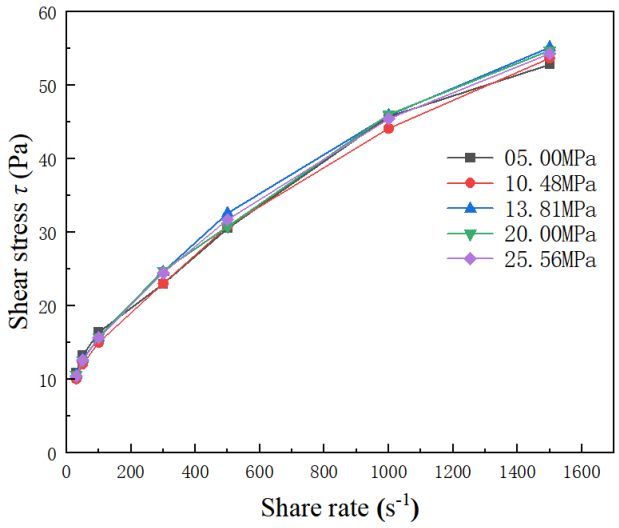


Figure 4. Relationship between shear stress and shear rate of liquid CO_2/guar fracturing fluid at different pressures (volume fraction 0.5, 13 °C)

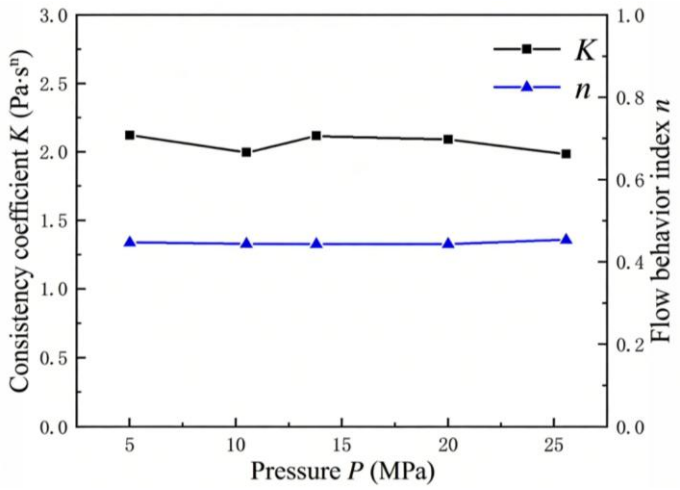


Figure 5. Variation of flow behavior index and consistency coefficient of liquid CO_2/guar fracturing fluid with pressure (volume fraction 0.5, 13 °C)

3.4. Correlation Model of Rheological Parameters for Liquid CO_2/Guar Fracturing Fluid

The rheological properties of liquid CO_2/guar fracturing fluid are influenced by multiple factors. Based on the previous experimental results, volume fraction and temperature are identified as the primary variables affecting rheological parameters. To ensure optimal proppant-carrying performance and consistency with field operations, the volume fraction corresponding to maximum viscosity (0.5) was selected as the fixed composition. Under liquid conditions, the influence of pressure on rheological behavior can be neglected. Therefore, this section considers only the effect of temperature and establishes empirical correlation models for the consistency coefficient (K) and flow behavior index (n) as functions of temperature.

In rheology, the temperature dependence of parameters is commonly described by an exponential form:

$$y = y_0 + Aexp(R_0 t) \quad (4)$$

Where y_0, A, and R_0 are fitting constants.

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Using this functional form, the experimental data of liquid CO_2/guar fracturing fluid were fitted to obtain the corresponding correlations.

$$n = 0.9615 - 0.57723\exp(-0.00962 \times t) \quad (5)$$

$$K = 0.40239 + 6.13197\exp(-0.1042 \times t) \quad (6)$$

By substituting Eqs. 5 and 6 into the power-law constitutive equation (Eq. 1), the constitutive equation for a volume fraction of 0.5 at different temperatures and pressures can be derived (Eq. 7).

$$\tau_w = (0.40239 + 6.13197\exp(-0.1042 \times t))\dot{\gamma}^{0.9615 - 0.57723\ \exp(-0.00962 \times t)} \quad (7)$$

Fig. 6 compares the calculated viscosities obtained from the fitted rheological parameters with the experimental values. The average prediction error is 0.658%.

After establishing the variation patterns of the rheological parameters for the power-law fluid, the generalized Reynolds number under different operating conditions can be calculated, providing support for subsequent studies on wellbore flow regimes and friction prediction.

