

Temperature-dependent viscosity model of HPAM polymer through high-temperature reservoirs



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ABSTRACT

Polymer flooding in high temperature reservoirs usually has shown poor performance because the injected polymeric solution tends to experience severe thermal degradation and ineffective in-situ sweep behavior. For the simulation results under such reservoirs, the real observation is likely to be out of estimation due to the absence of accurate viscosity model. The aim of this study was therefore to modify an existing numerical reservoir simulator to model HPAM hydrolysis, which is caused by thermal degradation in high temperature reservoirs, by employing the concept of half-life decomposition. The term 'half-life' has been proposed in numerical simulations to describe the kinetics of thermal decomposition of unstable polymers. This work analyzed rheological properties considering thermal hydrolysis with the goal of establishing an in-situ viscosity calculation for high temperature reservoirs. Comparison of the conventional Flory–Huggins' model to the proposed viscosity model allowed us to evaluate hydrolysis and the long-term stability of the polymer according to temperature. The results obtained using the new viscosity model indicated that polymer concentration loss was proportional to the initial concentration. However, viscosity reduction was more severe than concentration loss at higher initial polymer injection concentrations and was exaggerated as the initial concentration increased. Due to polymer decomposition at high temperatures, application of polymer flooding is limited at high-temperature reservoir.

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1. Introduction

Recently, polymer flooding has been highlighted as a feasible mobility control means to improve oil recovery throughout the world [4,7,10,11,25]. Hydrolyzed polyacrylamide (HPAM), one of the most widely used polymer types, has been successfully used as an additive to improve the oil recovery efficiency of waterflooding. However, full investigation of laboratory screening tests is necessarily required for assessing the feasibility of successful polymer flooding. Such procedures should incorporate polymer injectivity, retention, and brine compatibility tests along with a study of the microbial, mechanical and chemical degradation characteristics of the process [2]. Reflecting the need for a better understanding of polymer viability, a series of studies have investigated a broad range of polymer characteristics.

Early studies reported the effectiveness and applications of polymer floods in laboratory as well as field tests [6,9,30]. Among many comprehensive tests, the long-term stability of HPAM for specific field applications was evaluated [32]. summarized the main parameters acting on the stability of hydrolyzed polyacrylamides in brines containing divalent ions. Refs. [20,21] summarized the terminology related to polymer degradation and addressed hydrolysis of HPAM, including its sensitivity to chemical and thermal degradation mechanisms. In his studies, the term of hydrolysis was considered as different phenomenon from the "chemical degradation," which is sensitive to calcium ions. Chemical degradation should not be confused with cleavage of the acrylic backbone by radical mechanisms, which is referred as "thermal degradation." By distinguishing these technical terms, an increased understanding of the continued hydrolysis of partially HPAM was achieved.

Ref. [19] carried out thorough experiments at various temperatures to figure out the stability limit temperature for the application of polymer EOR (Enhanced Oil Recovery). Based on their experimental approaches, they developed a set of guidelines for the use of PAM and HPAM such that expected hydrolysis and measured

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cloud-point data can be estimated. However, polymer projects in high temperature reservoirs have not been considered due to temperature limitations, despite the fact that other reservoir properties are highly suitable for the polymer EOR process.

According to Refs. [14–16] the distinction between the two phenomena of chemical degradation and thermal cleavage can largely be addressed separately to decouple their competing effects on polymer stability. Refs. [22,23] carried out a set of experiments at various temperatures to determine the effect of temperature on viscosity in the absence of divalent cations. Their experimental data demonstrated that significant viscosity reduction took place at higher temperatures, even though divalent cations that could react with the polymer molecules were absent.

Viscosity is one of the most important factors in polymer EOR, and determines the success of polymer flooding in the simulation estimations. However, the existing models in commercial reservoir simulators are not sufficient to satisfy the qualified estimation because the degradation causing concentration loss and viscosity reduction was not taken into account. Development of a more accurate viscosity model that considers thermal characteristics is necessary to optimize experimental design and minimize potential risk. This requires examiners to move beyond simple comparisons of polymer lifetime with the expected timescale of polymer flooding [2].

The main aim in this study is to develop an in-situ rheological model of polymer in high temperature porous media, which can minimize the potential problems resulting from underestimation of laboratory calculations compared to in-situ observations. The purpose was accomplished by implementing the half-life decomposition due to thermal degradation of hydrolyzed polyacrylamide (HPAM) in this model, which is strongly sensitive to the temperature. An accurate in-situ rheological model of polymer viscosity will allow determination of critical flooding temperatures, and reduce risks associated with polymer flooding applications. Furthermore, the potential of polymer flooding can be reconsidered in light of the new model because restricted criteria can be expanded.

