



Assessment of Biopolymers Rheological Properties and Flooding Results Under Reservoir Conditions for Enhanced Oil Recovery Processes

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Abstract

The utilization of biopolymers as an alternative to synthetic polymers in chemical flooding for enhanced oil recovery (EOR) has gained importance due to their ability to withstand harsh reservoir conditions and environmental friendliness. Understanding biopolymer behavior under such conditions is critical to determine if they exhibit consistent behavior or vary from one to another. This study focuses on evaluating the rheological properties and core flooding outcomes of three specific biopolymers, namely hydroxyethyl cellulose (HEC), xanthan gum, and guar, under reservoir conditions of 212°F, the salinity of 135,000, and pressure of 2200 psi where the previous works lacked to examine the behavior of these biopolymers under such combined conditions. Findings indicate the non-uniform behavior of biopolymer rheological properties under these conditions, highlighting the critical need to evaluate them before using them in the EOR process. At the reservoir conditions, increasing pressure resulted in decreased viscosity for xanthan gum but increased viscosity for guar. The viscosity of HEC initially decreased with increasing pressure but then showed an increase. Also, all biopolymers displayed shear thinning and weak gel behavior (storage modulus/loss modulus > 0.2) under reservoir conditions. Core flooding experiments using actual Bahariya formation cores showed xanthan, guar, and HEC recovered 22%, 8.9%, and 1.8% of the residual oil saturation which is equivalent to 6%, 2.7%, and 0.6% of original oil in place respectively. This suggests xanthan gum exhibits superior rheological properties and oil recovery effectiveness among the tested biopolymers under harsh reservoir conditions.

Keywords: Xanthan Gum, HEC, Guar Gum, Storage and Loss Modulus, Oil Recovery Factor, Resistance Factor, Residual Resistance Factor.

1. Introduction

Biopolymers have gained significant attention in the field of enhanced oil recovery (EOR) due to their unique properties and potential for improving oil production. These natural polymers, derived from renewable sources such as plants and microorganisms, offer several advantages over synthetic polymers,

including biodegradability, eco-friendliness, and compatibility with reservoir conditions [1].

Biopolymers have shown promise in enhancing oil recovery from reservoirs [2, 3]. These biopolymers possess viscoelastic properties that can improve the sweep efficiency of injected fluids, leading to increased oil displacement. They can also alter the wettability of reservoir rocks, improving the contact between the injected fluid and the oil [1]. One of the key advantages of biopolymers is their stability under

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high-salinity and high-temperature conditions, which are commonly encountered in oil reservoirs [2]. This makes them suitable for application in various reservoir types and conditions. Biopolymers can also reduce the fingering effect, which occurs when injected fluids preferentially flow through high-permeability zones, leaving behind trapped oil [1, 4].

Xanthan gum, HEC, and guar gum are some of those biopolymers used in enhanced oil recovery processes. Xanthan gum is a polysaccharide produced by the bacterium *Xanthomonas*. It consists of a glucose backbone substituted by a trisaccharide side chain [5, 6]. It was discovered in the middle of the last century and commercial production began in early 1964 [7, 8]. It has excellent salinity, and mechanical stability and exhibits better compatibility with injected fluids used in tertiary oil recovery [9]. Soliman et al. [10], investigated rheological properties and flooding outcomes at 20000 ppm, 25 °C, and 14.5 psi. The results showed viscosity reduction and xanthan gum degradation with incremental salt addition. Flooding with 55% Pore Volume (PV) of xanthan gum resulted in 3% oil recovery of Original Oil in Place (OOIP). Ghomrassi-Barr et al. [11], conducted rheology experiments on xanthan gum at 1500 ppm, 68 °C, and 14.5 psi. Increasing xanthan gum concentration heightened viscosity and induced shear thinning. With rising temperatures, solutions exhibited gradual viscosity loss, confirming weak-gel behavior. Emilie et al. [12], performed rheology experiments at temperatures from 25 to 80 °C and 14.5 psi, with xanthan dissolved in distilled water. Results showed relaxation time decreases with temperature and increases with xanthan concentration. Shear rate-viscosity curves indicated shear thinning, suggesting temporary network formation of interconnected chains. Song et al. [13], investigated the rheological properties of xanthan gum at 1500 ppm, 68 °C, and 14.5 psi. Concentrated xanthan gum solutions exhibited elastic behavior due to a gel-like structure. Wolfgang Littman [14], conducted a pilot test on xanthan gum at 50000 ppm, 22 °C & 14.5 psi. The incremental oil production was somewhat higher than the predicted 6 % of the OOIP.

Guar gum is a hydrophilic biopolymer derived from the endosperm of two annual leguminous plants, primarily produced in India and Pakistan. The chain is formed by a mannose backbone with galactose side chains. The mannose to galactose molar ratio is approximately 1.8 [15-18]. Temitope et al. [19],

observed shear-thinning behavior in guar gum, particularly effective at high shear rates across various concentrations. In sandstone core flooding tests, guar gum yielded cumulative oil recoveries of 41.8%, 57.1%, and 61.2% at concentrations of 1000 ppm, 2000 ppm, and 3000 ppm, respectively. Casas et al. [20], investigated the rheology of guar gum at 14.5 psi using distilled water up to 80°C. Guar gum solutions exhibited pseudo-plasticity, with higher concentrations leading to increased apparent viscosity.

