Journal of Petroleum Science and Engineering 194 (2020) 107476

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: http://www.elsevier.com/locate/petrol

Application of polymeric nanofluid in enhancing oil recovery at reservoir condition

Augustine Agi [a], Radzuan Junin [a,b,*], Mohammed Omar Abdullah [c], Mohd Zaidi Jaafar [a], Agus Arsad [b], Wan Rosli Wan Sulaiman [a], M.N.A. Mohd Norddin [a], Muslim Abdurrahman [d], Azza Abbas [a,e], Afeez Gbadamosi [a], Nur Bashirah Azli [a]

[a] *Department of Petroleum Engineering, School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Johor Bahru, Malaysia*

[b] *Institute for Oil and Gas, Universiti Teknologi Malaysia, 81310, Johor Bahru, Malaysia*

[c] *Department of Chemical Engineering and Energy Sustainability, Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, Sarawak, Malaysia*

[d] *Department of Petroleum Engineering, Universitas Islam Riau, Jl. Kaharudin Nasution, No. 113 KM 11, Perhentian Marpoyan, Pekanbaru, 28284, Riau, Indonesia*

[e] *School of Computing, Engineering and Technology, Asia Pacific University of Technology & Innovation (APU), 57000, Kuala Lumpur, Malaysia*

ARTICLE INFO

Keywords:
EOR
Cissus populnea
IFT
Wettability
Ultrasound
Nanofluid

ABSTRACT

In this study, ascorbic acid was used to synthesize *Cissus populnea* nanoparticles (CPNP). The synthesized CPNP was isolated and the influence of the process variables on the physical properties were studied. The rheology of the formulated *Cissus populnea* nanofluid (CPNF) was measured and compared with *Cissus populnea* (CP) solution and commercial polymer xanthan. Moreover, the interfacial properties of CPNF were studied at various concentrations and temperatures, and the influence of salinity and their interaction with ultrasound was investigated. Sessile drop contact angle method was used to determine the wettability alteration efficiency of CPNF on an initially oil-wet sandstone core surface. Finally, CPNF and CP solutions were evaluated for EOR purposes at typical reservoir condition. The displacement process was scaled to reduce the number of parameters investigated using dimensionless parameters. The synthesis methods were efficient in generating sphere-shaped and elongated nanoparticles (50 nm mean diameter). Experimental results show that an increase in temperature of CP and CPNP yielded increased viscosity of the solutions in stark contrast to xanthan whose solution viscosity declines as the temperature increases. Besides, the CPNF was effective in lowering IFT at oil-water (O/W) interface and altered the wettability of the sandstone cores to water-wetting condition. The novel CPNF increased the oil recovery by 26% and was effective at high-temperature high-pressure (HTHP) reservoir condition. The result shows a transition from capillary dominated flow to gravity dominated flow as decrease in IFT decreased residual oil saturation and increased capillary and Bond number. The energy consumption and cost estimation of the proposed novel polymeric nanofluid shows it is cost-effective than conventional EOR chemicals.

1. Introduction

Recently, the oil and gas industries are grappling with the reality of scarcity of new sizeable or commercial discoveries and low production from existing reservoirs. Significant amount of oil remains in the reservoir after the primary and secondary recovery methods due to capillary trapping and heterogeneity of reservoirs (Gbadamosi et al., 2018). To recover the remaining oil, enhanced oil recovery (EOR) methods are the only viable option which can reduce the gap between demand and supply. Since the exploration of new fields requires huge amount of capital, EOR processes are used to improve the productivity of the fields which aims to recover the oil left in the reservoirs after the primary and secondary oil recovery methods.

To overcome the low oil sweep efficiency, numerous EOR methods such as gas, chemical, and thermal, have been devised and utilized (Gbadamosi et al., 2019a). Amongst all the EOR techniques, chemical EOR (CEOR) method has been adjudged as the most promising because of its higher efficiency, reasonable capital cost, technical and economic

* Corresponding author. Department of Petroleum Engineering, School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310, Johor Bahru, Malaysia.

