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Polymers in petroleum fluids: advantages, disadvantages, applications, and economic and environmental perspectives

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ABSTRACT

With the increasing global demand for energy and the decline in accessible oil reserves, Enhanced Oil Recovery (EOR) methods have gained significant importance. Among various EOR techniques, the use of polymers is recognized as one of the most effective chemical methods for increasing oil recovery factors. This article provides a comprehensive review of polymers used in the petroleum industry. Synthetic polymers such as polyacrylamide (PAM) and partially hydrolyzed polyacrylamide (HPAM), and natural polymers such as xanthan gum and guar gum are introduced as the most widely used polymers in this field. The advantages of using polymers include increasing the viscosity of the injected fluid, improving the mobility ratio, and enhancing sweep efficiency. However, challenges such as temperature and salinity sensitivity, shear degradation, and environmental concerns arising from polymer accumulation in produced water exist. From an economic perspective, although the initial cost of polymer injection is high, the significant increase in oil recovery (up to 28% OOIP under optimal conditions) provides economic justification for this method. Environmental aspects include the potential production of the toxic monomer acrylamide from HPAM degradation and the difficulties in treating produced water containing polymers, necessitating the development of biodegradable polymers and advanced treatment methods.

Keywords: Petroleum polymers, enhanced oil recovery, HPAM, xanthan gum, guar gum, polymer flooding, petroleum economics, environment

1. INTRODUCTION

The oil and gas industry, as one of the main pillars of global energy supply, is constantly seeking methods to increase the oil recovery factor from reservoirs. According to estimates, after primary and secondary recovery stages, approximately 60 to 70 percent of the original oil in place (OOIP) remains in the reservoir [1]. Enhanced Oil Recovery (EOR) methods have been developed to extract this remaining oil. Among various EOR methods, chemical methods, particularly polymer flooding, have received special attention due to their high efficiency and relatively reasonable cost [2].

Polymers have been used in the petroleum industry since the 1970s. The first commercial application of polymer flooding was conducted in 1964 in the Louisiana oil basin [3]. Since then, extensive research has been conducted on the development of new polymers with greater resistance to harsh reservoir conditions (high temperature and salinity).

The main objective of this article is to provide a comprehensive review of the types of polymers used in petroleum fluids, their mechanisms of action, advantages and disadvantages, operational applications, and an examination of the economic and environmental aspects associated with the use of these materials.

2. MAIN BODY OF THE ARTICLE

2.1 Types of Polymers Used in the Petroleum Industry

Polymers used in EOR are generally divided into two main categories: synthetic polymers and natural polymers (biopolymers) [4].

2.1.1 Synthetic Polymers

Polyacrylamide (PAM) and Partially Hydrolyzed Polyacrylamide (HPAM): HPAM is the most widely used synthetic polymer in polymer flooding operations [5]. This polymer is produced by copolymerization of sodium acrylate with acrylamide or partial hydrolysis of PAM. The molecular weight of HPAM typically ranges from 3 to 30 million Daltons [6].

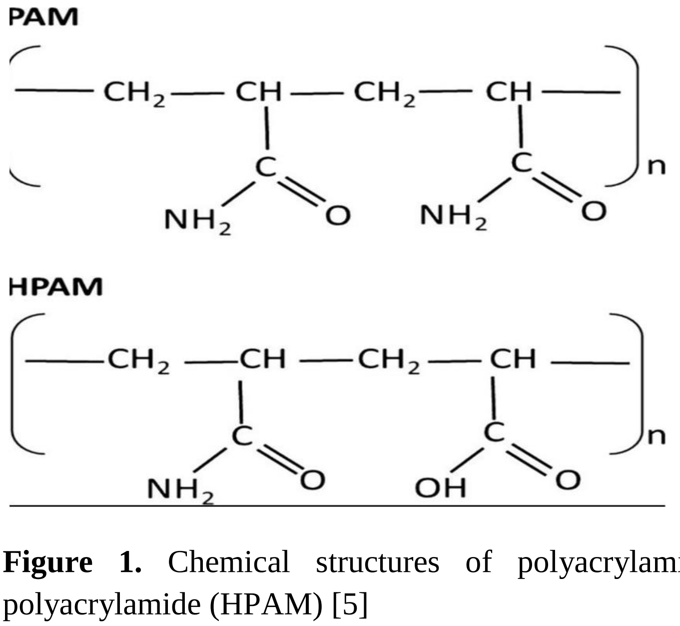

Figure 1. Chemical structures of polyacrylamide (PAM) and partially hydrolyzed polyacrylamide (HPAM) [5]

Due to the negative charges on the polymer backbone, HPAM dissolves in water and increases the solution viscosity. The optimal degree of hydrolysis for HPAM is approximately 25 to 35 percent [7]. A lower degree of hydrolysis reduces solubility, while a higher degree increases salinity sensitivity.

