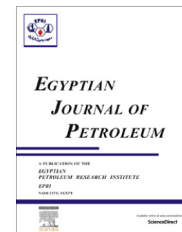


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FULL LENGTH ARTICLE

# Evaluation of solution and rheological properties for hydrophobically associated polyacrylamide copolymer as a promised enhanced oil recovery candidate

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## KEYWORDS

Hydrophobically associated polyacrylamide;  
 Rheological & solution properties;  
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**Abstract** Crude oil is the most critical energy source in the world, especially for transportation, provision of heat and light as there has not been a sufficient energy source to replace crude oil has broadly integrated, so there is an urgent need to maximize the extraction of the original oil in-place for every reservoir, and accelerating the development of enhanced oil recovery (EOR) technologies. Polymer flooding by hydrophobically associated polyacrylamides (HAPAM) is a widely used technique through EOR technology. For successful application of these polymers, one should evaluate rheological and solution properties at simulated reservoir conditions as a function of polymer concentration, salinity, temperature and shear rate. The results showed that these copolymers exhibit favorable salt tolerance, temperature resistance, and recoverable viscosity after shearing, reasonable thickening behavior and improved viscosity enhancement properties due to presence of hydrophobic association in the copolymer main chains. Moreover, its capacity for oil production improvement was evaluated during flooding experiments through one dimensional sandstone model at simulated reservoir conditions.

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## 1. Introduction

Petroleum products are crucial to the global economy today due to increasing energy demand approximately 1.5% per year [1] associated with population growth and improving life styles, so there is a dire need to produce more unrecoverable crude oil through different enhanced oil recovery (EOR) techniques. Polymer flooding through hydrophobically associated

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**Nomenclature**

PV	pore volume, cc	$V_{Or}$	volume of oil remain, cc
$V_B$	bulk volume, cc	$S_{Wi}$	initial water saturation, %
$V_{Oi}$	volume of oil injected, cc	$S_{oi}$	initial Oil Saturation, %
$V_{Wr}$	volume of water remain, cc	$S_{or}$	residual oil saturation, %
OOIP	original oil in place		

polyacrylamide polymers (HAPAMs) have attracted much attention in oil industry [2,3] because of their unique structures and properties, including their thickening properties, shear thinning, anti polyelectrolyte behavior as a mobility control agents and rheology modifiers [4]. These polymers synthesized by free radical emulsion copolymerization are processed through grafting or incorporating hydrophobic chain cross-linking segments onto their hydrophilic main chain [5,6] or by copolymerization of hydrophilic and hydrophobic monomers [7]. Polymer flooding aims to increase viscosity of aqueous phase, so decreases water/oil mobility ratio to less than unity ( $M \leq 1$ ), which in turn improves sweeping efficiency [8]. One of the routine screening parameters used for a preliminary analysis of a reservoir is the mobility ratio that represents effects of relative permeability and viscosity of water and oil on mobility based on Darcy's Law (Eq. (1)) [9].

$$M = \frac{\lambda_w}{\lambda_o} = \frac{K_w/\mu_w}{K_o/\mu_o} = \frac{K_w\mu_o}{K_o\mu_w} \quad (1)$$

