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# Application and Optimization of Rheological Mathematical Models in Preparation and Injection Process of Polymer Flooding

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**Abstract:**

The impact of shear on the properties of polymer solutions is not fully accounted for in the simulation of conventional rheological models. To optimize the application of these mathematical models, the shear rheological characteristics of polyacrylamide at various concentrations were investigated under different shear rates and shear modes. The results indicate that pseudoplastic fluid polymers exhibit two distinct rheological characteristics within their "shear thinning" rate range. The critical shear rate at this threshold signifies the point at which shear stress begins to disrupt the structure of the polymer solution, resulting in a rheological curve that transitions from high to low shear rates without reverting back to a low-to-high state. The concentration of the solution has minimal effect on the critical shear rate of the polymer, which is primarily determined by the inherent properties of the polymer itself. The application of rheological models during preparation and injection processes can elucidate the effects of shear on polymers by analyzing changes in apparent viscosity. Furthermore, the rheological model following supercritical shear rates requires modifications to the consistency coefficient (K) and flow index (n) based on shear rheological data obtained from high to low shear rates.

## 1. INTRODUCTION

Under specific reservoir conditions, polymer flooding often determines the type of polymer solution and the means of preparation and use based on the reservoir conditions. That is to say, if the conditions such as water temperature, mineralization degree, and polymer type are determined, then the polymer injected into the formation only has the influence of shear on its solution performance [1-4]. Therefore, researchers use the generalized Newtonian fluid model [5-10] to construct a polymer flooding model for simulating the rheological properties of polymers based on the general range of polymer shear rates in practical applications in mines, which is 0.1~100$s^{-1}$. Ignoring the destructive effect of strong shear during polymer formulation on polymer solutions and relying solely on rheological experiments to obtain rheological curve characteristics under target concentration conditions for simulation applications is inaccurate.

Currently, the actual polymer injection process is primarily divided into two stages: preparation and maturation, followed by high-pressure injection [11]. During the preparation and maturation stage, the polymer solution experiences a large volume channel and a low flow rate due to the action of a screw pump, which mitigates the mechanical shear effect. Consequently, simulation analyses can be conducted based on the rheological curves obtained under corresponding concentration conditions in controlled environments [12, 13]. However, once the polymer solution is pumped through the polymer injection pump, it inevitably encounters strong shear effects (such as reflux and directional turbulence) before being injected into the formation via the pipe column [14, 15]. Therefore, utilizing the rheological curves obtained in controlled settings to fit the power-law model for calculations and simulations may no longer yield accurate results. In the context of polymer flooding and injection, it is essential to fully consider the actual damage to the polymer caused by shear action and to apply a suitable mathematical model to accurately guide applications in the mining sector. Accordingly, this article thoroughly examines the influence of shear on polymer rheology, investigates the shear rheological characteristics of partially hydrolyzed polyacrylamide (HPAM), and establishes an appropriate shear rheological model and application method for describing the behavior of polymers during the injection process.

## 2. EXPERIMENTAL CONDITION

### 2.1. Experimental Materials and Equipment

Polyacrylamide polymer (industrial application polymer in Daqing) -600000 molecular weight, mechanical stirrer (German company Aika), RS600 rheometer (US), 3000mg/L NaClsolution, 1L glass beaker.

### 2.2. EXPERIMENTAL PLAN AND STEPS

Polymer solutions of partially hydrolyzed polyacrylamide (HPAM) with concentrations of 1000 mg/L, 1400 mg/L, 2000 mg/L, and 2500 mg/L were prepared. Initially, the viscosity of these solutions was measured under varying concentration conditions using a cloth viscometer at a shear rate of 7.34 $s^{-1}$. Subsequently, the rheological properties were assessed using an RS600 rheometer across shear rate ranges of 0.1 to 100 $s^{-1}$, 0.1 to 1000 $s^{-1}$, 0.1 to 2000 $s^{-1}$, 0.1 to 2500 $s^{-1}$, 0.1 to 5000 $s^{-1}$, and 0.1 to 10000 $s^{-1}$, respectively.