Hydrophobically Associating Polyacrylamides (HAPAM): To overcome the limitations of HPAM under high temperature and salinity conditions, hydrophobically associating polymers have been developed. These polymers contain small hydrophobic groups in the polymer chain that, above the critical association concentration (CAC), form hydrophobic domains and cause a significant increase in viscosity [8].

Thermoviscosifying Polymers (TVP): These smart polymers contain thermosensitive blocks or grafts that self-associate with increasing temperature, thereby increasing the solution viscosity. Unlike HPAM, which exhibits thermothinning behavior (viscosity decrease with temperature), TVPs exhibit thermoviscosifying behavior (viscosity increase with temperature) [9].

2.1.2 Natural Polymers (Biopolymers)

Xanthan Gum: Xanthan gum is an extracellular polysaccharide produced by fermentation of glucose or fructose by the bacterium Xanthomonas campestris [10]. This biopolymer has a pentasaccharide repeating unit composed of glucose, mannose, and glucuronic acid. The molecular weight of xanthan gum ranges from 2 to 50 million g/mol [11].

Due to its unique helical structure, xanthan gum exhibits good thermal resistance and salinity tolerance. Compared to HPAM, xanthan gum shows greater resistance to mechanical shear, salt stress, and divalent ions, and is stable over a wide pH range [11]. However, this polymer is susceptible to bacterial attack and biological degradation, becoming biodegradable after two days [12].

Guar Gum: Guar gum is extracted from the seeds of the Cyamopsis tetragonoloba plant. This environmentally friendly polymer has good compatibility with salts and exhibits excellent hydration properties. Guar gum is highly stable in the pH range of 4.5 to 10 and shows resistance to oils, chemicals, and fats [13].

Other Biopolymers: Other biopolymers under investigation include welan gum, scleroglucan, hydroxyethyl cellulose (HEC), and carboxymethyl cellulose (CMC) [14]. Welan gum is an anionic polysaccharide that exhibits good stability under high temperature and salinity conditions and has shown up to 70% OOIP recovery in core flooding experiments [15].

2.2 Mechanisms of Polymer Action in Oil Recovery

2.2.1 Mobility Control

The primary objective of polymer injection is to increase the viscosity of the injected aqueous phase. The mobility ratio (M) is defined between the displacing fluid and the reservoir oil:

$$M = \lambda w/\lambda o = (kw/\mu w)/(ko/\mu o)$$

Where λ is phase mobility, k is relative permeability, and μ is viscosity. By increasing the viscosity of the injected water (μw), the mobility ratio decreases, preventing the occurrence of viscous fingering [16]. The mechanism of polymer flooding is schematically shown in Figure 2.

