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New insights into guar gum as environmentally friendly polymer for enhanced oil recovery in high-salinity and high-temperature sandstone reservoirs

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Abstract

Chemical enhanced oil recovery (EOR) processes are usually used as additives for hydrocarbon production due to its simplicity and relatively reasonable additional production costs. Polymer flooding uses polymer solutions to increase oil recovery by decreasing the water/oil mobility ratio by increasing the viscosity of the displacing water. The commonly used synthetic water-soluble polymer in EOR application is partially hydrolyzed polyacrylamide (HPAM). However, synthetic polymers in general are not attractive because of high cost, environmental concerns, limitation in high temperature, and high-salinity environment. Guar gum is an environmentally friendly natural water-soluble polymer available in large quantities in many countries and widely used in various applications in the oil and gas industry especially in drilling fluids and hydraulic fracturing operations; however, very limited studies investigated on guar as a polymer for EOR and no any study investigated on its uses in high-temperature and high-salinity reservoirs. The objective of this study is to confirm the use of guar gum as a natural polymer for EOR applications in sandstone reservoirs and investigate its applicability for high-temperature and high-salinity reservoirs. The study experimentally investigated rheological characteristics of a natural polymer obtained from guar gum with consideration of high temperature (up to 210 °F) and high salinity (up to 20% NaCl) and tested the guar solution as EOR polymer. The results of this study show that the guar solution can be used as an environmentally friendly polymer to enhance oil recovery. Based on the results, it can be concluded that guar gum shows shear-thinning behavior and strongly susceptible to microbial degradation but also shows a very good properties stability in high temperature and salinity, where in low shear rate case, about 100 cp viscosity can be achieved at 210 °F for polymer prepared in deionized water. Guar polymer shows good viscosity in the presence of 20% NaCl where the viscosity is acceptable for temperature less than 190 °F. Also, the flooding experiment shows that the recovery factor can be increased by 16%.

Keywords Guar gum · Chemical EOR (chemical EOR) · Polymer-flooding · High salinity · High temperature · Sandstone reservoirs

Introduction

Chemical EOR techniques are usually used as additives for hydrocarbon production due to its simplicity and relatively reasonable additional production costs (Wang 2003; Sheng 2010; Olajire 2014; Hassan et al. 2017 and 2019). Alkali–surfactant–polymer and polymer are the common flooding systems used in chemical EOR operations (Sveinstrup et al. 2016; Gao et al. 1995; Hou et al. 2005; James 2013; Kang et al. 2000). Polymer flooding is an EOR method that uses polymer solutions to increase oil recovery by decreasing the water/oil mobility ratio by increasing the viscosity of the displacing water. As a result, the oil recovery and the sweep efficiency improve (Wolfgang

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1988; Nasr-El-Din et al. 1991; Sorbie 1991; Gao et al. 1995; James 2015; Sveistrup et al. 2016; Ivonete et al. 2018).

Water-soluble polymers are widely used in petroleum field operations like well-drilling, hydraulic fracturing fluids, and EOR processes (Huggins 1942; Nasr-El-Din and Noy 1992; Wei Yu et al. 2014; Andrew et al. 2016; Almansour et al. 2017; Lee and Lee 2019). Partially hydrolyzed polyacrylamide (HPAM) is the most extensively implemented synthetic water-soluble polymer used in EOR applications (Sveistrup et al. 2016; Wang 2018). However, the synthetic polymers as general are not attractive because of high cost, environmental concerns, limitation in high salinity, and limitation in high temperature (Samanta et al. 2011; Mohammadi et al. 2012; Shiran and Skauge 2013). Researchers are always working to find suitable natural polymer to solve these problems. Guar gum is an environmentally friendly natural polymer applicable as a candidate for EOR applications, which is available in a huge amount in Pakistan and India, with a great quantity in the USA, Sudan, Australia, and Brazil (OEPA 2015; Hassan et al. 2019a, b). Guar plant tolerates different types of soil ranging from sandy to heavy clay soil (Hymowitz 1979). Guar gum is a seed endosperm portion gained from the cluster bean herbal. It generally comprises of high molecular weight polysaccharides of galactomannans ranges between 0.1 and 2.8 million which are a linear chain of (1 → 4)-linked β -D-mannopyranosyl units with (1 → 6)-linked α -D-galactopyranosyl remains as side chains (Mudgil et al. 2014). Guar gum is solvable in cold water without heating, but it is insolvable in organic solvents. High viscous solution can be made depending on the guar concentration. The efficiency of polymer solutions highly depends on its rheological properties (Nasr-El-Din et al. 1991; Taylor et al. 1998; Airey 2003; Kim et al. 2010; Jang et al. 2015).

