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Hybrid Polymer-Thermal Flooding of Heavy Oil Production: A Critical Review of Experimental and Numerical Advancements

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ABSTRACT

Conventional heavy oil recovery methods are reliant on the reduction of thermal viscosity to mobilise the oil; a major disadvantage of this is poor sweep efficiency resulting from steam override and channelling. This review involves the systematic examination of recent experimental and numerical advancements involved in hybrid polymer-thermal flooding for the production of heavy oil. The traditional polymers, such as partially hydrolyzed polyacrylamide (HPAM), are vulnerable to degradation by high temperature and high salinity conditions of reservoirs. New developments such as the use of nanocomposite systems or natural biopolymers (xanthan gum, guar gum, gum arabic) enhanced with silica, alumina, or magnesium nanoparticles are also promising. Laboratory experiments (core flooding and ECLIPSE simulations) show that under simulated reservoir conditions, the viscosity of the oil is reduced, leading to higher oil recovery. Gum arabic nanocomposites demonstrate a certain potential even with a reduced base viscosity. It is a synthesis of existing knowledge on polymer-thermal EOR mechanisms, identifies gaps in the current knowledge, and suggests future research directions, including material innovation and development of tools to simulation to achieve sustainable heavy oil recovery.

INTRODUCTION

The high viscosity of heavy oil limits recovery under the conventional method. The conventional recovery methods, such as primary and secondary techniques, produce only 30-40% of the original oil in place (OOIP) and leave significant untapped resources (Miller and Sorrell 2006; Godec *et al.,* 2013). Primary recovery depends upon intrinsic reservoir energy that includes the expansion of fluids, the gas driving action, and influx of water without the introduction of external agents (AlAbbasi *et al.,* 2019). In secondary recovery, which mainly occurs in water floods, the reservoir pressure is maintained, but with poor mobility ratios as water is less viscous than oil, especially in the extra heavy oil deposits. The water is inclined to avoid massive quantities of hydrocarbons through high-permeability streaks, fractures, and heterogeneous areas (Ahmed and Meehan 2012). Gas injection, on the other hand, incurs challenges such as limited availability, high cost, gravity segregation, low sweep efficiency, and corrosion risks (AlSofi *et al.*, 2017).

Enhanced Oil Recovery (EOR) is one of the methods used in addressing the limitation of low oil recovery. EOR involves injecting special agents that alter its wettability, interfacial tension (IFT), oil viscosity, and behaviour of the phases (Alfarge *et al.*, 2019). There are four types of EOR schemes, including thermal (steam injection, in-situ combustion, Steam-Assisted Gravity Drainage (SAGD), chemical (polymer, surfactant, ASP flooding), miscible gas injection (CO2), hydrocarbon gas, water alternating gas (WAG)), and microbial EOR (Ahmed and Meehan, 2012). Thermal EOR is particularly helpful in heavy and viscous oils, potentially recovering 40-50% of OOIP by reducing their viscosity. Nevertheless, thermal processes are of great environmental concern, with complexities of equipment and safety issues (AlAbbasi *et al*., 2019; Green and Willhite, 1998). Chemical EOR aims at microscopic displacement efficiency. To overcome the weakness of specific methods, researchers have come up with hybrid polymer-thermal EOR, a method that combines both to maximize recoveries when dealing with a complex reservoir environment. Polymer-thermal EOR injects polymer solutions and thermal energy, which can be a combination of steam and thermal energy or solely requires thermal energy or steam. The polymer component also viscosifies the aqueous phase, increasing the mobility ratio and reducing viscous fingering, and also thermal input decreases oil viscosity to enhance flow (Ahmed and Meean, 2012; AlAbbasi *et al*., 2019).

This synergy is particularly useful in heterogeneous reservoirs that are heavy oil (Ahmed and Meean, 2012). Nevertheless, there are significant difficulties in field implementation: high salinity leads to acceleration of hydrolysis of traditional polymers at temperatures above 90oC, conventional polymers are vulnerable to viscosity loss, and high salinity and divalent cations accelerate hydrolysis in organic polymers (Kong and Ohadi, 2010; Mokheimer *et al*., 2019; Nasr-El-Din and Qasem, 2020). Others are issues of injectivity in low-permeability horizons, retention of polymers due to adsorption and mechanical entrapment, and inability to predict performance due to complexity in the reservoir (Kong and Ohadi, 2010; Mokheimer *et al*., 2019).