where, ( $M$ ) mobility ratio; ( $\lambda_w$ ) water phase mobility; ( $\lambda_o$ ) oil phase mobility; ( $K_w$ ) relative permeability of water phase, mD; ( $K_o$ ) relative permeability of oil phase, mD; ( $\mu_w$ ) water phase viscosity, cp; ( $\mu_o$ ) oil phase viscosity, cp. Consequently, we can conclude that; by increasing of aqueous phase viscosity, mobility ratio decrease, so enhance sweeping efficiency which in turn increases recovered oil amount [10]. Several polymer field projects have been referenced or reported in the literature. Vossoughi and Buller [11]; and Manrique et al., [12] reported some advantages in using anionic polyacrylamide/acrylic acid (PAM/AA) in tests carried out on sandpicks and native cores from the Richfield East Dome Unit (REDU) in California. Platt and James [13] prepared poly (alpha-alkoxy) acrylamides and claimed improved stability in brine solutions. Similar claims were made by Hunter [14] and Cao et al. [15] who prepared N-substituted PAM/AA via ethoxylation. Murduchowitz [16] disclosed terpolymers of acrylamide, acrylonitrile and acrylic acid [17]. McCormick et al. [18] copolymerized sulfonated monomers such as 2-acrylamido-2-methylpropane sulfonic acid (AMPS) with acrylamide monomers, which provide a somewhat improved calcium ion tolerance. HAPAMs possess unique solution and rheological characteristics even at high temperatures and high ionic strength [19] which can be summarized as follows; (1) in aqueous solutions, above a critical association concentration ( $C^*$ ), their hydrophobic groups develop intermolecular hydrophobic associations in nanodomains, leading to building up of a 3D-transient network structure [20] in high ionic strength medium [21] so, providing excellent viscosity building capacity [6,3,22], remarkable rheological properties and better stability with respect to salts than the unmodified hydrolyzed polyacrylamides (HPAM) precursors [23], (2) reduce interfacial tension at solid/liquid interface,

since hydrophobic moieties associates forming aggregates or micelles, (3) shows an unusual adsorption isotherm [24] so, can be considered as a wettability modifier, (4) does not undergo mechanical degradation under high shear stress, since the physical links between chains are disrupted before any irreversible degradation occurs, also they reform and retain their viscosity upon shear decreasing [25], (5) high resistance to physicochemical conditions (temperature, pH, and ion content) prevailing around the wells, so considered a prospective EOR candidate as thickeners or rheology modifiers in high temperature, high pressure reservoirs [26–28] and tertiary oil recovery [29]. In this research, the authors reported about evaluation of solution and rheological properties of a novel copolymer poly (4-Dodecyl-benzenesulfonate-3-[5-(butane-2-sulfonyl)-3-carbamoyl-1-methylheptyl] imidazol-3-ium) previously reported in our previous literature [30]. Flooding experiments were carried out through one dimensional sandstone model to calculate recovery factor at simulated reservoir conditions, moreover the prepared copolymer ability to alter wettability of sandstone rock from oil-wet to water-wet was evaluated by static sessile drop method as had been previously reported in our previous literature [30,31]. To the best of our knowledge, the novel copolymer hadn't been previously reported in enhanced oil recovery applications as a wettability modifying agents, also it reduces oil-water interfacial tension (IFT), to ultra low values, so improves oil displacement efficiency. Also, there is a difference in rheological behavior between this polymer and the one that had been previously reported in our literature [31].

**2. Experimental setup**

Preparation of surfmer (4-Dodecyl-benzenesulfonate-1-vinylimidazol-3-ium; DBSV) and HAPAM copolymer "Poly(4-Dodecyl-benzenesulfonate-3-[5-(butane-2-sulfonyl)-3-carbamoyl-1-methyl-heptyl] imidazol-3-ium)" as well as characterization and structure determination had been previously reported in our previous literature [30]. Rheological measurements were performed on Brookfield programmable DV-II<sup>+</sup> viscometer, equipped with LV (SC4-25) adapter spindle cone/plate geometry (diameter = 60 mm, angle = 1°, plate-to-plate gap = 0.104 mm). Viscosity of aqueous polymer solutions was investigated with respect to the polymer concentration, shear rate, salinity and temperature. The salt tolerance experiments were made in salty solutions simulating injection sea water in the field with different salinity concentrations (1, 40, 80 and 100 gL<sup>-1</sup>). Then, the polymer samples were added to such salty solution for the apparent viscosity measurement at shear rate of 7.3 s<sup>-1</sup> and temperature of 25.0 ± 0.1 °C [31]. We call the attention to the viscosity at this shear rate because

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