Guar gum is widely used in various applications in the petroleum industry. For example, Guar gum is used in drilling fluids and hydraulic fracturing operations; however, its applications in EOR are still limited. Few experimental works investigated the use of guar gum as a polymer in alkaline surfactant polymer (ASP) flooding for reservoir temperatures less than 50 °C and for very low salinity (Mohd et al. 2018). However, to date, there is no comprehensive investigational study for the use of guar gum as a polymer for enhancing oil recovery under high specific salinity and temperature environments.

This study experimentally investigated rheological properties of a natural polymer obtained from guar gum and salinity brine with consideration of high salinity and high temperature (20% NaCl and 210 °F), respectively, and tested

the guar gum solution as promising EOR polymer in sandstone reservoirs.

Experimental studies

Materials

Guar gum was used as a natural polymer in all the experiments. To check the applicability of guar gum as a polymer for EOR, polymer solution with different guar gum concentrations was prepared and tested for the viscosity in the different shear rates at room temperature. When the tests showed good results, a polymer solution containing 5000 ppm guar gum was prepared using a laboratory blender. This solution was tumbled for 2 h and allowed to stand overnight to ensure full hydration. The process of tumbling for 2 h and allowed to stand overnight; has been repeated for the preparation of the guar solution in deionized water, brine with different NaCl concentrations, and specific low salinity brine prepared in the laboratory with the description in Table 1.

To minimize oxygen uptake, polymer solutions were stored in closed containers with no other additives for all the experiments. Only one sample was subjected to investigate the optimum quantity of tetrakis hydroxymethyl phosphonium sulfate (THPS) biocide that may control the bacteria degradation on natural polymer.

Dead oil was obtained from an oil field from west Texas. Water and suspended solids were removed by centrifuging the oil for 20 min at 3,000 rpm. The density and viscosity of the dead-crude oil were 0.82 g/cm³ and 3.03 cp, respectively, at ambient conditions.

Rheology measurements

The rheological parameters were measured using a high-pressure and high-temperature (HPHT) viscometer (Grace

Table 1 Salt contents of the low salinity brine prepared in the lab

Salt	g/l
NaCl	0.3
CaCl ₂ ·2H ₂ O	0.01
MgCl ₂ ·6H ₂ O	0.01
KCl	0.02
Na ₂ SO ₄	0.01
NaHCO ₃	0.75
	1.10

M5600). The viscometer used an R1/B5 bob, which required a sample volume of 52 cm³ and had an oil bath for heating; a temperature sensor was present to monitor the sample temperature. A pressure of 400 psi was applied with nitrogen gas to prevent sample boiling. The dynamic viscoelastic properties were measured using a hollow B5 bob in oscillatory testing mode. These tests required sample volumes of 60 cm³.

Core-flood Setup

Figure 1 shows a schematic of the core-flood setup utilized in this study. Three stainless-steel piston accumulators were used to store crude oil, brine, and polymer solutions. A positive displacement syringe pump was utilized to inject the polymer solution into the core. The pressure drop across the core was measured by a pressure transducer, and software was used to record the data with time.