Additionally, viscosity decreased with rising temperature during measurement. Torres et al. [21], examined the rheology of guar gum solutions with concentrations ranging from 1 g/L to 20 g/L at room conditions. Steady shear tests revealed a transition from a semi-dilute state (below 10 g/L) to an entangled state at higher concentrations. The behavior of the guar gum solutions was primarily viscoelastic, with the degree of viscoelasticity determined by the concentration of the polymer. Akinleye et al. [22], employed guar gum for sandpack flooding in EOR, achieving a total recovery of 55.1% and an incremental recovery of 15.76%. Musa et al. [23], tested guar gum up to 210°F and in 20% NaCl solutions. It exhibited shear-thinning behavior and withstood high temperatures and salinity well. However, guar gum is susceptible to microbial degradation. Flood experiments demonstrated guar gum increased oil recovery factors by up to 16%.

HEC is a hydrophilic polysaccharide that is derived from water-insoluble cellulose through chemical modification. By reacting the insoluble cellulose with ethylene oxide, a hydroxyethyl group is added to the backbone, which makes the polymer soluble in water. Due to its rigid backbone, HEC can viscosify brines at low concentrations [15, 24]. HEC is also extensively used in EOR, well workover and completion, and hydraulic fracturing [15, 25]. Sayeed Abbas et al. [24], reported an HEC flood conducted in 1992 at the Romashkino field under field conditions of 38 °C temperature and 250,000 ppm salinity. Approximately 3,500 tons of HEC were injected into 180 wells, resulting in an additional production of 1,000,000 tons of oil. Sandeep et al. [26], highlighted improved rheological properties and altered wettability demonstrated by HEC. In the flooding stage, HEC exhibited a higher potential for additional oil recovery (5.83%) compared to polyacrylamide, a commonly used commercial EOR polymer.

In this study, the rheological properties of xanthan gum, guar gum, and HEC were evaluated under the conditions shown in Table 1.

Table 1. Rheological Properties Evaluated Conditions

Condition No.	Condition of Rheology Evaluation
Condition-1	Variations in temperature up to 212 °F, salinity up to 200000 ppm, and shear stress up to 5001/s.
Condition-2	Reservoir temperature (196 °F), salinity (135000 ppm), and shear stress (10 1/s) while the pressure was varied until it reached the reservoir pressure of 2200 psi
Condition-3	Reservoir conditions of temperature = 196 °F, salinity = 135000 ppm, and pressure = 2200 psi while the shear stress was changed until 500 1/s.

This work establishes a foundation for understanding the behavior of biopolymers under reservoir conditions and whether these biopolymers exhibit similar behavior. Furthermore, it highlights the importance of utilizing biopolymers to improve EOR processes in low-productivity regions. **Figure 1** depicts the experimental workflow of this study.

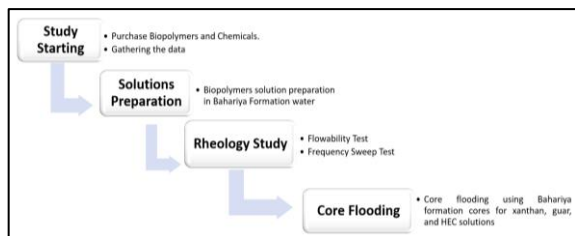


Figure 1: Study Workflow

2. Materials and Methodology

Calcium chlorides (CaCl_2), magnesium chlorides (MgCl_2), and sodium chloride (NaCl) were purchased from TopChem-Egypt with a purity of at least 99%. Guar gum was purchased from ADVENT CHEMBIO PVT. LTD-India, while xanthan gum and HEC were obtained from Sigma-Aldrich, Egypt. All of these biopolymers were used in the form of pure powder. The core plugs were cut from the Bahariya outcrop sandstone, western desert, Egypt.

2.1 Biopolymers Solution Preparation

Solutions of xanthan gum, guar gum, and HEC were prepared by adding 3, 4, and 4 gm/L, respectively, to two solvents: (1) synthetic brine with a salinity of 135000 ppm and (2) distilled water. These concentrations were selected based on the critical association concentration concept by constructing concentration-viscosity curves for different concentrations from xanthan gum, guar gum, and HEC providing molecular insights to guide appropriate biopolymer usage [27, 28]. Additions were conducted separately over time intervals according to API-RP-63

recommendations to prevent biopolymer aggregation. Each stock solution was mixed via magnetic stirring at 500 revolutions per minute to homogenize the mixture while avoiding mechanical degradation of the biopolymers. All solutions were then stored in sealed bottles to prevent evaporation.

2.2 Core Preparation, Flooding and Calculations

Core plugs from the Bahariya formation were cut to the desired dimensions and cleaned using soxhlet distillation extraction to remove salts and deposits from weathering exposure. The plugs were then dried in an oven at 60°C and 4% humidity to remove sticking methanol. Then the core plug length (L), diameter (D), porosity (Φ), weight, and permeability (K) were measured (Table 2) and bulk (V_B)/pore volume (V_P) and porosity were calculated as follows:

$$V_B = \pi r^2 L \quad (1)$$

$$\Phi = V_P / V_B \quad (2)$$

Where r & L are the radius and length of the core.

