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Enhanced oil recovery performance and viscosity characteristics of polysaccharide xanthan gum solution

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ABSTRACT

This study compared the potential applications of xanthan gum and hydrolyzed polyacrylamide (HPAM) as polymer-flooding agents for heavy oil recovery applications under a range of salinity conditions. Rheological measurements were carried out to examine the change in shear viscosity when the polymer was applied under a range of reservoir conditions. The results showed that the shear viscosity of the xanthan gum solution was less sensitive to increasing temperatures and salinity than that of the HPAM solution. Accordingly, a xanthan gum injection is more effective than HPAM under higher salinity reservoir conditions.

1. Introduction

Since the introduction of chemical enhanced-oil-recovery (EOR) methods several decades ago, it was often considered to be unprofitable to apply those technologies to heavy oils because of the low oil prices. On the other hand, with the current increases in the demand and prices of oil, which are led by increasing oil consumption in countries, such as China and India, heavy oil reservoirs have attracted considerable attention from the oil industry. Therefore, heavy oil production needs to be increased using the EOR techniques [1,2]. Common EOR methods include thermal, miscible, and chemical processes, of which chemical treatment is one of the main methods to limit water production [3]. This has been operated by building up flow resistance, which is achieved by increasing the shear viscosity of the injected water and/or reducing its permeability through polymer adsorption [4].

In particular, a polymer flooding method is considered one of the most promising chemical EOR processes in many reservoirs due to its lower cost. Because high molecular weight water-soluble polymers can increase the viscosity of the aqueous phase easily, it also results in an increase in sweep efficiency during EOR processes [5]. In addition, the shear viscosity of a polymer solution corrects the poor water/oil mobility ratio responsible for the conformance control problems that lead to poor water flood performance on intermediate heavy oil [6,7]. Therefore, the polymer-induced EOR technique is widely accepted for various mature oil fields [2].

Currently, both water-soluble polyacrylamide and polysaccharides are used widely in oil fields to enhance oil recovery. Among these, xanthan gum, a natural polysaccharide and an important industrial biopolymer, has attracted considerable attention as an EOR agent in oil drilling, fracturing, pipeline cleaning [8]. Xanthan gum is an extracellular polysaccharide produced by the fermentation of a cellulosic backbone consisting of five monosaccharides by the bacterium, *Xanthomonas campestris*, to give a pentasaccharide repeating unit. The cellulosic backbone is substituted at C-3 on the alternate beta-1,4-D-glucopyranosyl residues with the trisaccharide side chains of beta-D-rhamnopyranosyl, beta-1,4-D-glucuronopyranosyl and alpha-1,2-D-mannopyranosyl with various amounts of acetyl and pyruvate substituents [9]. The backbone of the polymer is similar to that of cellulose. Therefore, in addition to the EOR area, the xanthan gum is also used widely in engineering, such as a viscosity-enhancing agent in foods, in cosmetics and pharmaceuticals, and turbulent drag reduction with interesting characteristics including good temperature stability, fine emulsion stabilization, and compatibility with food ingredients [8,10]. The strong ability to increase the shear viscosity, coupled with its excellent stability under high salinity, high temperature and mechanical shear conditions, makes it suitable for EOR. Because the viscosity of the displacing fluid is vital in EOR projects, it is

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important to control the viscosity of xanthan gum under given salinity and temperature conditions [11]. In both EOR and polymer-induced turbulent drag reduction, very dilute solutions of flexible polymers can have extremely high extensional viscosities, which can be orders of magnitude higher than those expected based on a Newtonian fluid [12].

In this study, the polymer flooding characteristics of xanthan gum were examined to explore the possibility of improving heavy oil recovery in a range of salinities and compared to those of hydrolyzed polyacrylamide (HPAM) solutions. In addition, rheological analysis of xanthan gum was also carried out to assess its relation to the polymer flooding.

2. Experimental

The polymer solutions were prepared by dissolving the respective polymer powder in distilled water using a magnetic stirrer for five days at room temperature. A salt concentration of up to 20 wt% and two types of commercial polymers, xanthan gum with a mean average molecular weight of 5×10^6 Da and HPAM with a molecular weight of 13×10^6 Da, were used. The xanthan gum was 99% pure (Sigma–Aldrich Co., Germany). HPAM (AN910VHM, OCI-SNF) was obtained from OCI, Korea with a 12 mol% degree of hydrolysis [6]. These polymers are soluble in aqueous sodium chloride solutions, and have been used successfully to reduce the mobility of injected fluids and EOR from oil fields as well as in water-control operations.

Rheological measurements were conducted using a rotational rheometer (Physica, MCR 300, Austria) with a Couette cell geometry (DG 26.7) to examine the characteristics of the xanthan gum solutions at concentrations ranging from 1500 to 8000 ppm in a 3 wt% saline solution. Some polymer solutions were prepared by mixing with synthetic brine (1–20 wt% salinity), which resembled the concentrations of local reservoirs that contain 99% sodium chloride. The polymer solutions of the 3 wt% saline solutions were tested at 25, 50, 70 and 85 °C. Rheological tests were carried out to examine the effects of salinity and temperature on the polymer solutions at a concentration of 1500 ppm.