Sandstone cores were used (6 in. length and 1.5 in. diameter, bulk volume = 173.6 cm³). Each core plug was first dried in an oven at 150 °F for 24 h. The dried core weight

was measured as W_0 . The core was then saturated with 5 wt% brine (described in Table 1 after an increase of NaCl to 10%) under vacuum for 4 h and then inserted in the core holder; 5 wt% brine was injected at a constant flow rate at room temperature. After stabilization of the pressure drops that across the core, the initial core permeability was determined. The saturated core weight was then weighed as W_1 . The core pore volume (PV) was calculated from the density of the brine ($\rho_{brine} = 1.089 \text{ g/cm}^3$ at 77 °F) and the weight difference between the dry and saturated cases (Taylor and Nasr-El-Din 1998) (Eq. 1). The cores were kept in the brine until the time to run the experiment.

$$PV = \frac{W_1 - W_0}{\rho_{brine}} \quad (1)$$

where PV is the core pore volume, W_1 and W_0 are the core weight in brine saturated and dry cases, respectively, and ρ_{brine} is the density of the brine.

After pore volume and permeability measurements were taken, the core was saturated with the crude oil. The core was inserted vertically in the core holder, the backpressure

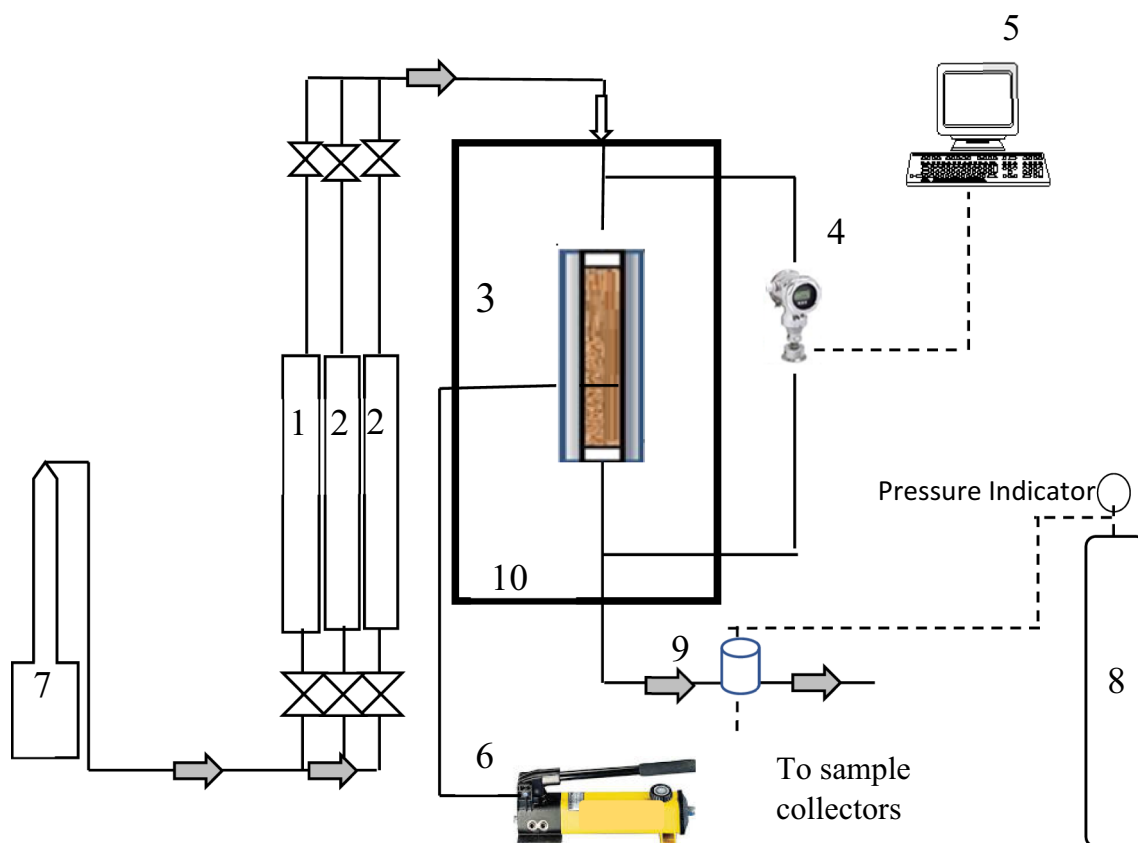


Fig. 1 A schematic diagram of core-flooding. Accumulators = 1&2, core holder = 3, pressure transducer = 4, computer = 5, overburden pressure pump = 6, syringe pump = 7, N₂ cylinder = 8, back pressure regulators = 9, oven = 10 (After Ibrahim et al. 2017).