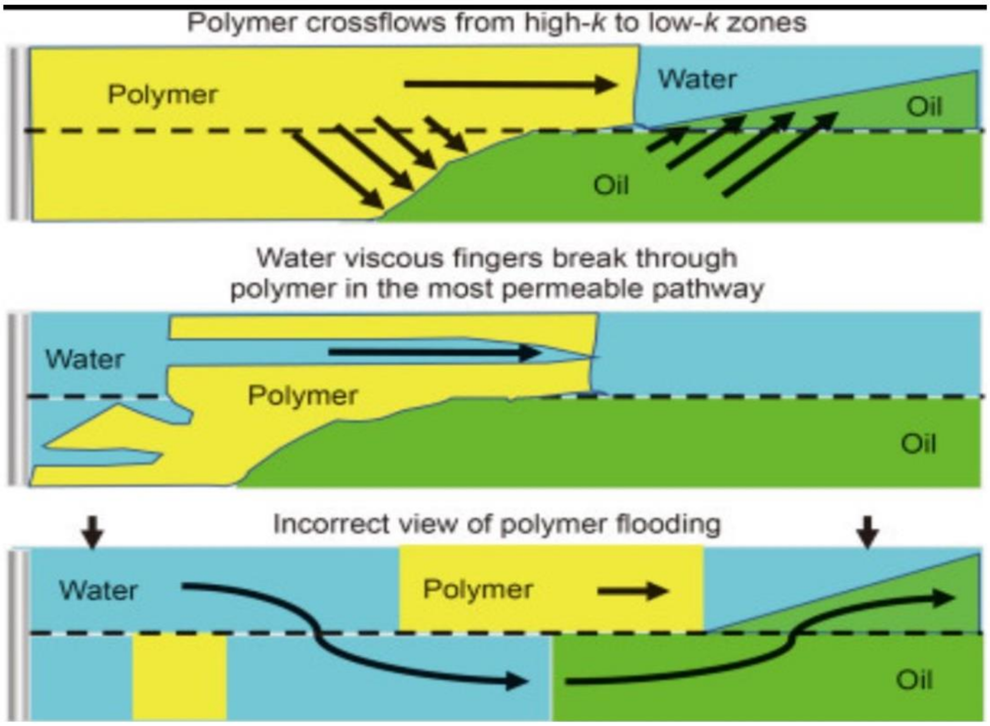

Figure 2. Schematic of the polymer flooding mechanism and flow control in the reservoir [16].

2.2.2 Improvement of Sweep Efficiency

By increasing the viscosity of the injected fluid, flow in high-permeability pathways is controlled, and the fluid is directed toward lower-permeability regions of the reservoir. This leads to an increase in overall macroscopic sweep efficiency [17].

2.2.3 Microscopic Oil Displacement Mechanisms

Recent studies have shown that polymers, in addition to improving macroscopic sweep efficiency, also affect oil displacement at the microscopic scale. The viscoelastic properties of polymers cause residual oil adhered to the reservoir rock surface to be detached by the elastic forces of the polymer and produced [18].

2.3 Advantages and Disadvantages of Various Polymers

Table 1 provides a comprehensive comparison of the advantages and disadvantages of common polymers used in EOR.

Table 1. Comparison of advantages and disadvantages of various polymers used in EOR [4, 12, 19].

Polymer	Advantages	Disadvantages
HPAM	High viscosity, low cost, widely available	Temperature and salinity sensitivity, shear degradation
Xanthan Gum	Good thermal resistance, salinity tolerance, shear resistance	Susceptible to bacterial attack, higher cost than HPAM
Guar Gum	Eco-friendly, good salt compatibility, excellent hydration	Limited thermal stability, biological degradation
HAPAM	High temperature and high salinity (HTHS) resistance	Higher cost, limited commercial availability
TVP	Thermoviscosifying behavior, HTHS resistance, thermal smartness	Higher cost, synthesis complexity, limited commercial availability
Welan Gum	Excellent thermal and salinity stability	Higher cost than HPAM, limited availability

2.4 Operational Applications and Field Results

2.4.1 Field Polymer Flooding Projects

Polymer flooding has been implemented commercially since the 1970s. The Daqing oil fields in China are among the most successful examples of polymer flooding application. In these fields, the use of HPAM has led to an increase in the recovery factor of up to 13% OOIP [18].

2.4.2 Hybrid Methods

The combined use of polymers with other chemicals leads to synergy and higher recovery:

• **Alkali-Polymer (AP):** Combination of alkali with polymer for interfacial tension reduction and viscosity increase [20].

• **Surfactant-Polymer (SP):** Interfacial tension reduction by surfactant and mobility control by polymer [21].

• **Alkali-Surfactant-Polymer (ASP):** The triple combination that has shown high recovery in Chinese oil fields [22].