New developments based on polymer chemistry have enhanced the effectiveness of the polymer-thermal EOR. Better resistance to the harsh environmental conditions of the reservoir is achieved with high-temperature, salt-resistant polymer, including HPAM variants and biopolymers (xanthan gum). The promises of nanotechnology allow the customization of polymer properties to apply them to a particular reservoir. Nanoparticles can improve the displacement efficiency through better mobility control, change in wettability, and reduced IFT when used together with the conventional polymer-thermal flooding (Smith *et al*., 2020; Zhang *et al*., 2021; Soppimath *et al*., 2001; Wang *et al*., 2012; Zhang and Elliott, 2006).

This review extensively covers polymer-thermal EOR methods, outlines the system's underlying mechanisms, new technological developments, laboratory and field experiments, numerical modelling systems, and performance measurement. This paper will be used in the development of more effective recovery strategies to meet the needs of heavy and extra-heavy oil wells.

LITERATURE REVIEW

Thermal Enhanced Oil Recovery Methods

Thermal EOR refers to the methods of introducing heat to the formations to lower the viscosity of the crude oil to promote movement through the porous media. Principal methods include:

Cyclic Steam Stimulation (CSS): This method is known as the huff and puff method and involves injecting steam into a single well, then allowing the well to soak and, lastly, extracting oil from the same well. CSS is ideal in shallow, heavy oil reservoirs where 10-40% improvement of recovery is realized, but suffers losses of heat in deeper oil reservoirs (Nune *et al*., 2009).

Steam Flooding: The oil is moved to the producers as the continuous steam injection through injector wells displaces the oil. Steam flooding can greatly enhance recovery by a factor of 60 but requires substantial water and energy and also exhibits channeling (Padmanabhan *et al*., 2016).

In-Situ Combustion (ISC): Lighting off some existing in-place oil produces heat and combustion gases, which move remaining crude. ISC efficiently operates in deep or tight formations with lower water requirements, potentially achieving 70% recovery, but requires precise control of the combustion front (Abidin *et al*., 2021). Steam-Assisted Gravity

Drainage (SAGD): Horizontal wells (shared) with a steam injection by upper wells and a collected production of oil by lower producers achieve a recovery of 60-70 percent of oil in oil sands, albeit at a high capital cost with strict requirements of well placement, and have to be doctored (Zhou *and* Liu, 2021).

Developments in Chemical Enhanced Oil Recovery Methods

Chemical EOR entails injecting polymers, surfactants, alkali, or a combination of any of these to mobilize residual oil. Polymer flooding is used to enhance the injected water viscosity to attain a good mobility ratio (M< 1) to reduce viscous fingering and increase sweep. HPAM and xanthan gum are some of the common polymers (Seright, 2020). Surfactant flooding reduces IFT to ultra-low values (<0.01 mN / m) and changes the wettability of rocks (Ahmed *et al*., 2020). The in-situ surfactants in alkaline flooding are formed by saponification of the acidic crude constituents (Liu *et al*., 2020). The mechanism of alkali-surfactant-polymer (ASP) flooding is a combination of the three mechanisms (Li *et al*., 2025). New approaches include the use of nanoparticles, switchable surfactants and low-salinity brines (Seright, 2020).

Types of polymers used in Enhanced Oil Recovery

Partially Hydrolyzed Polyacrylamide (HPAM): This is the most used synthetic polymer as it possesses both high viscosity at low concentration and is economical. HPAM improves the sweep efficiency of low-salinity and low-temperature reservoirs, but reduces above 80 C or in high-salinity different reservoirs with divalent cations (Ahmed *et al*., 2020).