was set at 500 psi, and the overburden pressure was set at 1000 psi. The oven temperature was set at 194 ° (90 °C). The crude oil was then injected at 0.2 cm³/min for 5 PV until no water was noted in the core outlet. This step was repeated at 0.5, 1, and 2 cm³/min for 2 PV to ensure reaching the maximum oil saturation in the core. OOIP in the core is equal to the collected displaced water. The weight of the oil-saturated core was measured (W_2). OOIP was also confirmed from the weight difference between the brine saturated and oil-saturated cases (Eq. 2).

$$V_{oi} = \frac{W_1 - W_2}{\rho_{brine} - \rho_{oil}} \quad (2)$$

where V_{oi} is the OOIP in the core.

The water-flooding stage was followed as a secondary recovery mode. 5 wt% brine was injected at 0.5 cm³/min, and the produced oil was collected for 5 PV until no further oil was recovered from the core. Then, the flow rate was increased to 1 and 2 cm³/min to ensure reaching the residual oil saturation. The weight of the water-flooded core was measured (W_3).

The residual oil volume in the core after the water flooding stage was calculated by the weight difference between the brine saturated and water-flooded cases (Eq. 3).

$$V_3 = \frac{W_1 - W_3}{\rho_{brine} - \rho_{oil}} \quad (3)$$

where V_3 is the residual oil volume in the core after the water flooding stage. W_1 and W_3 are the core weights of brine saturated and water-flooded cases, respectively.

The remaining oil was recovered by guar gum polymer which prepared from the same brine with 5000 ppm guar concentration. 2.5 PV (87 cm³) brine followed by 0.5 PV (17.5 cm³) guar gum and 1.5 PV (52 cm³) brine were flooded in a constant flow rate.

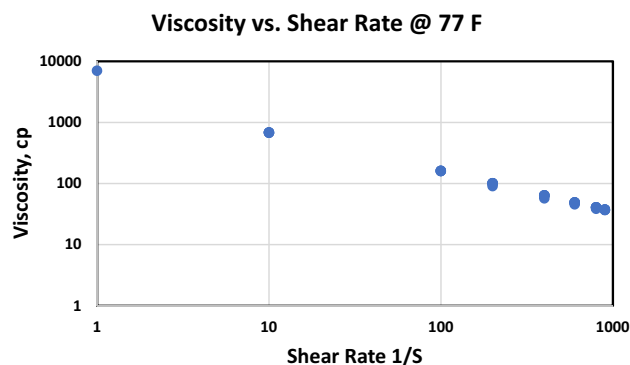


Fig. 2 Variation of 5000 ppm guar gum polymer viscosity with the shear rate at 77°F

Results and discussion

Effect of shear rate and concentration on viscosity measurements

The viscosity was measured in different shear rates (Fig. 2). Guar polymer solutions show pseudoplastic or shear-thinning performance, where viscosity decreasing with increasing shear rate is very clear as noticed by many other high molecular weight polymers (Mudgil et al. 2014). The viscosity reduction is due to uncoiling and alignment of guar polymer chains when exposed to shear flow (Khan et al. 2009; Samanta 2011). Grace M 5600 was run for the same sample with different shear rates to check the value of the approximate viscosity for guar gum polymer. The results show the average viscosity for the 5000 ppm guar polymer in deionized water at 77 °F is approximately 500, 300, and 150 cp for share rate 10, 30, and 100 S⁻¹, respectively (Fig. 3).