The core flooding tests were conducted in the core flood system shown in Figure 2. The synthetic brine, crude oil, and biopolymer flow rates were kept at a constant rate during the test. The core plug was saturated with the synthetic brine and absolute brine permeability at 4000 psi confining pressure was measured. After that, the Bahariya formation crude oil with 29 °API and 10 cP viscosity (μ) was used to displace the synthetic brine from the core plug until no brine was ejected. The volume of both retained crude in the core which is equivalent to OOIP and the water production during displacement of water by oil (V_w) are measured from the outlet effluents. The connate water saturation (S_{wi}) can be calculated as follows:

$$S_{wi} = (V_P - V_w) / V_P \quad (3)$$

Different pore volumes (0.25, 0.5, 0.75, 1, 5, 10 & 15 PV) of synthetic brine were used to displace the oil from the core plug until no oil was ejected in the effluent. The total oil production during the water flooding process (V_o) and water (V_w) are collected in a graduated cylinder and measured. The experiment time, and pressure difference (ΔP) through the core plug in and out are measured also. The residual oil saturation (S_{or}) and water permeability at residual oil saturation, $K_w @ S_{or}$ can be calculated as follows [29]:

$$S_{or} = (OOIP - V_o) / V_P \quad (4)$$

$$K = \frac{q \times \mu \times L}{1.127 \times 10^{-3} \times A \times \Delta P} \quad (5)$$

Where q is the flow rates (bbl/d), k is the effective permeabilities of water/oil (mD), ΔP is the pressure drops across the core for water /oil (psi), A is the core area in (ft²), L is core length (ft) and μ is the viscosity of water/oil (cp).

Displace through the core plug 0.5 VP of biopolymer solution flowed by formation brine. The additional produced oil volume (V_{op}), time, and pressure difference (ΔP) are measured. The residual oil saturation after polymer flooding (S_{orp}), was calculated as follows:

$$S_{orp} = \left(OOIP - (V_o + V_{op}) \right) / V_p \quad (6)$$

Two important factors were considered during the core plug flooding. First, the resistance factor (F_R), which is a function of the pressure drop during the biopolymer's flood and the water flood, can be formulated as shown in Equation 7. Second, is the permeability reduction factor (F_{RK}) which represents the ratio of effective brine permeability to effective biopolymer permeability that reveals the influence of the entrained or adsorbed biopolymer and can be formulated as shown in Equation 8 [30, 31].

$$F_R = \Delta P_p / \Delta P_w \quad (7)$$

$$F_{RK} = K_w / K_p \quad (8)$$

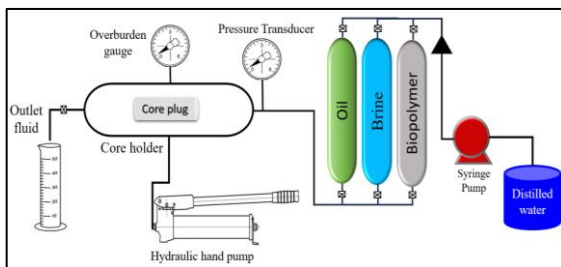


Figure 2. Core flooding system.

Table 2. Core plugs basic parameters.

Plug No.	Plug pore volume @ 2500 psi (PV)	Plug length L	Plug diameter D	Plug porosity ϕ	Water permeability K_w @ 100% saturation
	(cc)	(cm)	(cm)	(%)	(mD)
3	23.02	5.59	3.84	36.8	793
5	19.39	4.70	3.83	36.9	579
9	23.30	5.62	3.84	37.5	759

3. Results and Discussion

3.1. Biopolymer Rheology under Pressure, Temperature, and Salinity Variation.

As the viscosity of the biopolymer solutions generally is sensitive to temperature, salinity and, pressure effects, viscosity is estimated at different temperatures, salinity and, pressure ranges [32-34]. Figure 3 depicts a temperature-dependent trend where the viscosity of three biopolymers, including xanthan gum, guar gum, and HEC, decreases with increasing temperature [11, 27, 35]. The reduction in viscosity at higher temperatures occurs as the entanglement between polymer chains is weakened. Higher temperature also increases the mobility of polymer chains, reducing entanglement and allowing easier flow. Temperature also influences viscosity by inducing a transition from ordered helix conformations to random coil conformations, reducing viscosity and pseudo plasticity until a Newtonian plateau is reached. At high temperatures, an ordered-to-random conformational transition occurs abruptly, dominating the rheological behavior. This turns gel-like behavior into Newtonian flow. Yield stress decreases with increasing temperature because polymer chains do not entangle as much, making flow easier [36-40]. However, the viscosity of xanthan gum decreases at a greater rate than guar gum and HEC when the temperature increases. This behavior can be explained by several reasons. Firstly, xanthan gum has a more complex molecular structure compared to guar gum and HEC. It consists of a long chain of sugar molecules with side chains, which allows it to form a more entangled and structured network. This network becomes less stable and breaks down more easily with increasing temperature, leading to a greater decrease in viscosity. Secondly, xanthan gum has higher solubility in water compared to guar gum and HEC. As the temperature increases, the solubility of xanthan gum also increases, leading to a decrease in its viscosity. Lastly, xanthan gum has a higher number of hydrogen bonding sites compared to guar gum and HEC. With increasing temperature, the strength of hydrogen bonding decreases, resulting in a more fluid-like behavior and a greater decrease in viscosity [9, 41].