Sulfonated Polyacrylamide Copolymers (ATBS, AMPS): Advanced polymers used in deep-sea, high-temperature, or salty reservoirs, which include a sulfonic acid functional group to give resistance to degradation even at salinities greater than 200,000 ppm and temperatures higher than 100 °C. They are very expensive such that they cannot be applied on a large scale (Zhou *and* Liu, 2021).

Xanthan Gum: A biopolymer that has good abilities of retention of viscosity and maintenance of viscoelasticity, which would be effective in heterogeneous and salty reservoirs. Xanthan is resistant to multivalent ions, possesses good shear-thinning properties and demonstrates poor resistance to microbial degradation and high production costs (Liu *et al*., 2020).

Guar Gum and Derivatives: Neutral pH, low-salinity water can be biodegraded with guar gum and derivatives. Hydroxypropyl guar increases at higher temperatures, but it also decays at high temperatures and over 70ºC (Zhang *et al*., 2021).

Gum Arabia: An amphiphilic biopolymer that is biodegradable and has a broad salinity matchability. These are constrained by low intrinsic viscosity and low thermal stability at temperatures greater than 70º C (Musa *et al*., 2021).

Nanocomposite Polymer Systems

The polymer-nanocomposite systems are systems consisting of conventional, water-soluble polymers, along with the nanomaterial (silica, magnesium oxide, alumina). Nanoparticles improve the stability of polymer matrices because of interaction effects between particles and polymer, making them resistant to shear degradation and thermal breakdown. Molecular-wise nanoparticles decrease polymer retention by reducing adsorption on rock surfaces, modifying the wettability of rocks, and decreasing interfacial tension, enhancing the efficiency of displacement and the sweep macroscopically (Pal *and* Mandal, 2022). Its benefits encompassed increased salinity and temperature resilience, reduced polymer loss, as well as increased compliance. These limitations are the complexity of formulation, the possibility of agglomeration, the lack of commercial-scale realworld application, and high costs of production (Pal *and* Mandal, 2022).

Polymer-Thermal Enhanced Oil Recovery

Polymer-thermal EOR is a combination that involves thermal techniques with polymer flooding to increase oil mobility, sweep efficiency, and reduce oil viscosity in challenging reservoir conditions.

Principle and Mechanism: The principle here is to introduce polymers either in advance of or following thermal treatment. In combination with steam, polymers raise aqueous phase viscosity to enhance the mobility ratio defined as M = ~ μw/μo of the product. Steam can greatly reduce oil viscosity (μo) and polymer can raise water viscosity (μw); a good displacement efficiency can be achieved. Polymers may be gels, viscoelastic structures that plug high-permeability channels (Zhang *et al*., 2022; Daripa and Mishra, 2023). Significant Strategies: Polymer-Assisted Steam Flooding involves the use of polymer pre-flush or co-injection with steam to stabilize the steam front, prevent viscous fingering, and early breakthrough (Liu *et al.,* 2021). Steam-Alternating-Polymer (SAP) injects steam and polymer slugs alternating in cycles, which delays the production of water and reduces the steam-oil ratio (Kumar *and* Singh, 2021). Polymer-based foams are used to combine polymer with steam foams to reject high-permeability routes and to decrease steam-break (Nassar *et al*., 2022),

They have advantages such as an increased ability to control mobility, elimination of early water breakthrough, and uniform sweep. Sulfonated acrylamides (thermally resistant polymers) stabilize at temperatures greater than 150 C (Lee *and* Choe, 2021). The properties of viscoelastic polymer mobilize residual oil that is trapped in the throats of the pore throats. A decrease in the ratio of steam oil reduces energy use, water use and CO^2 emissions (Mistry *and* Ghosh, 2022).

Difficulties: Under extreme conditions, the thermal and chemical degradation of normal polymers is the leading one. HPAM is vulnerable to high temperatures or when these are present in the presence of divalent cations. Biopolymers (xanthan gum, gum arabic) demonstrate higher salinity tolerance but have not shown resistance to thermal degradation above (70-80)^{o}C (Yuan *et al*., 2023). The high cost of operation of thermally stable formulations with advanced additives massively increases the material costs (Nassar *et al*., 2023). Plugging and pressure buildup occur as a result of injectivity issues in tight or low-permeability formations (Liu *et al.,* 2022). There continue to be few full-scale field applications, with most of the work confined to experimentation (Zhang *and* Ghalambor, 2023).