5000, 4000, 3000, and 2000 ppm guar concentration were tested to show the effect of concentration of guar gum versus

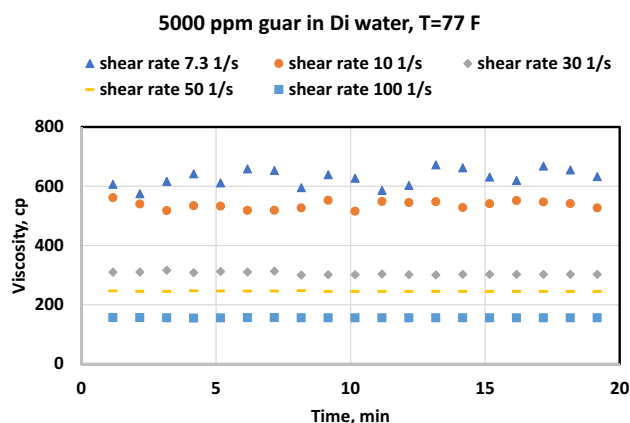


Fig. 3 Viscosity of 5000 ppm guar gum polymer at a different shear rate

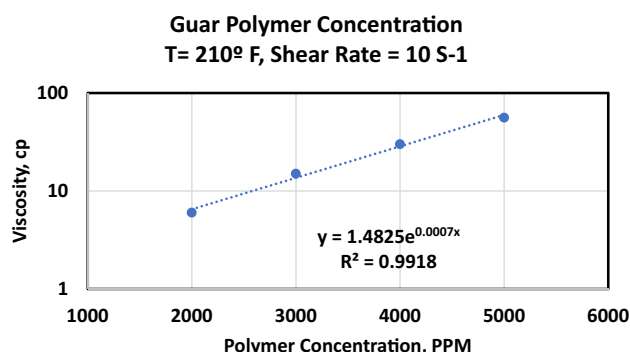


Fig. 4 The relationship between the viscosity of the polymer solution and polymer concentration

different shear rate. The results showed very low viscosity (2–3 cp) at a temperature above 210 °F at 100 S⁻¹ shear rates for concentration less than 5000 ppm. The relationship between the viscosity of the guar gum polymer and the guar concentration is presented in Fig. 4. Although the viscosity measurements were done in 210 °F, it is clear that from the plot, the polymer has good viscosity increasing performance, and the viscosity of the polymer is directly proportional to the increase in polymer concentration which agreed with many authors (Nasr-El-Din et al. 1991; Samanta 2011; Purwono et al. 2012).

Effect of salinity and temperature

The types and amounts of salts present in brine solutions and the temperature at ambient conditions were significantly affecting the polymer rheology. Therefore, complete

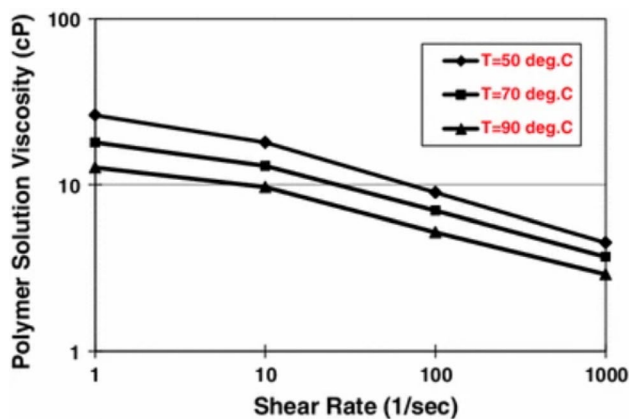
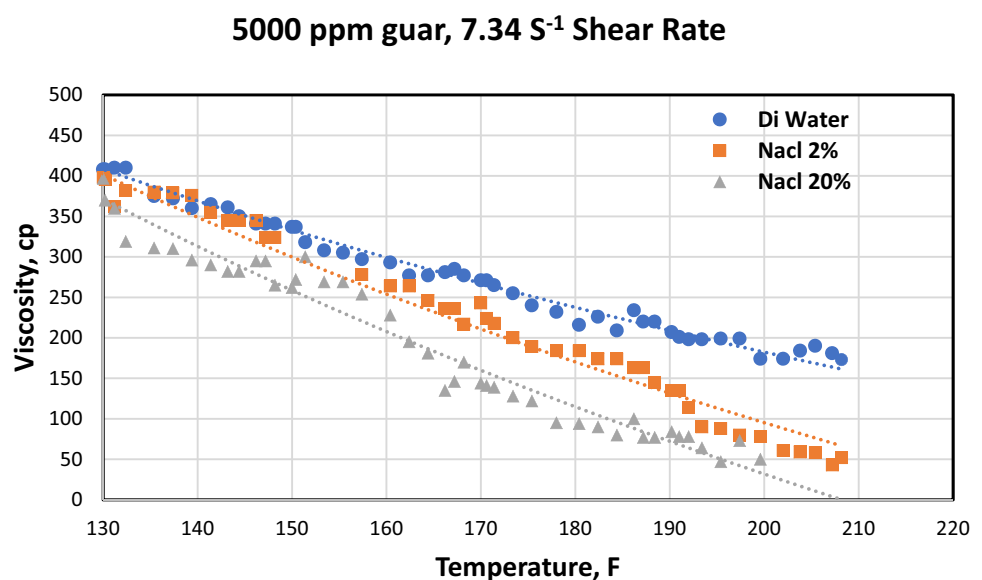