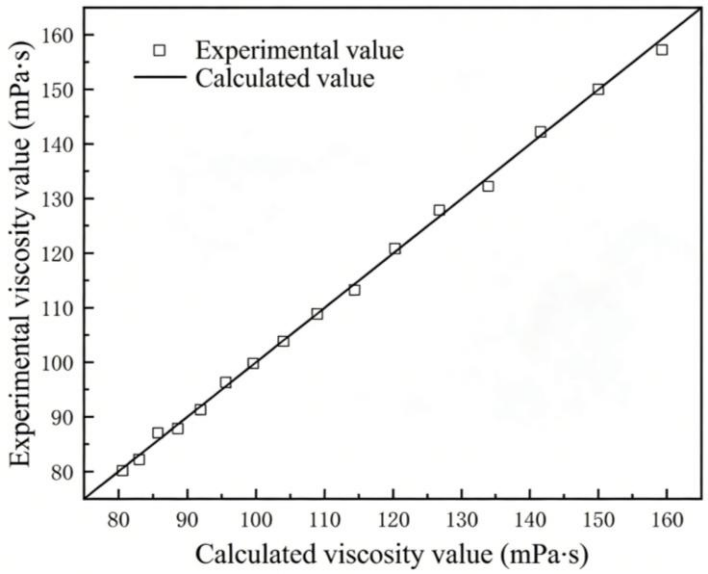


Figure 6. Comparison between calculated and experimental viscosities of liquid CO_2 foam

4. CONCLUSION

Based on the high-pressure rheological testing system for CO_2 fracturing fluids, this study successfully achieved high-precision, repeatable, low-cost, and well-controlled measurements of the rheological parameters of liquid CO_2/guar fracturing fluids under various operating conditions. The experimental platform effectively overcame the limitations of traditional devices, including low pressure resistance, restricted shear rate range, and foam instability. The following conclusions are drawn:

When the volume fraction is 0.5, the viscosity of the liquid CO_2/guar fracturing fluid reaches its maximum. As temperature increases, the shear stress (and viscosity) of the foam fracturing fluid decreases. Under liquid-phase conditions, pressure variations have only a minor effect on the viscosity of the liquid CO_2/guar fracturing fluid.

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The liquid CO_2/guar fracturing fluid exhibits pseudoplastic behavior. Under high shear rate conditions, the power-law constitutive equation provides a better fit than the Herschel–Bulkley and Bingham models.

The variation of rheological parameters of the liquid CO_2/guar fracturing fluid with temperature follows an exponential functional relationship. The average fitting error of the proposed model is 0.658%.

REFERENCES

[1] Z.G. Wang, et al: Study on rheological properties of supercritical CO_2/HPG foam fracturing fluid, Chemical Engineering of Oil & Gas, (2003) No. 1, p. 42-45+1.

[2] J.N. Hu, et al: Preparation and performance evaluation of a self-crosslinking emulsion-type fracturing fluid for quasi-dry CO2 fracturing, Gels, Vol. 9 (2023) No. 2, p. 156–156.

[3] T.Y. Liu, G.j. Chen, and K. Tan: Application of CO2 foam fracturing technology in deep gas reservoirs, Natural Gas Industry, Vol. 27 (2007) No. 8, p. 88–90.

[4] X. Wang, J. Wu, and J. Zhang: Application of CO2 fracturing technology for terrestrial shale gas reservoirs, Natural Gas Industry, Vol. 34 (2014) No. 1, p. 64-67.

[5] Q.C. Lv: Investigation of stability, rheology and leakoff characteristics of N2/liquid CO2 foam fracturing fluid (Ph.D., China university of petroleum, China 2018), p.46.

[6] Jawad A.D., et al: Water chemistry role in the stability of CO2 foam for carbon sequestration in water aquifers. Gas Science and Engineering, Vol. 118 (2023), p. 205090.

[7] C.W Xiao, B.S. N., and C.L. W: Rheology of viscous CO2 foams stabilized by nanoparticles under high pressure, Industrial & Engineering Chemistry Research, Vol. 56 (2017) No. 29, p. 8340–8348.

[8] Z.J. Wang, et al: Rheological behavior and flow characteristics of oil-based CO2 foam under varying petroleum industry conditions, Fuel, Vol. 385 (2025), p. 134086–134086.

[9] S.L. Yang, et al: Study on friction calculation for CO_2-foam fracturing fluids under high temperature and high pressure, Petroleum Drilling Techniques, (2007) No. 6, p. 1-4.