Table 1: Summary of key research studies on Polymer-Thermal EOR

Author(s)	Polymer Type	Research Methodology	Main Results	Identified Gaps
Zhang *et al.* 2022	HPAM	Lab-scale polymer-steam flooding	28% oil recovery increase; reduced channeling	Scale-up feasibility; polymer degradation in the field
Li *et al.* 2025	Sulfonated polymers	High-temperature core flooding	75% viscosity maintained at 120°C in brines	Long-term chemical stability; cost reduction
Wang *et al.* 2012	HPAM	Field pilot with polymer pre-flush	20% SOR reduction; 18% incremental oil	Polymer placement models for heterogeneous reservoirs
Chen *and* Ghomian 2023	HPAM	Simulation of polymer-SAGD	25% water reduction compared to steam-only	Economic assessment of polymer-SAGD integration

Liu *et al*. 2022	HPAM, ATBS	High-temperature stability tests	HPAM degraded >50% at 90°C; ATBS better retention	New generation polymers for >120°C, high salinity

Nanoparticles in Enhanced Oil Recovery

Nanoparticles, structures falling within the 1-100 nanometers range, possess different properties compared to bulk counterparts, such as an increase in surface area-to-volume by more than a factor of ten, concomitant change in mechanical strength, as well as defining magnetic properties (Chen *et al* 2023). These nanomaterials overcome chemical EOR challenges, including permeability decrease, adsorption losses and plugging. Nanoparticles can be used to control mobility, stabilize emulsions and foams, and modify reservoir wettability (Alam *and* Idris, 2022). Nanoparticles required to be used in the subsurface should be cost-effective, unreactive in brine solutions, be able to propagate through the porous rocks, and be compatible with an injection system. Capping agents that create a surface functionalization inhibit aggregation and increase dispersion (Mandal *and* Chauhan, 2023).

Table 2: Experimental matrix for nanocomposite *and* biopolymer systems

Author(s)	**Polymer *and* Nanocomposite**	**Temp. Range (°C)**	**Research Methodology**	**Results**	**Gaps / Recommendations**
Zhang *et al.* 2021	HPAM	60-90	Lab-scale polymer-steam flooding	28% improvement; delayed breakthrough	Field-scale trials; thermal degradation analysis
Wang *et al.* 2012	HPAM	50-85	Field pilot with polymer pre-flush	20% SOR reduction; 18% incremental recovery	Model polymer placement in heterogeneous reservoirs
Liu *et al.* 2025	HPAM, ATBS copolymer	90-130	Brine stability *and* thermal flooding tests	ATBS copolymers retained >70% viscosity	Develop polymers for >130°C and high salinity
Yuan *et al.* 2023	HPAM + SiO_2 NPs	80-110	Nano-enhanced polymer core flooding	Improved viscosity retention; lower adsorption	Explore nano-polymer pore-scale interactions under heat

Types of nanoparticles currently under investigation include metal oxides (SiO_2, Al2O3, TiO2), carbon-based materials (nanotubes, graphene, and fullerenes), quantum dots, polymer-based nanoparticles and metallic nanoparticles (Das *and* Daripa, 2023). Nanoparticles used in EOR alter the mobility ratio, wettability, and fine migration control, and contribute to enhanced sweep efficiency and increased recovery factors, in particular in reservoirs where conventional methods are unable to penetrate narrower pore spaces.

Simulation Techniques of Polymers EOR

Numerical reservoir simulators, such as ECLIPSE by Schlumberger, CMG-STARS and UTCHEM, are mainly used in simulating polymer behaviour in porous media.

ECLIPSE 100: Industry standard simulator with full polymer module modeling polymer-induced viscosity increase, adsorption onto rock surfaces, retention and change in relative permeability. The relationship between concentration and viscosity of polymer determines the viscosity of the in-situ fluids. Isothermal adsorption of polymer involves

Langmuir-type isotherms. Shear-thinning behaviour is a behaviour that modifies effective viscosity according to the local flow behaviour (Seright, 2010).

