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# Rheological behavior of hydrolyzed polyacrylamide solution flowing through a molecular weight adjusting device with porous medium☆

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ABSTRACT

The separate-layer injection in different interlayers and the injection of the same-molecular-weight polymer solution in a layer are necessary in the polymer flooding process because of heterogeneous multilayer sandstone reservoirs in EOR projects. To alleviate the matching problems between the layer permeability and the injected polymer molecular weight, a molecular weight adjusting device with porous medium was designed on the basis of mechanical degradation principle. In terms of four variables (polymer concentration, pore diameter, length of shear component and flow rate), the rheological behavior of hydrolyzed polyacrylamide (HPAM) solution flowing through the device was investigated in detail. The change of these variables is able to control the shear rate of HPAM solutions through ceramic foam, and achieve the desired degree of shear degradation and the final rheological parameters—viscosity loss, viscoelasticity and pressure drop. Therefore, a linear relationship between viscosity loss and shearing rate was established so as to obtain the targeted viscosity easily. Field tests in the Daqing Oil Field showed that the polymer molecular weight could drop 20% to 50%. In a word, the results could guide the industrial application of the novel device and the further study of polymer degradation flowing through the porous medium.


## 1. Introduction

With the recent surge of interest in enhanced oil recovery (EOR), improved polymer flooding [1] has been applied in the Daqing Oil Field in northern China on a large scale basis. As is known, Chinese oil fields are characterized by heterogeneous multilayer sandstone reservoirs which need partially hydrolyzed polyacrylamide (HPAM) solutions with appropriate molecular weight. This indicates that the viscosity and size of the emulsion formed in the reservoir are of great importance. If the size is too large and viscosity is high, it can plug the pore spaces thus reducing the overall recovery; if the size is too small and viscosity is very low, the desirable sweep efficiency will not be achieved, also causing reduction in recovery [2,3]. Therefore, combining separate-layer injection technology during polymer flooding with the same-molecular-weight polymer injection in the similar layer, the challenge of interlayer differences could be resolved effectively and expediently. Liang *et al.* [4] developed different-molecular-weight polymer injection technology which achieved the designed requirements of controlling both separate-layer injection rate and molecular weight, but it can lead to the blockage of sandstone because the polymer in the interlayers is prone to cause detention problem and the speed of injection is limited. Consequently, how to obtain different molecular weights and viscosities going with the changed zone permeability [5] whenever and wherever possible is of great importance. Except for several special injection technologies depending on correspondent relationship between molecular weight and reservoir under study and application in the Daqing Oil Field, there is no further research and application of polymer molecule weight regulating mechanisms or devices at home and abroad. Hence, we designed a small-scale polymer molecular weight adjusting device to realize the separate-layer injection into different interlayers.

As a kind of water soluble polyelectrolyte with negative charges along its chain, HPAM [6] is widely used as mobility control agents in polymer injection chemical EOR applications [7]. HPAM is particularly sensitive to shear degradation [8] for its fragile molecular chains so that the viscosity and molecular weight can decrease at different degrees under powerful shear force. Based on the earlier literature evidences and observations [9], HPAM solution exhibited the non-Newtonian behavior with shear-thickening areas. Combined with its viscosity property, the use of HPAM could improve the sweep of the oil bypassed due to reservoir heterogeneity. Zhang *et al.* [10] declared the mechanistic features of polymer solution through porous medium. Zhang *et al.* [11] also concerned the viscoelastic behavior of HPAM

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solution in porous medium and its effects on displacement efficiency. Morris and Jackson [12] explained the degree of mechanical shear degradation of polymer solutions derived from polymer molecular weight, polymer concentration, core permeability, and flow rate, and they also indicated that the pressure drop on both ends of the porous medium cannot be too large. Therefore, many researchers paid more attention to the viscoelastic effects of the polymer solution flowing through porous medium, especially the relationship between pressure drop and flow rate [13,14]. In this study we mainly focus on and analyze the rheological change of HPAM solution and the press drop through porous medium in order to get the polymer solution with different targeted viscosities and the design of the novel device.

Polymer rheology [15] not only affects the polymer injectivity but also dominates the oil production rate and the final oil recovery during the chemical-enhanced EOR process [16]. Thus, the exhaustive research on rheological behavior is not only a very important part in the polymer flooding technology [17], but also the foundation of polymer flooding reservoir engineering and guideline for field experiment. Considering effects of variable factors on polymer flow through the porous medium, rheological models were established to predict the experimental results effectively and easily [18], and Liberatore *et al.* [19] has researched the effect of mechanical degradation on molecular weight distribution. Though many researches were focused on the rheological behavior of HPAM solution flow and the HPAM solution related device, few studies have discussed the case HPAM flows through separate-layer injection device made of porous medium.