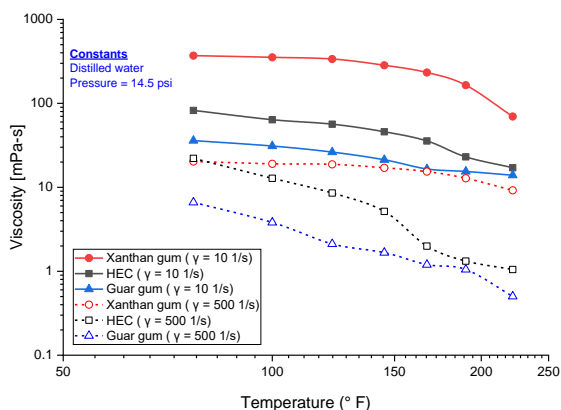


Figure 3. Temperature effect on HEC, guar, and xanthan viscosity

For the salinity, the viscosity of biopolymer solutions is dependent on salinity levels. Higher salt concentrations can either increase or decrease viscosity based on polymer type through interactions altering the semi-rigid helical structure. Most biopolymers are insensitive to salts due to their non-ionic character. The impact of salt on viscosity is intricate, determined by multiple factors including biopolymer type, salt concentration and type, and solution pH [42]. The decrease in viscosity observed in some biopolymer solutions with increasing salinity can be ascribed to the perturbation of biopolymer-solvent interactions by salt ions. Salt ion's presence can interfere with the interactions among biopolymer molecules, resulting in a decrease in the entanglement and aggregation of the biopolymer chains. These interactions comprise hydrogen bonds, electrostatic interactions, and hydrophobic interactions, which play a critical role in preserving the three-dimensional structure and solvation of the biopolymer [38, 43, 44]. However, the relationship between shear rate and viscosity can be more complex. In some cases, with increasing shear rate, the viscosity of these biopolymers may increase again. This phenomenon is known as shear thickening or dilatancy as shown in **Figure 4** when the shear rate increased for the guar gum solution. Shear thickening occurs when the applied shear forces cause the biopolymer chains to align and form temporary networks or clusters within the solution. These networks or clusters impede the flow of the solution, increasing viscosity. The exact mechanisms behind shear thickening can vary depending on the specific biopolymer and its molecular structure. It can involve processes such as chain alignment, intermolecular interactions, and the formation of particle-like structures. Therefore, the viscosity behavior of some biopolymers can exhibit a

decrease with increasing salinity, as salt disrupts the biopolymer-solvent interactions. However, with increasing shear rate, the viscosity can sometimes increase again due to shear thickening, where the alignment and formation of temporary networks within the biopolymer solution impede its flow [2, 45, 46].

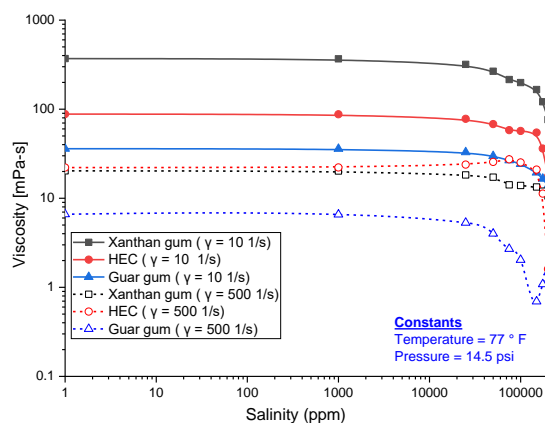


Figure 4. Salinity effect on HEC, guar, and xanthan viscosity

On the pressure side (**Figure 5**), it is generally observed that as the pressure increases at low temperatures, the viscosity also increases. This suggests that the material becomes more resistant to deformation and flow. This phenomenon can be attributed to the fact that increased pressure leads to a more compact and interlocked arrangement of long-chain molecules, resulting in heightened resistance to flow. Moreover, under higher pressure conditions, the biopolymer solutions may exhibit a more solid-like behavior (elastic) rather than a liquid-like behavior (viscous), thereby influencing its rheological properties to a greater extent [47-49].

The decrease in viscosity of xanthan gum solutions with increasing pressure was found to be caused by the deformation and compression of xanthan gum molecules under high pressures. This decreases their effective size and, consequently, their capacity to form a network structure that contributes to solution viscosity at higher salinity, shear rate, and temperature [32, 39, 47]. There was a clear inverse relationship between the viscosity of the xanthan gum solution and the pressure as shown in Figure 5.

Regarding guar gum as shown in Figure 5, the relationship between its viscosity and the increase in pressure is a direct relationship, and this may be due to several reasons. Firstly, guar gum is a biopolymer composed of long chains of repeating units. At higher pressures, the chains become more compressed and

closely packed, resulting in increased intermolecular interactions. This compact arrangement leads to enhanced entanglement and greater resistance to flow, thereby increasing viscosity. secondly, the presence of salinity affects the interactions between guar gum and the surrounding solvent. At higher pressures, the solvation of guar gum molecules by the solvent can be altered, causing changes in the effective size and shape of the polymer chains. This modification in the molecular arrangement influences the flow behavior and contributes to the increased viscosity. Lastly, under high-pressure conditions, the hydrodynamic interactions between the guar gum molecules become stronger. These interactions occur due to the movement of the surrounding fluid molecules, and they impede the flow of the polymer solution, resulting in increased viscosity [23, 47-50].

In the case of the HEC solution, the relationship between its viscosity and increasing pressure is not linear as shown in **Figure 5**. Initially, as the pressure increases, the viscosity of the HEC solution decreases up to a certain pressure. However, beyond this pressure, the viscosity begins to increase once again with further pressure increases. The decrease in viscosity with increasing pressure can be attributed to the compression of the HEC polymer chains under high pressure, leading to a reduction in the resistance to flow. The compression of the polymer chains results in a more compact structure, allowing for easier movement of the HEC molecules and a decrease in viscosity [51-53].