CMG-STARS: Sophisticated thermal-compositional simulator of thermal-chemiluminescent-non-Newtonian fluid dynamics. STARS can capture shear-thinning traits through power-law or Carreau-Yasuda models, as well as temperature-dependent polymer degradation using kinetic degradation models. The simulator simulates chemical and nanoparticle-enhanced formulations, such as polymer-nanoparticle and surfactant-polymer systems (Albonico *et al*., 2014).

UTCHEM/UTCHEM-RS: University of Texas at Austin research-oriented platform of chemical EOR, with a multicomponent reactive transport framework to allow detailed modeling of polymer concentration profiles, chemical reactions, adsorption, dispersion, and fluid-solid interactions. The UTCHEM models are the electrostatic interactions on polymers and formation rocks coupled with salinity, pH and ion exchange models, essential to model the chemical stability and solubility of polymer formulations (Chen *et al*., 2015).

Table 3: Comparison of simulation tools for Polymer-Thermal EOR

Simulator	Developer / Origin	Advantages	Disadvantages
ECLIPSE 100	Schlumberger	Widely accepted commercial simulator; Supports polymer injection (PLYVISC, PLYADS, PLYROCK); Shear-thinning *and* adsorption models; Integrates easily with field data	Lacks viscoelastic behaviour modeling; Limited temperature-dependent degradation; Less flexible for complex chemistries
CMG-STARS	Computer Modelling Group (Canada)	Advanced modeling of thermal-chemical EOR; Temperature-dependent polymer viscosity *and* degradation; Models non-Newtonian behaviour; Integrates surfactant-polymer blends *and* nanoparticles; Suitable for SAGD *and* heavy oil	High computational cost; Steeper learning curve; Requires detailed input data *and* tuning
UTCHEM/UTCHEM-RS	University of Texas at Austin	Research-grade flexibility for polymer *and* surfactant EOR; Models coupled salinity, pH, ion exchange; Plug-in architecture for custom polymer modules; Lab-to-field scale-up	Less user-friendly interface; Not commercially supported; Computationally intensive for large fields

Ongoing Limitations: The current simulators have important limitations when it comes to accurately modeling viscoelastic behaviour, flow in heterogeneous reservoirs, and polymer stability under harsh conditions. The models of shear thinning neglect the effects of stress relaxation and memory, and underestimate mobility control (Slater *and* Cook, 2012). The flow prediction in complex formation is limited by the coarse grid and simplistic assumptions (Nasr-El-Din *and* Taylor, 2014). Empirical models such as Langmuir isotherms do not describe coupled thermal, chemical and ionic interactions on polymer retention and degradation, particularly in high-temperature and high-salinity environments (Singh *and* Kumar, 2015).

RESEARCH GAPS AND FUTURE DIRECTIONS

Research Gaps

(a) Field-Level Performance of Advanced Polymers: Although sulfonated copolymers and biopolymers have been developed, their field-level performance remains unknown. There is acute demand for high ionic and oxidative stability polymers with reinforced backbones, validated by field trials in high-temperature (>100°C) and ultra-high salinity (>200,000 ppm TDS) environments (Zhou *and* Liu, 2021).

(b) Injectivity in Low-Permeability Reservoirs: High molecular weight polymers improve mobility control but cause injectivity issues in low-permeability reservoirs due to pore-blocking, mechanical entrapment, and adsorption losses. Future directions should focus on innovative designs of low-resistance polymers with optimized molecular weight or branched molecules and development of new injectivity models that consider pore-scale heterogeneity (Liu *et al*., 2022).

(c) Polymer Retention and Adsorption: Significant polymer loss occurs via adsorption on rock surfaces, mechanical trapping, and hydrodynamic retention. Formulating predictive models that combine rock chemistry with fluid properties and heterogeneity, enabled by microfluidics and molecular simulations, is an important priority (Liu *et al*., 2020).