The testing procedure for the rheometer is as follows:1) Add the CS/CR Rotation step icon to the task window.2) In the Parameters section of the Rotations tab, select CR mode to set the shear rate. 3) Choose logarithmic mode in the Distributor and set the test data points. 4) In the Acquisition section of the Rotation tab, select 15 seconds from the Maximum waiting time option. 5) Switch to the temperature tab and set the temperature prior to commencing the test.

In step (2), there are two types of shear rate mode settings. The first method involves: Setting the pre-shear rate to 7.34 $s^{-1}$ for 20 seconds, Adjusting the shear rate from low to high (e.g., 0.01 to 100 $s^{-1}$), and Adjusting the shear rate from high to low (e.g., 100 to 0.1 $s^{-1}$). The second method consists of: Setting the pre-shear rate to 7.34 $s^{-1}$ for 20 seconds,Adjusting the shear rate from high to low (e.g., 100 to 0.1 $s^{-1}$), andAdjusting the shear rate from low to high (e.g., 0.01 to 100 $s^{-1}$).

## 3. RESULTS AND DISCUSSION

### 3.1. Rheological Characteristics Under Different Shear Rates

The rheological curves of a polymer solution with a concentration of 2000 mg/L under various shear rate conditions are presented in Figure **1**.

From Figure **1**, it is evident that the rheological curve characteristics at lower shear rates exhibit a high

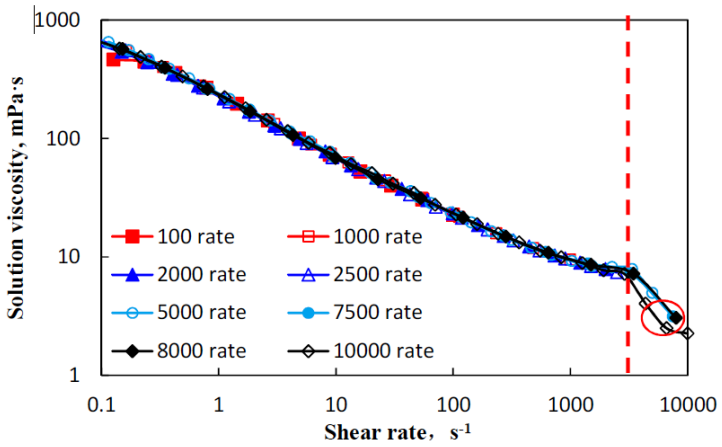


**Figure 1:** Rheological curves of polymers under different shear rate conditions.

degree of consistency. As the shear rate increases, particularly around 2500 $s^{-1}$, the rheological shear characteristics of the polymer display a significant mutation in the double logarithmic coordinates, while still adhering to the "shear thinning" behavior. With further increases in shear strength, the rheological characteristic curve demonstrates a gradual trend across the shear rate range of 0.1 to 10000 $s^{-1}$. This indicates that additional increases in shear rate completely disrupt the molecular structure of the polymer solution, transitioning into the second Newtonian zone and reaching the ultimate viscosity value, $\mu_\infty$[16, 17].

The nodes exhibiting significant changes in rheological characteristics within the shear thinning range have implications for the fitting of rheological models. Furthermore, the analysis suggests that the polymer's molecular structure has been compromised under the current shear rate conditions. Therefore, it is essential to conduct a thorough analysis at this critical point.

### 3.2. The Influence of Shearing Methods on the Characteristics of Rheological Curves

This study analyzes the effect of shear mode on the rheological curve of a polymer solution with a concentration of 2000 mg/L under high shear rate conditions (0.1 to 10000 $s^{-1}$). Mode A refers to the low-high-low shear rate pattern, while Mode B refers to the high-low-high shear rate model. In this context, "a" denotes the shear rate increasing from low to high, and "b" denotes the shear rate decreasing from high to low, as illustrated in Figure **2**.

Based on Figures **1** and **2**, it is evident that under Mode A conditions, a high shear rate significantly impacts the rheological state of the polymer solution. When shearing from high to low, the rheological curve of the polymer solution does not return to its original state; instead, it exhibits distinct rheological characteristics. This observation indicates that high shear rates cause damage to the molecular structure of the polymers, preventing them from retaining their original rheological properties. Consequently, the damaged polymer behaves as a pseudoplastic fluid with shear-thinning rheological characteristics. In contrast, under Mode B conditions, the two shear rheological curves demonstrate consistency, suggesting that the polymer fluid, following a certain degree of shear failure, exhibits stable rheological properties without further significant shear degradation. This stability arises because the rheological characteristic curve serves as a macroscopic representation of polymer solutions, with each state corresponding to specific rheological curve characteristics.