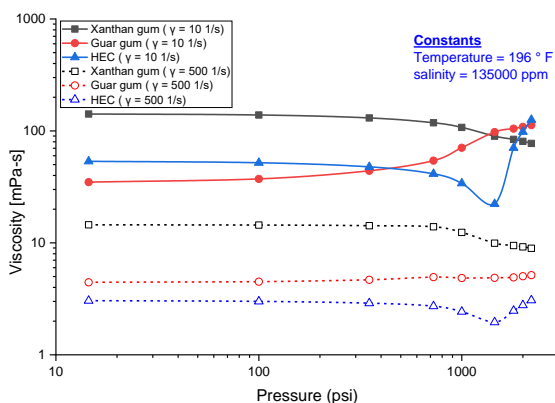


Figure 5. Pressure effect on HEC, guar, and xanthan viscosity

Based on the experimental results summarized in Table 3, it is evident that the behavior of biopolymers under varying salinity and pressure conditions is not

constant. Specifically, at low shear rates, the viscosity of solutions decreases with increasing salinity; however, this trend reverses at higher shear rates.

Additionally, during the injection phase to pressure increase and return to the original reservoir pressure, the behavior of biopolymer solutions varies depending on the specific biopolymer. For example, xanthan gum exhibits an inverse relationship between pressure and viscosity, while guar gum displays a direct relationship. In contrast, HEC shows no specific relationship between these factors. Therefore, it is crucial to investigate the rheological properties of any biopolymer before its application in a particular context since there is no general rule that can be applied universally to all biopolymers. Furthermore, studying the impact of pressure, salinity, and temperature on these polymers' behavior is essential to optimize their performance in EOR applications.

Table 3. Temperature, Salinity, and Pressure effect on Viscosity direction at 10 and 500 Shear rate

Items	Temperature		Salinity		Pressure	
	10	500	10	500	10	500
Shear rate (1/s)	10	500	10	500	10	500
Xanthan gum	↓	↓	↓	↓	↓	↓
Guar gum	↓	↓	↓	↑	↑	↑
HEC	↓	↓	↓	↓	↑	↑

However, the non-uniform biopolymer behaviors may result from various mechanisms influencing their response to reservoir conditions, including molecular interactions and conformational changes. Molecular interactions involve forces like hydrogen bonding, electrostatic interactions, van der Waals forces, and hydrophobic interactions, playing a pivotal role in determining rheological properties. The strength and nature of these interactions depend on biopolymer composition, sequence, and environmental conditions. Temperature, salt concentration, and solvent composition changes can alter these interactions, leading to rheological variations; for instance, increased temperature disrupts hydrogen bonds and hydrophobic interactions, decreasing viscosity [54-56]. Conformational changes, such as transitions between random coils, α -helices, and β -sheets, based on sequence and environmental conditions, significantly impact rheological properties. Changes in pH or temperature may induce conformational transitions, altering stiffness, flexibility, and

intermolecular interactions, causing variations in viscosity, elasticity, and shear behavior [57-59].

Rheological Properties

At room conditions, where the temperature, salinity, and pressure are constant, xanthan gum, guar gum, and HEC rheology are primarily influenced by changes in shear rate. As the shear rate increases, the viscosity of these substances decreases. However, it's important to note that the rate at which viscosity decreases can vary among these biopolymers, as depicted in **Figure 6**. The decrease in viscosity of biopolymers with increasing shear rate is commonly observed and can be explained by the phenomenon of shear-thinning or pseudoplastic behavior. Shear thinning refers to the decrease in viscosity of a material when subjected to increasing shear rates or shear stresses [60]. The underlying mechanism for shear thinning in polymers is related to their molecular structure and the arrangement of polymer chains. In quiescent or low-shear conditions, the polymer chains may be entangled or coiled, leading to a higher viscosity due to the resistance to flow. However, when shear is applied, the chains start to align and stretch along the flow direction, reducing the entanglements and allowing the flow to occur more easily. This alignment and stretching of polymer chains under shear disrupts the temporary network formed by entangled chains, leading to a decrease in viscosity [61-63].

At reservoir conditions, the viscosity of xanthan, guar gum, and HEC is influenced by the combined effects of temperature, salinity, shear rate, and pressure. For xanthan, an increase in shear rate under reservoir conditions leads to a decrease in viscosity, as previously discussed. In the case of guar gum, under low shear rates, the presence of reservoir conditions enhances its viscosity, which may seem contradictory to the effects of temperature and salinity. However, analysis of Figures 3 and 4 reveals that the viscosity reduction caused by temperature and salinity at low shear rates is significantly smaller compared to the viscosity increase resulting from elevated pressure. As the shear rate increases, the viscosity of guar gum only experiences a minimal rise due to pressure and salinity elevation. Therefore, temperature and shear rate contribute to a decrease in guar gum viscosity, while pressure and salinity increase it. In the case of HEC, at room conditions, an increase in shear rate leads to a decrease in viscosity due to shear-thinning or

pseudoplastic behavior, characterized by a decrease in viscosity with increasing shear rates or stresses [60]. Under reservoir conditions, HEC viscosity is affected by temperature, pressure, and salinity. The impact of temperature and salinity on viscosity at both low and high shear rates results in a decrease in viscosity, as depicted in **Figures 3 and 4**. However, it should be noted that increasing temperature and salinity also negatively affect viscosity. Increasing temperature expands the free volume within the biopolymer structure, causing the constituent units to be less constrained, more active, and less organized, thereby reducing their relaxation times and resulting in viscosity reduction [36]. Similarly, increasing brine salinity neutralizes the ionic charge of the biopolymer macromolecular structure, causing elongated HEC molecules to transform into a helical shape occupying a smaller volume, leading to viscosity loss [64, 65].