(d) Viscoelasticity Effects: Normal stress generation and stretch-recoil dynamics of viscoelastic polymers mobilize residual oil, but their effects are poorly understood at the reservoir scale. Integrated multi-scale studies using core flooding, pore-scale imaging, and simulations are necessary to quantify and translate viscoelastic behaviours into predictive EOR performance measures (Li *et al*., 2025).

(e) Biopolymer Performance Data: Biopolymers face challenges including microbial degradation, lower thermal stability, and low injectivity. Long-term field data under harsh conditions are scarce. Stabilizing biopolymer formulations and conducting comparative studies against synthetic alternatives are important (Yuan *et al*., 2023).

(f) Nanoparticle-Polymer Interactions: The mechanisms of interaction, entanglement, bonding, and dispersion behaviour are not well defined. Understanding nanoparticle-polymer interactions requires pore-scale experiments and models to optimize nanoparticle-polymer systems (Pal *and* Mandal, 2022).

(g) Environmental and Economic Sustainability: Polymer flooding has environmental and cost issues due to chemical production, fresh water use, and byproduct generation. Life-cycle analyses and development of renewable, green, biodegradable, and affordable polymer alternatives are critical (Ahmed *et al*., 2020).

(h) Standardization of Evaluation Protocols: Variations in polymer screening, rheology, and core flooding test methodologies cause data inconsistencies. Implementing common evaluation protocols is necessary for credible simulation, benchmarking, and scalability across different reservoir environments (Musa *et al*., 2021).

Future Directions and Recommendations

Based on the identified gaps, the following future directions are recommended:

(a) Develop next-generation polymers: Create low-resistance polymers with optimized molecular weight or branched architectures to improve injectivity while maintaining mobility control.

(b) Build new injectivity models: Develop predictive models that incorporate pore-scale heterogeneity, mechanical entrapment, and adsorption losses.

(c) Conduct field validation programs: Perform long-term field trials for sulfonated copolymers, biopolymers, and nanocomposite systems under high-temperature (>100°C) and ultra-high salinity (>200,000 ppm) conditions.
(d) Advance simulation capabilities: Develop coupled thermal-chemical-mechanical-viscoelastic simulators that go beyond current empirical models (Langmuir isotherms) to include coupled thermal, chemical, and ionic interactions.
(e) Establish standardized scaling schemes: Create common evaluation protocols for polymer screening, rheology, and core flooding to enable cross-study comparisons and benchmarking.
(f) Perform life-cycle assessment: Quantify environmental and economic sustainability of polymer-thermal EOR, including water use, chemical production, and byproduct management.
(g) Integrate machine learning: Combine physics-based simulation with machine learning and uncertainty quantification to improve predictive performance and optimize field-scale implementation.

CONCLUSION

Polymer-thermal enhanced oil recovery forms a synergistic hybrid concept where thermal viscosity reduction and polymer flooding's sweep efficiency achieve a combined benefit. This method addresses basic problems such as reservoir heterogeneity, viscous fingering, and low oil mobility that individual methods cannot fully resolve. Recent developments in polymer science — temperature-tolerant and salinity-tolerant variants — have significantly widened the operational window of polymer-thermal EOR. The integration of nanomaterials into polymer-thermal systems has emerged as a key innovation, providing enhanced thermal stability, reduced polymer degradation, improved injectivity, and superior mobility ratio control through intelligent rheological behaviour. Nanocomposite and associative polymers show higher resistance to shear, temperature, and salinity with minimal adsorption and pore plugging. Although laboratory and pilot-scale results are promising, field application remains limited due to polymer degradation mechanisms, injectivity limitations in low-permeability formations, and cost-effectiveness issues. Simulation tools such as ECLIPSE, CMG-STARS, and UTCHEM offer valuable predictive performance but require further development to model viscoelastic behaviour, complex reservoir heterogeneity, and coupled thermal-chemical processes. Overcoming these hurdles demands multidisciplinary research incorporating polymer chemistry, nanotechnology, reservoir engineering, and computational modelling, along with comprehensive field validation programs. Continued investment in materials and process optimization is key to realizing the full potential of polymer-thermal EOR for future energy demands with better resource efficiency and reduced environmental footprint.

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