### 3.3. Limit of Shear Rate Affecting Rheological Characteristics

The variation characteristics of polymer solutions with a concentration of 2000 mg/L across different rheological shear rate ranges were identified through the aforementioned experimental methods. A further analysis of the influence of shear methods on the rheological characteristics at a shear rate of 2500 $s^{-1}$ is presented in Figure **3**.

The shear rheological properties within the shear rate range of 0.1 to 2000 $s^{-1}$ exhibit a high degree of consistency, indicating that the structure of the polymer solution remains intact. However, when the shear rate increases further to 2500 $s^{-1}$, the two rheological curves diverge, suggesting that the solution's structure has altered under high-speed shear conditions. This indicates that the polymer solution continues to exhibit

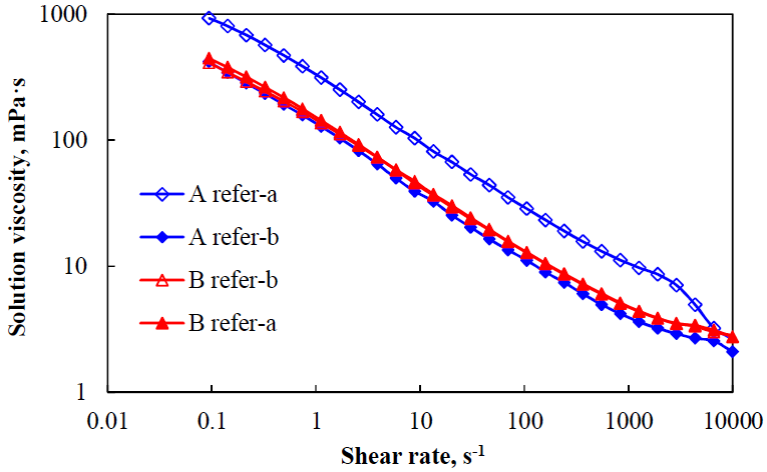


**Figure 2:** Effect of Rheological Shear Methods on Rheological Curve.

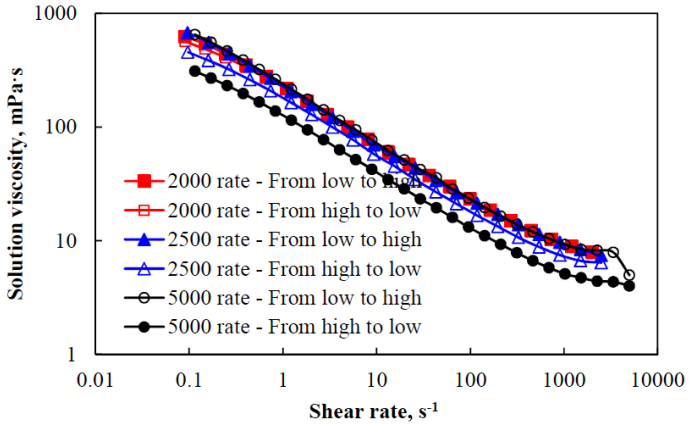


**Figure 3:** Rheological curves under different shear rate conditions.

"shear-thinning" rheological characteristics. The differences between the two rheological curves within the shear rate range of 0.1 to 5000 $s^{-1}$ become more pronounced, and analysis suggests that this is attributable to the varying degrees of damage inflicted on the polymer molecules by shear action. The intense shear forces disrupt the structure of the polymer solutions, resulting in changes to their rheological behavior. Nevertheless, the bulk of the solution remains a non-Newtonian fluid with inherent rheological properties, albeit with altered performance characteristics. Consequently, the application of the rheological curve of polymers has practical limitations, as the shear rate at which changes in their rheological behavior occur defines the boundaries of their applicability.

### 3.4. The Effect of Concentration on Critical Shear Rate

The critical shear rate limits under different polymer concentration conditions are shown in Figure **4**.