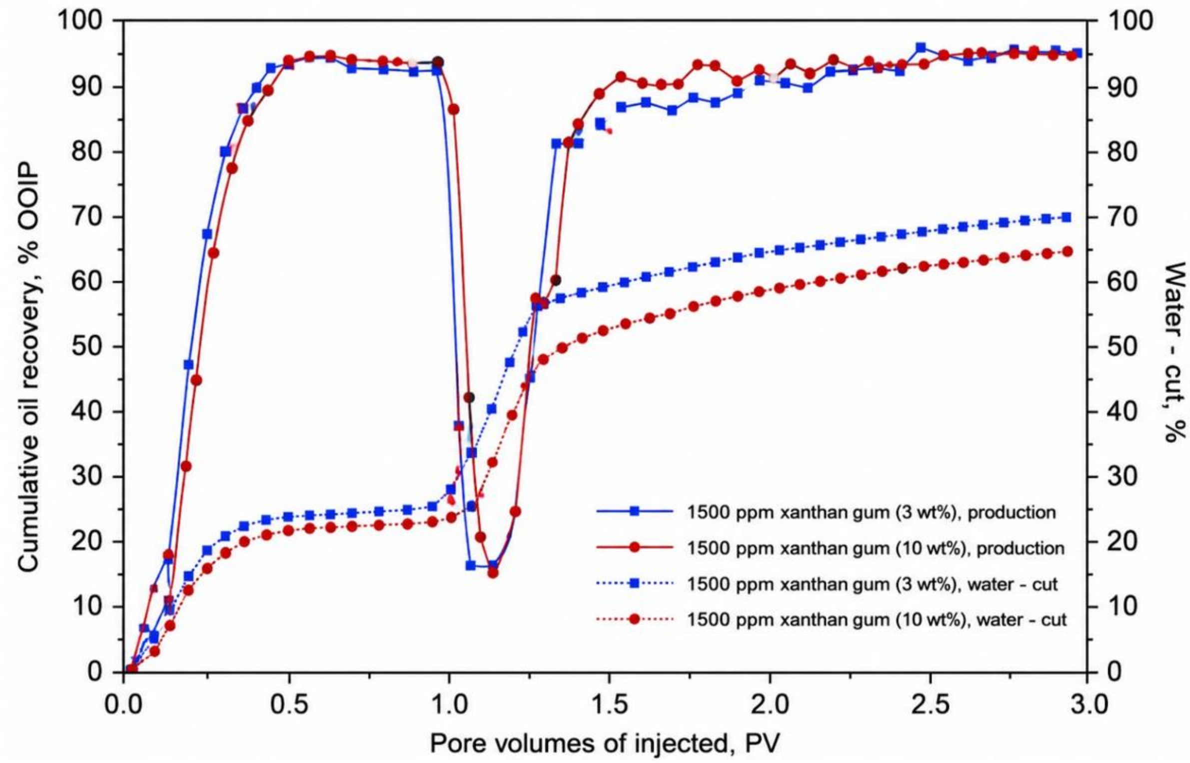

Figure 3. Core flooding results for xanthan gum at different concentration conditions [23]

2.5 Economic Perspective Analysis

2.5.1 Costs Associated with Polymer Flooding

The costs of implementing polymer flooding projects include:

Capital Expenditures (CAPEX): Includes water injection facilities, polymer injection equipment, and initial costs [24].

Operating Expenditures (OPEX): Includes polymer costs, water, personnel, and maintenance.

Based on a case study at the EOR 26 field, the polymer cost was approximately $0.78 per barrel, and the total polymer gel injection cost was estimated at $220,383 [24].

2.5.2 Return on Investment Analysis

Assuming an oil price of $50 per barrel, the revenue from additional oil production over a 10-year period is significant. In the EOR 26 field study, maximum production of 44,350 barrels of crude oil in 2022 and gross revenue of $2,217,500 was achieved [24].

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Table 2. Comparison of operational parameters for different flooding models [24]

Parameter	Water Flooding	Polymer Flooding	ASP Flooding
Recovery Factor (% OOIP)	35–45	50–60	60–70
Injection Cost ($/barrel)	0.10–0.20	0.50–1.00	2.00–4.00
Incremental Oil (%)	—	10–15	15–25

Parameter	Water Flooding	Polymer Flooding	Polymer Gel	Optimized
Total Oil Recovery (%)	18	22	26	28
Average Oil Saturation Reduction (%)	45	40	35	30
Water-Oil Ratio	95	65	45	35

2.6 Environmental Perspective Analysis

2.6.1 Environmental Challenges of HPAM

As the most widely used synthetic polymer, HPAM creates significant environmental challenges:

• **Accumulation in Produced Water:** HPAM concentration in produced water from the Daqing field reaches 1900 mg/L [25].

• **Production of Toxic Monomer:** Natural degradation of HPAM can lead to the production of acrylamide monomer, which is a toxic, carcinogenic, and mutagenic substance. Acrylamide is classified by the International Agency for Research on Cancer (IARC) in Group 2A carcinogens [26].

• **Increased Viscosity of Produced Water:** The presence of HPAM increases the viscosity of produced water, complicating biological and chemical treatment processes [25].

• **Impact on Ecosystems:** Produced water containing HPAM negatively affects plant species diversity and microbial communities in the environment [27].

2.6.2 Produced Water Treatment Methods

Various methods have been developed for HPAM removal from produced water:

• **Advanced Oxidation Processes:** Use of UV/H2O2 and UV/PDS for rapid HPAM degradation [25].

• **Photocatalysis:** Use of zinc oxide nanorods for photocatalytic degradation of HPAM [28].

• **Biodegradation:** Use of bacteria such as Bacillus cereus, Acinetobacter sp., and Alcaligenes faecalis for biological degradation of HPAM [29].

2.6.3 Biodegradable Polymers

Increasing attention is being paid to the use of biopolymers and modified environmentally compatible polymers. Xanthan gum, guar gum, and starch have been investigated as alternatives to HPAM [30].