Fig. 5 Effect of temperature on 3000 ppm HPAM polymer viscosity (Gao 2013)

Fig. 6 Temperature effects on guar polymer



knowledge of polymer behavior and rheology is very important for polymer flooding (Khan et al. 2009). Many studies proved that HPAM properties affected by salinity and temperature above 70 °C (Abidin et al. 2012). Gao (2013) found that 10 cp viscosity can be achieved for HPAM polymer at 90 °C (194° F) when 3000 ppm concentration was used (Fig. 5).

In the experiments of this study, a constant shear rate as 7.34 S⁻¹ was used to test the effect of temperature on 5000 ppm guar gum polymer (Fig. 6). It can be noticed that polymer viscosity diminished at a higher temperature just like other known polymers. As the temperature increases, the average speed of the molecules in the liquid increases and the time they spent in contact with their nearest molecules decreases (Khan et al. 2009). As a result, the average intermolecular forces decrease. The results showed good stability of guar gum polymer even at high temperature where more than 100 cp viscosity can be achieved at 210° F at 7.34S⁻¹ shear rate for polymer prepared in deionized water (Fig. 6). This result is better than xanthan gum which has significant hydrolytic degradation above 70 °C (158° F) (Abidin et al. 2012) and also is better than HPAM if it compared to Fig. 5. From Fig. 6, guar polymer shows good viscosity even in the presence of 20% NaCl where the viscosity is acceptable for temperature less than 190° F. After this temperature, a great reduction of viscosity has noticed. When the polymer chain stretched in distilled water due to the force of repulsion between the negative charges in the salt chain, there will be a reduction in the polymer viscosity (Fig. 6) (Abidin et al. 2012; Samanta et al. 2012).

Figure 7 compares the polymer viscosity versus the different shear rate at 77° F and 210° F. The results showed equal viscosity at low shear rate; however, a noticed difference is clear in 100 S⁻¹ shear rates and above.