The rheological curve characteristics of different solution concentrations within the shear rate range of 1 to 10000 $s^{-1}$ remained consistent with increasing solution concentration; however, all significant changes occurred around the critical shear rate of 2500 $s^{-1}$, at which point their rheological behavior altered. This indicates that, for a given polymer solution, the critical shear rate is independent of the solution concentration and is determined solely by the intrinsic properties of the polymer itself.

### 3.5. Formula Correction and Application of Polymer Injection Process

The critical shear rate condition represents the threshold at which the molecular structure of the polymer solution remains intact, referred to as the critical shear rate ($\gamma_{临}$). When the shear rate is less than the critical shear rate ($\gamma_{临} < \gamma$), the rheological characteristics of the polymer adhere to the power law formula [18]. Conversely, when the shear rate is equal to or greater than the critical shear rate ($\gamma \geq \gamma_{临}$), the

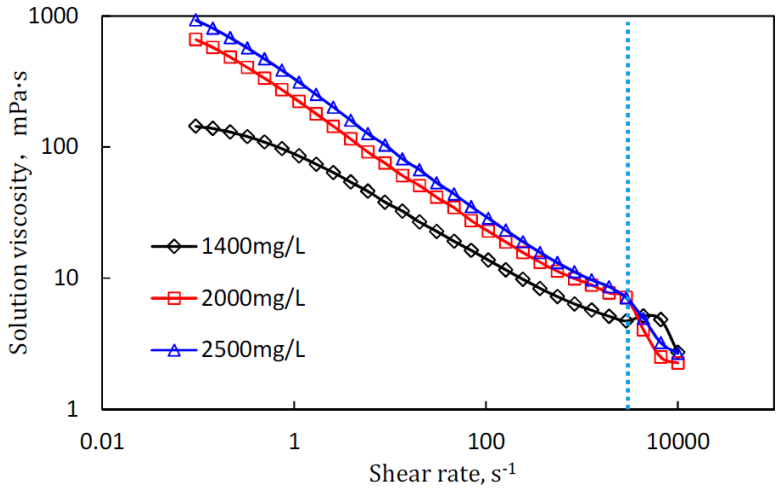


**Figure 4:** Critical shear rate under different concentration conditions.

mathematical description of the polymer's rheological characteristics requires further refinement.

An analysis of the shear rheological curves at shear rates of 2500 to 0.1 $s^{-1}$, 5000 to 0.1 $s^{-1}$, 10000 to 0.1 $s^{-1}$, and 0.1 to 2000 $s^{-1}$ is presented in Figure 5.

As illustrated in Figure **5**, the overall "shear-thinning" rheological behavior of the polymer solution persists even after exposure to strong shear; however, it exhibits significant differences compared to the rheological characteristics observed within the shear rate range of 0.1 to 2000 $s^{-1}$. These differences manifest in two key aspects: first, there are minor alterations in the flow behavior, and second, there is a general reduction in the viscosity of the solution. Consequently, it is necessary to redefine the power law formula for polymer rheology following the critical shear flow rate.

The commonly used power-law fluid formula (refer to Formula 1) delineates the shear rate limits of polymer rheology. Building upon the influence of shear on the rheological characteristics of polymer solutions, we introduce the product parameter α, which represents the corrected viscosity coefficient K, and the additive parameter β, which denotes the corrected fluidity index n. This is presented in Formula 2.

$$\mu = K\gamma^{n-1} \qquad \text{Formula 1}$$

$$\mu = \begin{cases} K\gamma^{n-1} & (\gamma < \gamma_s) \\ \alpha K\gamma^{n+\beta-1} & (\gamma \geq \gamma_s) \end{cases} \qquad \text{Formula 2}$$

In the formula: *μ*-viscosity, mPa•s; *K*-viscosity coefficient; γ-shear rate, $s^{-1}$; n-fluidity index; *α*-Correction parameters for alpha viscosity dilution; *β*-Correction parameters for liquidity index

Figure **5** illustrates the fitting of rheological curves used to calculate the $K_2$ and b values under various shear rate conditions. Based on these calculations, the corrected parameter values are compared with the solution viscosity measured by the viscometer. The results are presented in Table **1**.