E-mail address: r-radzuan@utm.my (R. Junin).

https://doi.org/10.1016/j.petrol.2020.107476
Received 22 October 2019; Received in revised form 29 May 2020; Accepted 29 May 2020
Available online 5 June 2020

feasibilities. CEOR methods are effective in increasing oil recovery. CEOR chemicals can alter fluid-fluid and/or fluid-rock interaction in the reservoir by reducing interfacial tension (IFT) between the imbibing fluid and oil and/or increase the viscosity of the injected fluid for mobility control. The injected chemicals can also alter wettability of the rock to increase oil permeability (Zhou et al., 2015a, 2018a; Abbas et al., 2020).

Polymer flooding, surfactant and/or alkaline flooding are the conventional EOR methods (Gbadamosi et al., 2020). Recently, the use of foam enriched by surfactants or polymers for mobility control have been studied and found to be effective in improving oil recovery (Zhou et al., 2015b, 2018b). Field practices have shown that polymer flooding can increase oil recovery up to 5–30% original oil initially in-place (OOIP) (Pope, 2011). Hydrolysed polyacrylamide (HPAM) are widely used in polymer flooding because of inexpensive handling cost, relatively resistant to bacterial attack, high solubility in water and high ability to reduce permeability of water (Gbadamosi et al., 2019b, c). However, with variation in reservoir conditions (high temperature, pressure and salinity) and crude oil properties, existing chemical flooding materials used in CEOR, such as polymers and surfactants do not function desirably. These conditions have detrimental effect on the performance of EOR chemicals, such as degradation and precipitation. Therefore, various studies are being carried out to improve the limitation of polymer such as HPAM against high temperature and high salinity reservoir conditions. More recently, researchers have reported the use of nanofluid in CEOR process. Nanofluid which is the synergy of base fluid with nanoparticles has the advantages of being more tolerant to high salinity, high temperature, longer stability, less plugging and retention in highly permeable reservoir (Zhou et al., 2017). Nevertheless, despite the sterling results reported in earlier works, concerns have been raised on the cost of the full-scale field implementation and toxicity of the nanofluids (Agi et al., 2018a). As the oil and gas industry continue to deal with the reality of scarcity of new sizeable or commercial discoveries and low production from existing reservoirs, it is essential that low-cost and environmental friendly nanoparticles obtained from organic source are considered (Agi et al., 2018b).

Cissus populnea (CP) is one of the most abundant biopolymers found mostly in the tropics and used as a renewable raw material in a wide range of applications (Bouatay et al., 2014; Oladimeji and Okechukwu, 2016). It has close resemblance to xanthan gum used in confectionary and oil industry. The choice of this biopolymer as a starting raw material is because it contains cellulose, starch and fibres which are known to have rigid and long polysaccharide chain that is stable at high temperature condition (Agi et al., 2018b). It is an in-expensive and non-toxic biopolymer which makes it attractive for industrial applications (Moon et al., 2011).

The main approach adopted to produce biopolymer nanoparticles is acid hydrolysis (Chin et al., 2011; Bel Haaj et al., 2013). This approach is effective in producing small size nanoparticles (5–7 nm) but has its limitations. These include long duration of synthesis and low yield of the nanoparticles (LeCorre et al., 2010; Shahrodin et al., 2015). Also, nanoparticles obtained by classic acid tends to aggregate in powder form and are limited for industrialized utilization (Dufresne, 2008). Ultrasound have been proven to be a very effective method of synthesizing biopolymers (Suslick, 2001). Ultrasonic treatment of biopolymers can reduce molar mass of the biopolymer, reduce the synthesis time and prevent aggregation (Agi et al., 2019a). Although, Kim et al. (2013) and Goncalves et al. (2014) stated that ultrasonic can reduce the crystallinity of nanoparticles, contrariwise, ultrasonic can also improve the crystallinity of the synthesized nanoparticles by intensifying the process (Kim et al., 2013; Agi et al., 2019a). Preservation of crystallinity after synthesis will improve the industrial applicability of the nanoparticles (Kim et al., 2013; Goncalves et al., 2014).