However, the presence of pressure has a more significant effect on increasing the viscosity of HEC compared to the influence of temperature and salinity. As pressure increases, biopolymer structure compression and reduced molecular mobility result from the biopolymer structure's internal free volume decreasing. This increase in internal friction force and flow resistance leads to an increase in viscosity [66].

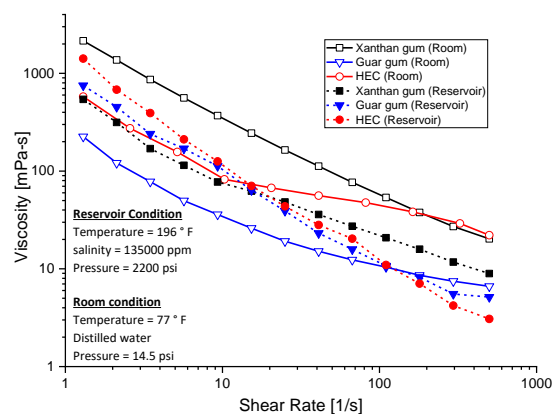


Figure 6. Viscosity of HEC, guar, and xanthan at room/reservoir condition

The shear stress-shear rate relationship for HEC, guar gum, and xanthan gum demonstrated in **Figure 7** can be accurately described by the Herschel Bulkley model, with minimal standard errors, as detailed in Table 4. The Herschel Bulkley model is mathematically expressed as follows:

$$\tau = \tau_0 + K * \gamma^n \quad (9)$$

At room conditions, xanthan gum exhibited the highest yield stress of the three polymers tested, with a yield point of 1.397. It also had the lowest consistency index

of 1.093 and flow behavior index of 0.330, suggesting relatively shear-thinning behavior. Guar gum showed more elastic properties, as seen from its higher flow behavior index of 0.551. However, it displayed the lowest yield point of 0.224 and a consistency index of 0.093. Of the three hydrocolloids, HEC demonstrated the most Newtonian-like flow with a flow behavior index closest to 1 at 0.657. While having an intermediate yield point of 0.190, it possessed the highest consistency index of 0.203.

At reservoir conditions, xanthan gum displayed the lowest yield stress at 0.219, indicating it begins to flow at a lower applied stress compared to guar gum and HEC. However, xanthan gum had a higher consistency index of 0.183 which indicates its viscosity [67]. This means that once flow has initiated, xanthan solutions resist deformation more than guar and HEC. The flow behavior index of xanthan was 0.512, meaning it demonstrates shear-thinning behavior to a moderate extent. Guar gum had the highest yield stress at 0.736, showing that it requires greater stress to start flow. Its consistency index was lower at 0.032, so guar solutions deform relatively easily under stress. The flow behavior index of 0.652 indicates guar gum is more strongly shear-thinning versus xanthan. Of the polysaccharides, HEC exhibited an intermediate yield stress of 0.689. However, it had the highest consistency index of 0.215, making HEC solutions the most resistant to deformation. HEC was the most Newtonian-like with a flow behavior index of 0.212. The three biopolymers' flow behavior indices are less than 1.0, demonstrating the behavior of pseudoplastic fluids and their ability to operate as shear-thinning fluids [25].

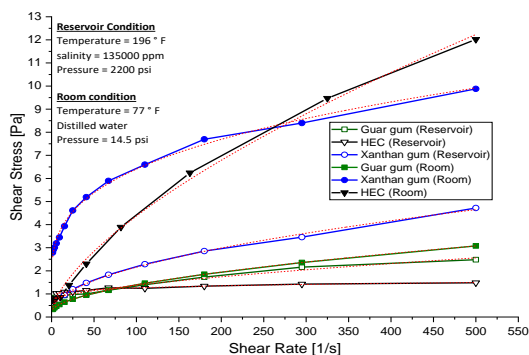


Figure 7. Shear rate versus shear stress for HEC, guar gum, and xanthan gum at reservoir condition

Table 4. Herschel Bulkley model parameters for HEC, guar, and xanthan.

Biopolymer Name	Condition	Yield Point, y_0 , (lb/ft ²)	Consistency Index, k	Flow behaviour Index, n	Adjusted R-square
Xanthan gum	Reservoir	0.219	0.183	0.513	0.997
	Room	1.397	1.093	0.330	0.995
HEC	Reservoir	0.689	0.215	0.212	0.979
	Room	0.190	0.203	0.657	0.996
Guar gum	Reservoir	0.736	0.032	0.652	0.987
	Room	0.224	0.093	0.551	0.994

Xanthan gum, HEC, and guar gum solution's viscoelastic properties under the reservoir conditions were estimated using a frequency sweep test. In this test, the angular frequency was plotted on a logarithmic scale against the storage modulus (G') and the loss modulus (G''), as shown in Figure 8 where the storage and loss moduli versus angular frequency curve is a commonly used tool to characterize the viscoelastic behavior [68]. The G' represents the material's elasticity, while the G'' represents the material's viscosity [69, 70]. The logarithm of G' and G'' shows a linear relationship with the logarithm of the frequency, with G' being greater than G'' . A higher G' value indicates greater elasticity and wider molecular weight distribution. Additionally, the ratio of G'' to G' is significantly greater than 0.2, indicating that the system can be classified as a weak gel. This mechanical spectrum is typical for systems with such a ratio [71-73].