Furthermore, to perform the polymer flooding tests, the core holder was filled with glass beads, and compacted tightly for more than 1 h. Through flow experiments, the porosity and permeability, measured using glass beads ranging in diameter from 63 μm to 106 μm, were 36.9% and 3.79 Darcy, respectively. These experiments were conducted in a glass-bead pack saturated with 3.0 wt% saline water and a viscous crude oil with 450 cP (obtained from SK Energy, Korea) at 25 °C. After packing the core holder with glass beads, it was placed vertically, and the brine was injected from its inlet. Heavy oil was also injected in the same direction using an ISCO pump and a transfer cylinder until the oil reached the outlet. A detailed schematic diagram of the experimental set-up is described elsewhere [7]. To restore the wettability, the core holder was filled with the formation brine and heavy oil, and left to saturate for 24 h. The fluid injection rate was maintained at 4 ml/min for the flooding experiments, and all of which were carried out at the same injection rate. In the water flood tests, water was injected at a 0.6 pore volume. Because water breakthrough occurred after a 0.6 pore volume, the polymer injection tests were started from this point until the water flood reached 3 pore volumes [7].

The xanthan gum polymer solution injection tests began at oil saturation after the water flood, and the effects of oil recovery were examined. The increased shear viscosity of the polymer solution improved the tertiary oil recovery. Within the optimal viscosity range of the polymer solution, an increase in the effective viscosity of the polymer solution resulted in an increase in oil production [7].

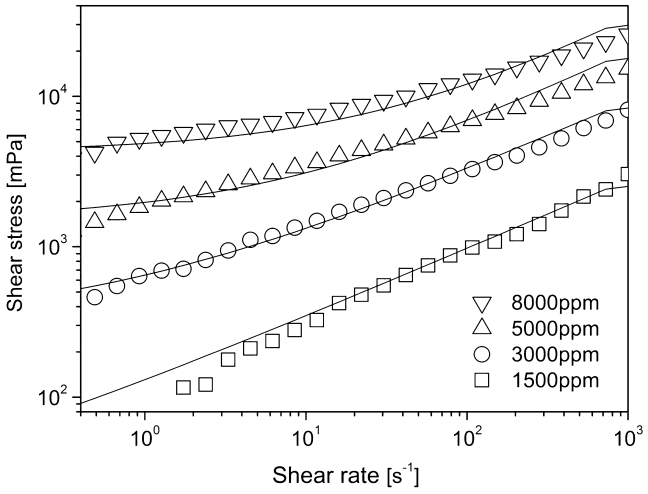

Fig. 1. Shear stress versus shear rate of xanthan gum solution at different concentrations at 25 °C. The solid lines are obtained from Herschel–Bulkley model.

3. Results and discussion

Fig. 1 shows the shear stress versus shear rate of xanthan gum solutions at different concentrations measured using a rotational rheometer at 25 °C at 3 wt% salinity. The xanthan gum solutions exhibited non-Newtonian behavior, and an increase in the xanthan gum concentration led to an increase in yield stress. The Herschel–Bulkley model (Eq. (1)) [12] was used to fit the experimental data.

$$\tau = \tau_0 m \dot{\gamma}^n \quad (1)$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate, τ_0 is the yield stress, m is the consistency coefficient, and n is the flow behavior index. Table 1 lists the parameters obtained from this Herschel–Bulkley model.

Fig. 2 shows the steady shear viscosity of the xanthan gum solutions at different concentrations as a function of the shear rate. An increase in shear viscosity was observed for the increased xanthan gum concentration. For polymer flooding in the EOR, the increased shear viscosity of the xanthan gum can increase the residual resistance factor and improve the sweep efficiency [9]. The data clearly shows that the Newtonian viscosity region noted at low shear rates was not observed at high concentrations. Instead, significant shear-thinning behavior was observed, which was attributed to the disentanglement and alignment of the xanthan gum polymer chains along the flow direction. In a drilling fluid of the EOR, shear thinning polymer solutions were designed that can suspend drilling cutting at low shear rates, but offer little resistance to flow at high shear rates [5]. On the other hand, polysaccharides that display interesting solution characteristics tend to form ordered structures in aqueous environments [13]. Large molecules in an aqueous solutions form aggregates and entangle, leading to high viscosity at low shear rates. Increasing the shear rate decreases the steady shear viscosity due to the uncoiling and partial alignment of the polymer chains at the high

Table 1
Fitting parameters for the xanthan gum solutions at various concentrations calculated from Herschel–Bulkley model.

	τ_0	m	n
1500 ppm	15	100	0.46
3000 ppm	300	300	0.47
5000 ppm	1500	401	0.53
8000 ppm	4300	469	0.57