2. HPAM characteristics

The most widely used polymer in EOR applications is HPAM. HPAM polymeric solution provides significantly higher viscosity than other types of polymers by employing partially hydrolyzed process [18,27]. As shown in Fig. 1, in-situ hydrolysis converts some of the amide groups in the polymer chain (CONH₂) to carboxyl groups (COO⁻). This development also has the advantage of increased injectivity during polymer injection because of the lower initial viscosity of HPAM [15].

The high viscosity of HPAM polymeric solution is mainly attributed to the hydrolysis. In more detail, HPAM polymer introduces negative charges on the backbones of its chemical chains that have a large effect on the rheological properties of the polymer solution. This polymer has been known as undergoing hydrolysis in brine solution. At moderate brine salinity, the negative electronic charges on the backbones repel each other. Repulsion between the negative charges on the polymer chains contributes to chain extension, thereby resulting in high viscosity. Because of its

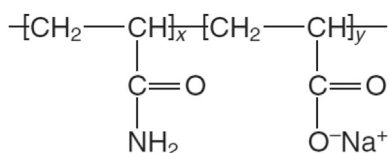


Fig. 1. HPAM polymer chemical structure [24].

chemical nature, HPAM can be used at very low concentrations while still yielding the desired viscosity levels [13]. The degree of hydrolysis is the mole fraction of amide groups converted by hydrolysis. At higher degree of hydrolysis above 40%, the flexible chains are seriously compressed and distorted, and a reduction in viscosity has been reported. Even in hard brine solution, HPAM polymers can form flocculation with reacting divalent cations (Ca²⁺ and Mg²⁺). Because most EOR projects are long-term projects, polymer stability is an important parameter. Generally, hydrolysis is required to be less than 40% after 3 months. For commercial applications, the suitable range of hydrolysis was reported as from 15 to 35% (James, 2011).

Hydrolysis is faster at higher than moderate temperatures. In other words, the nature of HPAM polymer is not tolerant to high temperature [28]. This process was explained by free radicals cleaving a long-chain of polymer. According to [22,23] the hydrolysis could occur at near room temperature in aqueous solutions of very low salinity. Seright found that the decay constant, which is defined as the time to reach half the initial viscosity, τ (days), is shortened in direct proportion to the logarithm of the temperature. He also related τ to the temperature based on his experimental data. Ref. [17] explored the changing reaction rate of HPAM according to temperature. HPAM has two activation energies (E_a). When the temperature is lower than 35 °C, E_a is low and viscosity does not change too much as temperature increases. In contrast, when the temperature is higher than 35 °C, E_a is high, and viscosity is subject to rapid variations in temperature [17].

Hydrolysis of HPAM polymer is regarded as a necessary parameter which should be examined in polymer fluid tests. We developed a new viscosity model that accounts for the hydrolysis characteristics of HPAM polymer.

3. Temperature-dependent viscosity model

The polymer concentration flowing through porous media under normal conditions can be expressed as:

$$\phi S_w \frac{\partial C_p}{\partial t} + \frac{(1-\phi)\rho}{\rho_w} \left(\frac{\partial C_{ads}}{\partial t} \right) = \nabla \cdot (D \cdot \nabla C_p) - u_w \cdot \nabla C_p \quad (1)$$

where ϕ and S_w are the porosity and the water saturation, respectively. C_p and D are the polymer concentration and the diffusion coefficient, C_{ads} the adsorbed polymer concentration, u_w the Darcy velocity (ft/day), ρ and ρ_w are the fluid density and water phase density (lbs/ft³). From the acquired chemical concentration, the polymer viscosity can be obtained. In this process, the conventional rheological model used in early numerical tasks has been considered only in the Flory–Huggins' viscosity function, including variables such as polymer concentration and brine salinity [5]. The Flory–Huggins equation [3] is given in this form [3]

$$\mu_p = \mu_w \left[1 + \left(A_{p1} C_p + A_{p2} C_p^2 + A_{p3} C_p^3 \right) C_{SEP}^{S_p} \right] \quad (2)$$

where μ_w is the water viscosity (cP), μ_p the polymer solution viscosity at zero shear rate (cP), C_p the polymer concentration in water (gmol/m³), A_{p1} , A_{p2} , A_{p3} and S_p the fitting constants, and C_{SEP} the effective salinity for polymer (meq/ml).

Although implementation of this simple equation is sufficient for a wide range of polymer fluid stability tests, the model does not accurately describe flow behavior affected by thermal degradation. Due to the sensitivity of hydrolysis to temperature, it is difficult to apply the conventional viscosity model to the process of polymer injection under high temperature conditions, leading to high injection costs as well as low oil recovery efficiencies. Failures of

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