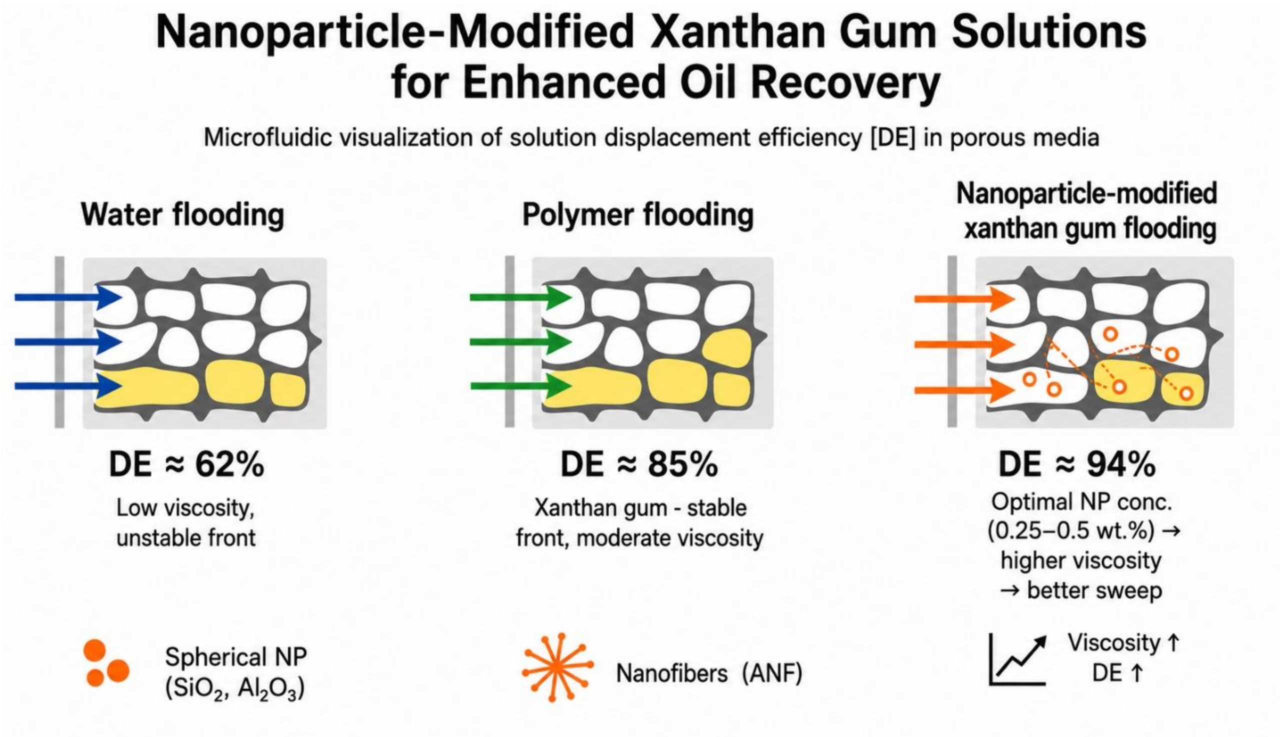

Figure 4. Comparison of displacement efficiency in porous media for water flooding, polymer flooding, and nanoparticle-modified xanthan gum [31].

3. RESULTS AND DISCUSSION

Research results indicate that the selection of the appropriate polymer for EOR strongly depends on reservoir conditions. Under moderate temperature and salinity conditions, HPAM is the first choice due to its low cost and high efficiency. However, in reservoirs with harsh conditions (HTHS), novel polymers such as TVPs and HAPAMs show better performance [9].

From an economic perspective, although the initial cost of polymer flooding is high, the increase in oil recovery up to 28% OOIP under optimal conditions provides a strong economic justification for this method [24]. Case studies have shown that polymer flooding increases oil recovery by 20–26% compared to conventional water flooding [23].

From an environmental perspective, the main challenge is the management of produced water containing polymers. The development of biodegradable polymers and efficient treatment methods is essential to reduce environmental impacts [29, 30].

4. CONCLUSION

Polymers, as one of the key tools in enhanced oil recovery, play an important role in increasing the recovery factor from oil reservoirs. The findings of this article can be summarized as follows:

1. HPAM is the most widely used polymer in EOR, but has limitations under HTHS conditions.

2. Biopolymers such as xanthan gum are environmentally friendly alternatives, but are susceptible to biological degradation.

3. Smart polymers such as TVPs offer promising solutions for harsh reservoirs.

4. From an economic perspective, polymer flooding is justifiable despite high initial costs.

5. Environmental management of produced water and development of green polymers are future priorities in this field.

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