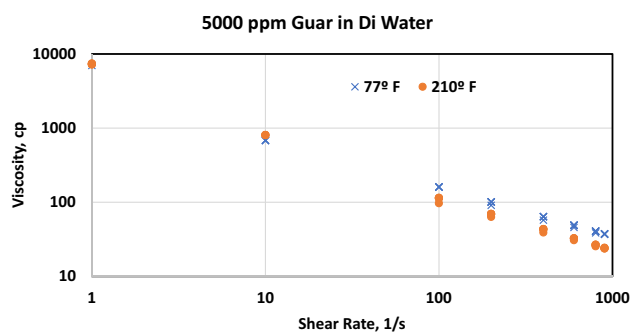


Fig. 7 Comparison between guar gum polymer viscosity at 77° F and 210° F

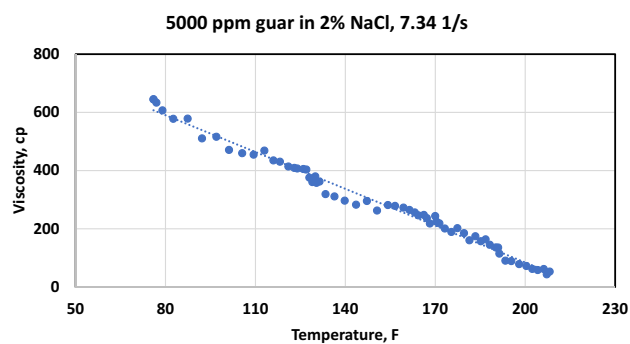


Fig. 10 Temperature effect on the polymer with 5000 ppm guar and 2% NaCl

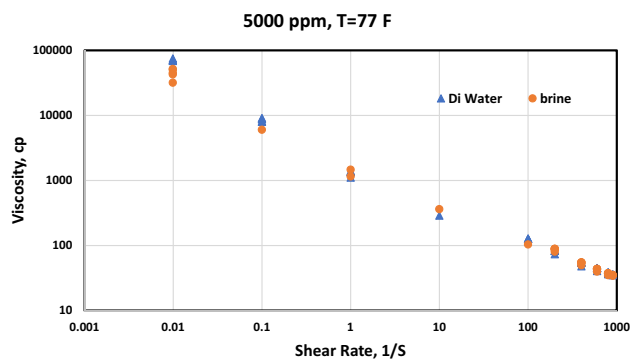


Fig. 8 Comparison between Di water and low salinity brine

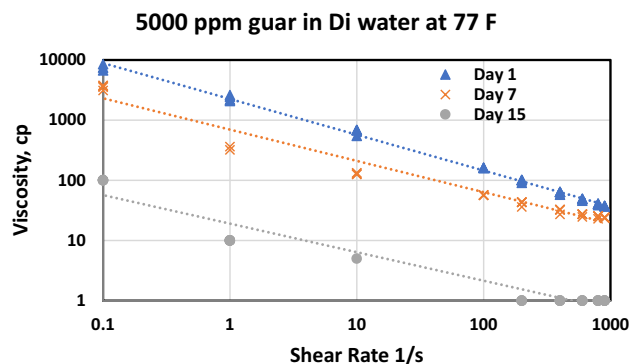


Fig. 11 Bacteria effects on guar gum polymer

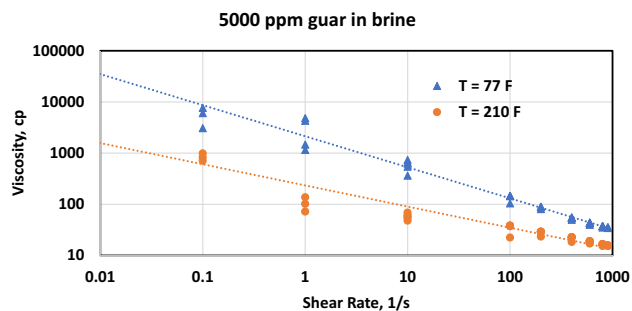


Fig. 9 Effects of temperature on viscosity of guar polymer solution

Viscosity for brine described in Table 1 was measured at 77° F and compared with the polymer in deionized water (Fig. 8). There is no difference for the polymers viscosity that is because the brine has very low salt concentration. From the results, it can be safe to use the guar gum polymer for reservoirs with low-salinity even at high temperature, where Fig. 9 shows the viscosity reduction in 210° F for the polymer in low salinity brine; however, more than 50 cp

viscosity can be achieved for 5000 ppm guar concentration for a shear rate less than 100 S⁻¹.

Figure 10 shows the effect of temperature on guar gum polymer viscosity for a polymer solution prepared with 2% NaCl and 5000 ppm guar. The polymer has an acceptable viscosity for temperature less than 210° F. Experiments also showed promising results for 5000 ppm guar polymer prepared with 10% and 20% NaCl; however, more experiments are needed to confirm the values of polymer viscosity.