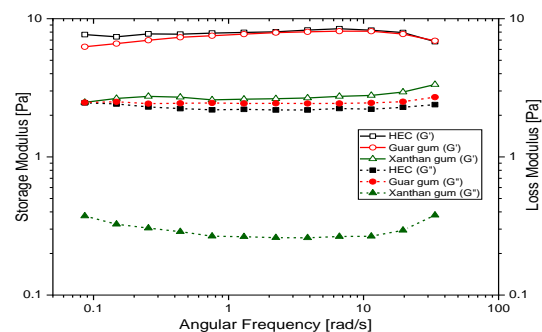


Figure 8. Storage/loss modulus versus angular frequency for HEC, guar gum, and xanthan gum.

3.2. Analysis of Core Flooding Experiments

Core flooding experiments were conducted in two phases. In the first phase, known as secondary oil recovery, the displacement of oil by brine was performed to determine the maximum oil recovery $(RF)_w$ achievable through water flooding. The second phase aimed to investigate the effectiveness of xanthan gum, guar gum, and HEC in enhancing sweep efficiency and subsequently increasing oil recovery $(RF)_p$, while reducing residual oil saturation in the reservoir. Synthetic brine with 135,000 ppm and oil

with an API gravity of 29° from the Bahariya formation was utilized in both flooding phases. The results of the flooding process are summarized in Table 5.

Table 5. Core Flooding Results

Plug No.	OOIP	S_{wi}	Secondary Recovery by Water Flooding				Tertiary Recovery, "EOR"				
			$(RF)_w$	$(S_{or})_w$	ΔP	$K_{wp}@S_{or}$	Biopolymer Name	$(RF)_p$	ΔP	$(S_{or})_p$	$K_{wp}@S_{or}$
			(%)	%	(Psi)	(mD)		(%)	(psi)	%	(mD)
3	16.9	26.59	64.64	25.96	3.2	125	HEC	0.59	9.8	25.52	40.95
5	12.3	36.57	66.67	21.14	2.8	57.8	Guar	2.68	7.1	19.44	22.81
9	17	27.04	73.53	19.31	3	59.2	Xanthan	5.88	7.3	15.02	35.99

Based on the core flooding results presented in Table 5, it is evident that xanthan gum outperformed HEC and guar gum in terms of additional oil recovery. Xanthan gum was able to achieve an additional oil recovery of 5.88% of OOIP, corresponding to an extraction of 22% of the residual oil saturation. This superior performance of xanthan gum can be attributed to its excellent tolerance to harsh reservoir conditions, as explained previously in the rheological properties of the three biopolymers. Xanthan gum exhibited better sweeping capabilities, leading to a significant reduction in oil saturation from 73% to 15%.

The previously observed shear-thinning behavior of xanthan gum, guar gum, and HEC has had significant implications for injection and displacement processes during the core flooding and consequently in the reservoir. This behavior, reducing viscosity under high shear rates during injection, enhances injectivity for EOR applications. Lower viscosity facilitates efficient biopolymer distribution through core plugs. Additionally, shear thinning enhances sweep efficiency by enabling better penetration of smaller pore spaces and high-permeability channels, resulting in improved oil recovery and thorough oil displacement in the reservoir.

Figure 9 illustrates the cumulative oil recovery and saturation profile for xanthan gum, HEC, and guar gum. The figure demonstrates that oil recovery increases and saturation decreases notably at the initial stage of the flooding process, where plug production consists solely of oil without any accompanying water percentage. However, as time progresses and breakthrough occurs (i.e., water reaches the production side from the injected side), the recovery rate gradually decreases due to the production of a substantial percentage of water. This continues until the plug production becomes 100% water. Subsequently, during the biopolymer injection stage,

there is a renewed increase in recovery, as indicated by the arrows in the figure. This increase enables the biopolymer to sweep an additional quantity of oil, with the specific percentage varying depending on the type of biopolymer, as shown in Table 5.

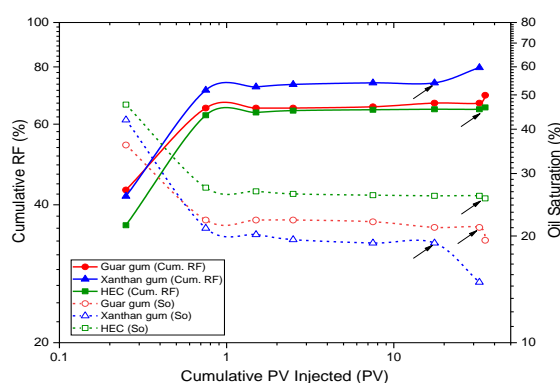


Figure 9. Plugs cumulative oil recovery & oil saturation profile during the flooding experiments.