Nanofluid application in EOR has recorded a lot of success and the performance is based on the material used and preparation method. Earlier works on synthesis of biopolymers used classic acid (HCl and H_2SO_4) but this method has recorded low yield. The combination of acid hydrolysis with ultrasonic has resulted in loss of crystallinity. However, the use of ascorbic acid, process intensification and homogenization were not considered. The use of inorganic and metal oxide nanofluids in EOR has been thoroughly investigated. However, the use nanoparticles from natural and/or organic source have not been considered.

Hence, in this study, a combined methods of ascorbic acid hydrolysis, ultrasound and nanoprecipitation were utilized for the first time to produce *Cissus populnea* nanoparticles (CPNP). Isolation and influence of the process variables on physical properties of CPNP were studied. Rheology of *Cissus populnea* nanofluid (CPNF) was compared with CP and xanthan solutions. Besides, the interfacial properties of CPNF were studied at various concentration and temperatures. Additionally, the effect of concentration, temperature, electrolyte and their interaction with ultrasound on the synthesized CPNF were determined. Sessile drop contact angle method was used to determine wettability effectiveness of CPNF on an initially oil-wet sandstone core. Finally, CPNF and CP solutions were evaluated for EOR purposes at typical reservoir condition. The displacement process was scaled to reduce the number of parameters investigated using dimensionless parameters. The energy and cost estimation of the methods and materials were determined and compared with conventional methods.

2. Materials and methods

2.1. Materials

CP was harvested from a local farm in Nigeria. The fruits (oranges and pineapples) were purchased from a grocery shop in Johor Bahru, Malaysia. Lemongrass was handpicked from Universiti Teknologi Malaysia (UTM) campus orchard. Palm wine, which acted as the alcohol and surfactant, was purchased from Kangkar Pulai, Johor and has a purity of 94%. Xanthan gum was purchased from R&M Marketing, Essex, U.K. Sodium chloride (NaCl) with molecular weight of 58.44 g/mol and a purity of 99% assay was purchased from QREC (ASIA) Sdn. Bhd., Selangor, Malaysia. Vinegar was purchased from PubChem, it has a molecular weight of 60.05 g/mol, acetic acid (5%) and density of 1.0446 g/mL @ 25 °C. Toluene with a molecular weight of 92.14 g/mol was supplied by PubChem. Crude oil sample (West Lutong) with density of 0.8283 g/mL @25 °C, API gravity 37.7 and viscosity of 10 mPa s @25 °C was obtained from an oil field in Sarawak, Malaysia. The oil was centrifuged to remove emulsified oil. Core samples from a sandstone formation located in Sarawak, Malaysia were used to simulate the reservoir condition of a typical reservoir rock of Sarawak oil field. Table 1 shows the properties of the core samples.

2.2. Methods

2.2.1. CPNP production

CP was prepared to dry powder form using the method described in previous study (Agi et al., 2019b). The dried CP was soak in 1 L of distilled water (DW) for 20 min to generate exudes. Vinegar (20 mL) was used to disperse the exudes to form a solution and subsequently added in drops to the alcohol. Ascorbic acid was extracted from pineapple,

Table 1
Properties of core samples.

Properties	Core #1	Core #2	Core #3
Length (cm)	9.7	9.8	9.9
Diameter (cm)	3.7	3.7	3.7
Bulk Volume (cm^3)	104.30	105.37	106.45
Pore Volume (cm^3)	16.00	16.00	16.00
Porosity (%)	15.3	15.2	15.0
Permeability (mD)	167.43	152.24	102.53
Initial Oil Saturation (%)	98.13	93.44	95.00
Injection rate (mL/min)	0.5	0.5	0.5