Bio degradation

The polymer is utilized to increase the viscosity of the mobile aqueous phase. The efficacy and success of the polymer immersion process can be measured by the polymer's ability to maintain viscosity while spreading in the reservoir (Silva et al. 2018). Polymers, in particular, natural-polymers are susceptible to microbial degradation. 5000 ppm guar was used in deionized water and viscosity was measured in different shear rates after 24 h of preparation, 7 days, and 15 days and stored at room temperature in closed containers. The results show that the viscosity was gradually



Fig. 12 Bacteria degradation after 15 days

decreased and completely lost after 15 days at a high shear rate (Figs. 11 and 12). This study confirmed that it is very important to monitor the guar gum polymer quality in the oil field by injecting suitable biocide to prevent microbial degradation.

To find the suitable and optimum biocide for guar gum polymer, 25 ppm of tetrakis hydroxymethyl phosphonium sulfate (THPS) biocide was added to the polymer solution in deionized water and allowed to stand overnight. On the next day; the solution was separated into two phases with a large viscosity reduction, whereas per Kesavan et al. (2014): "fluids contain a polysaccharide- mainly guar or guar derivatives- would be desirable to use THPS as a biocide and still maintain the viscosity of the fluid". For future works; we recommended to test glutaraldehyde as a biocide for guar polymer.

Table 2 Water and polymer flooding results:

	Property	Value
1	Total pore volume, ml	34.9
2	Permeability, md	1200
3	S_{wc}	38
4	Total oil in place, ml	21.6
5	Total oil produced by water flooding, ml	16 (74%)
6	Total oil produced by polymer flooding, ml	3.45 (16%)

Flooding experiments results

Water flooding followed by polymer flooding was implemented using the system in Fig. 1. The results are shown in Table 2. Figure 12 shows the cumulative oil production during the water and polymer flooding stages. At initial steady-state conditions where the only oil was producing, the produced oil volume equaled the injected water volume. Water breakthrough occurred after around 0.3 PV injected water where the recovery factor was 70%. With continuous injection up to 8 PV, the recovery factor increased 4–74%.

Polymer flooding was then able to increase the sweep efficiency and reduces the viscous fingering. Hence, the oil recovery factor increased by 16%. Although, many researchers observed that; water flood as general still leaves 50–70% oil in the formation (Abidin et al. 2012), in this experiment; 74% of the total oil in place has been produced using water flooding. That is because high permeability core (1.2 Darcy) and light oil have been used. After guar gum polymer flooding, an additional 16% of the original oil in place has been produced (3.45 ml) which is about 60% of the oil remaining after water flooding (Fig. 13). From this study, guar gum can be recommended as a polymer even during the secondary recovery stage.

Conclusion and recommendations

Guar gum polymer has been tested for its possibility to be used as an EOR chemical. The results show that guar gum has potential as EOR environmentally friendly polymer even at reservoir temperature up to 210° F and reservoirs with water salinity up to 20% NaCl. The outcomes of this study can be summarized that guar gum represents good stability and rheological properties in high temperature and salinity. However, Guar is just like other natural polymers and is susceptible to microbial degradation. As a result of this study;

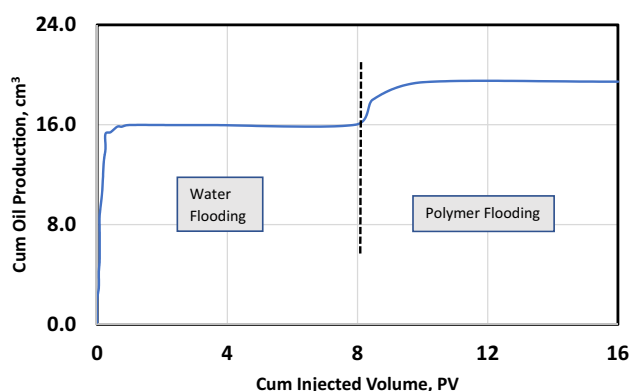


Fig. 13 Water and guar gum polymer flooding

tetrakis hydroxymethyl phosphonium sulfate (THPS) is not recommended as a biocide with guar gum. Also, the flooding experiment shows that the recovery factor can be increased by 16% when guar polymer is used.

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