Based on the rheological curve characteristics and fitting data presented in Figure **5** and Table **1**, it is observed that the corrected parameters α and β are dimensionless quantities influenced by shear strength. Specifically, α decreases with increasing shear strength, while β increases with increasing shear strength. Variations in shear strength characteristics lead to different correction values. Therefore, in mining applications, the initial step is to assess whether the polymer is affected by shear by measuring the apparent viscosity, which will help determine the appropriate calculation interval for the formula. Subsequently, rheological curves under varying conditions were measured by shearing from high to low, and the corresponding rheological relationship characteristics were analyzed to establish the correction parameter change characteristics of the current solution system. Finally, the appropriate rheological curve is selected by measuring the apparent viscosity using a capillary viscometer.

By optimizing and modifying the rheological application model, the influence of shear action on the characteristics of the rheological curve is thoroughly considered, thereby avoiding arbitrary adjustments of parameters during the numerical simulation process to better align with the actual rheological behavior.

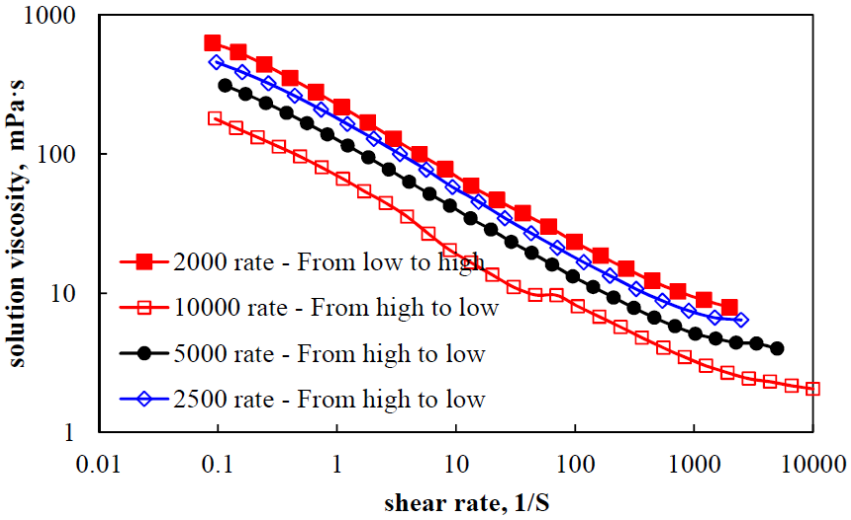


**Figure 5:** Rheological curve of shear mode from high to low.

**Table 1: Revised Parameter Values**

| Shear rate,$s^{-1}$ | $K_2$（$K_1$) | b | Fitting, R | α | β | viscosity |
|---|---|---|---|---|---|---|
| 0.1-2000 | *213.96* | 0.536 | 0.9968 | / | / | 539.53 |
| 2500-0.1 | 166.56 | 0.543 | 0.9946 | 0.778 | 0.007 | 414.18 |
| 5000-0.1 | 116.35 | 0.556 | 0.9908 | 0.544 | 0.020 | 281.93 |
| 10000-0.1 | 61.201 | 0.584 | 0.9862 | 0.286 | 0.048 | 140.25 |

## 4. CONCLUSION

1) The polymer hydrolyzed polyacrylamide (HPAM) exhibits rheological characteristics consistent with shear-thinning behavior typical of pseudoplastic fluids. Within a broader range of shear rates, two distinct rheological characteristics can be observed. Once the critical shear rate is surpassed, it indicates that shear stress begins to compromise the structural integrity of the polymer solution. Consequently, the shear rheological curve of the polymer solution, when measured from high to low shear rates, does not revert to the state observed when measured from low to high shear rates.

2) Changes in solution concentration do not influence the critical shear rate of the polymer; rather, the value of the critical shear rate is determined by the intrinsic properties of the polymer itself.

3) The rheological model for the polymer injection process necessitates an analysis of the shear rate magnitude encountered during injection. Once the critical shear rate is exceeded, it is essential to utilize shear rheological data obtained from high to low shear rates to accurately correct the viscosity coefficient and fluidity index.

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## DATA AVAILABILITY STATEMENTS

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

## CONFLICT OF INTERESTS

The authors declare no conflict of interest.

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