In view of mechanical degradation of HPAM solutions and the pressure drop across porous medium, we designed a device with ceramic foams aiming at adjusting the viscosity or molecular weight of polymer with small pressure drop. Ceramic foam is a promising porous material as the key shearing component because its light weight, high porosity, good mechanical strength, and complex geometry channels, plus the good chemical stability could keep the polymer solution clean all the time. These excellent properties made it different from the traditional packed bed layer [20], and capable of getting a better shearing effect with a smaller pressure drop. By changing the pore diameter and volume fraction of these microporous materials, the polymer molecular weight and viscosity can be degraded in different degrees. At the same time, compared to other similar equipment [4], the biggest advantage of the new equipment is that the non-Newtonian fluid is subjected to a uniform shearing force when flowing through the component, which is in line with the requirements of homogeneous injection. Moreover, the one-time investment cost of the equipment is low and the operation is simple, and more importantly, the ground equipment and pipe network in the oil field needn't be changed.

In this paper the rheological characterization of HPAM solutions was studied before and after polymer solutions flow through the designed molecular weight adjusting device. The theoretical basis for the field application of the new polymer molecule weight adjusting device was also explored *via* the experiment. Finally, the field tests were conducted in the Daqing Oil Field after we succeeded in the lab-scale application.

## 2. Experimental

### 2.1. Materials

Hydrolyzed polyacrylamide used in the experiment is provided by the Daqing Oil Field. Its average relative molecular mass is $2.5\times10^7$ g·mol$^{-1}$, hydrolyzation is 25%–30%, and solid content is 90%.

### 2.2. The preparation of HPAM solution

HPAM solutions at three concentrations (1000 mg·L$^{-1}$, 2000 mg·L$^{-1}$, and 3000 mg·L$^{-1}$) were prepared by adding polymer powders into the vortex of distilled water (pH = 6–7) under magnetic stirring. Gentle stirring was maintained for 5 h at room temperature (25 °C–30 °C) to avoid mechanical degradation of polymer. The polymer solutions were left standing for aging time to 24 h.

### 2.3. Experimental apparatus

The main components of the experimental setup include: a molecular weight adjusting element made of ceramic foam, a buffer tank for the prepared polymer solution, a metering pump to drive the stream through the shearing device, a pulse damper and a back pressure valve to make sure the stream with steady flow velocity, several pressure transducers and a computer with data collection board installed for accurate records of the pressure drop, and a storage tank for collecting effluents. The apparent porosity of porous SiC foam is provided by Shenyang Institute of Metals, CAS (prepared by sintering according to [21]). The porosity of the ceramic foam ranges from 70% to 90%, while the pore size varies from 2 to 4 mm. A schematic diagram of experimental setup is shown in Fig. 1.

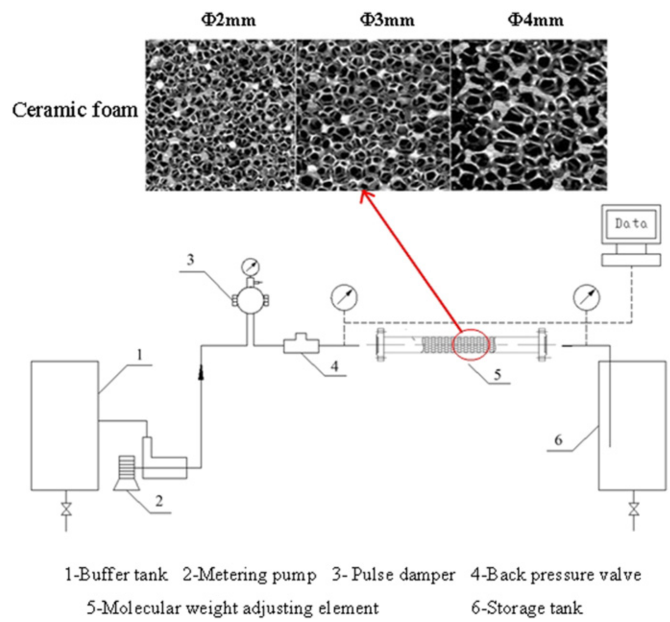


**Fig. 1.** Schematic diagram of the experimental setup.

On the basis of mechanical degradation principle, a stainless steel pipe (diameter: 15 mm) packed with dry ceramic foams (total length: 50 mm, pore diameter: ϕ2 mm, ϕ3 mm, ϕ4 mm, porosity: 75%) was designed as the key component of molecular weight adjusting device. The shear degradation of polymer solutions is mainly determined by the pore diameter of the ceramic foam. The smaller the pore diameter is, the higher the shear degradation. Through adjusting the valve opening, changing the pore diameter, and allocating appropriate number of ceramic foam components, this device can control the degradation degree and polymer molecular weight [22].

### 2.4. Analysis and test

Viscosity measurements were always performed by a DV-II + PRO viscometer (Brookfield, USA) at 6 r·min$^{-1}$ and the temperature of (20 ± 0.1) °C. Viscoelasticity measurements were carried out by a HAAKE rheometer with a cone and plate geometry at (20 ± 0.1) °C. Oscillation tests were conducted to measure the storage modulus $G'$, loss modulus $G''$ at a constant stress of 0.03 Pa and frequency range of 0.1–10 Hz. These ranges of frequency and strain were chosen to provide a stress of reasonable magnitude for purpose of sensitivity.