An important aspect to consider when using biopolymers in EOR processes is their impact on reservoir properties, particularly permeability. This is determined by analyzing the variations in permeability before and after the injection of these biopolymers, as well as the changes in pressure differentials between the plug's input and exit. These evaluations are presented in **Table 6**. The results reveal that the pressure difference after HEC injection increased threefold, indicating a negative effect on plug permeability, which decreased from 125 mD to 40.95 mD. Similarly, for guar gum, the pressure difference increased by two and a half times, accompanied by a decrease in plug permeability from 57.8 mD to 22.81 mD. In the case of xanthan gum, the pressure difference also increased by two and a half times, with

a decrease in plug permeability from 59.2 mD to 35.99 mD. These observations are further supported by the F_R and F_{RK} values presented in **Table 6**. The F_R and F_{RK} values for HEC are higher compared to both xanthan gum and guar gum. This suggests that HEC is absorbed more extensively into the plug compared to xanthan gum and guar gum. The results emphasize the significance of selecting appropriate concentrations and injection time for these biopolymers in EOR processes. It is crucial to consider their potential negative effects on reservoir properties, particularly permeability. However, it should be noted that the specific impact varies among different biopolymers, highlighting the need for careful evaluation and optimization in EOR applications.

Table 5: Biopolymer resistance and permeability reduction factor calculations.

Biopolymer Name	Biopolymer resistance factor (F_R)	Biopolymer permeability Reduction Factor (F_{RK})
HEC	3.063	3.061
Guar gum	2.536	2.534
Xanthan gum	2.433	1.645

4. Findings Significance in Oil Industry

The findings outlined above have significant practical implications for the oil industry, particularly in optimizing biopolymer selection for enhanced oil recovery (EOR) processes under harsh reservoir conditions. Operators can leverage this information to make informed decisions and enhance the efficiency of EOR operations. Here are the practical implications based on the provided findings:

- **Temperature sensitivity:** The inverse relationship between biopolymer viscosity and temperature is a crucial consideration for operators. Understanding this relationship allows operators to select biopolymers that maintain adequate viscosity at the elevated temperatures encountered in reservoirs. This knowledge helps in optimizing the selection of biopolymers that can withstand and perform effectively under high-temperature conditions.

- **Shear rate performance:** The finding that xanthan gum exhibits superior performance compared to HEC and guar gum under increased shear rates during the flooding process is valuable for operators. This knowledge enables operators to choose biopolymers that can maintain their viscosity and rheological properties when subjected to high shear rates during injection and displacement processes. Selecting biopolymers with superior shear stability ensures effective sweeping and displacement of oil, leading to improved recovery percentages.

- **Shear thinning behavior:** The observation of shear thinning behavior in HEC, xanthan gum, and guar gum at reservoir conditions is crucial for optimizing biopolymer selection. Shear thinning behavior allows the biopolymers to reduce viscosity under high shear rates, facilitating their flow through porous media. This property is desirable for EOR processes as it enables better mobility control, improved injectivity, and enhanced sweep efficiency in the reservoir.

- **Oil recovery effectiveness:** The core flooding experiments demonstrate the varying oil recovery effectiveness of different biopolymers under harsh reservoir conditions. Xanthan gum exhibited superior rheological properties and recovered a significantly higher percentage of residual oil saturation, indicating its potential as an effective biopolymer for EOR. Operators can utilize this information to prioritize the use of xanthan gum or explore its synergistic combination with other biopolymers to optimize oil recovery under similar reservoir conditions.

5. Conclusion

From this work, the following conclusions can be drawn:

1. The viscosity of biopolymers exhibits an inverse relationship with temperature, whereas no definitive relationship has been established between the viscosity of biopolymers and variations in pressure or salinity.
2. Under reservoir conditions (temperature, pressure, salinity, and shear rate), HEC exhibited elevated viscosity. However, as the shear rate increased during the flooding process, which begins at the surface lines and continues through the wellbore, it was found that xanthan gum exhibited superior performance compared to both HEC and guar gum. This superiority was evident in the significantly greater decrease in viscosity rate exhibited by both HEC and guar gum.
3. HEC, xanthan gum, and, guar gum show a shear thinning behavior at reservoir conditions (135000 ppm salinity, 196 °F temperature, 2200 psi pressure).
4. Core flooding experiments showed xanthan, guar, and HEC recovered 22%, 8.9%, and 1.8% of the residual oil saturation which is equivalent to 6%, 2.7%, and 0.6% of original oil in place respectively. This suggests xanthan gum exhibits superior rheological properties and oil recovery effectiveness among the tested biopolymers under harsh reservoir conditions.

5. X-ray photoelectron spectroscopy (XPS) experiments to evaluate rock pore throat changes before and after biopolymer flooding, especially with observed changes in permeability after biopolymer flooding is recommended.

6. Nomenclature

EOR	Enhanced Oil Recovery
FR	Resistance Factor
FRK	Permeability Reduction Factor
G'	Storage modulus
G''	Loss modulus
HEC	Hydroxyethyl Cellulose
K	Consistency index
n	Flow behavior index
OOIP	Original Oil in Place
PV	Plug pore volume
(RF) _P	Additional oil recovery by biopolymer
(RF) _W	Oil recovery achievable through water flood
S _{or}	Residual oil saturation
S _{orp}	Residual oil saturation after biopolymer flooding
S _{wi}	Connate water saturation
V _B	Plug bulk volume
V _{op}	Additional produced oil volume
τ ₀	Yield Point.
Ø	Porosity
μ	Viscosity

7. Conflicts of interest

“There are no conflicts to declare”.

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