Introduction

Half of the world’s oil reserves are experiencing a drastic decline in oil and gas production, to meet the global demand of petroleum products. Development of novel and efficient enhanced oil recovery (EOR) techniques are necessary to fulfil the endless energy demand. Nanotechnology from past few decades has been closely involved in oil and gas sector whether it be for well bore cleaning or in the form nanoeumulsions as injection fluid, etc. and still using the advantages of this technology (Kumar & Mandal, 2018; Sun et al., 2017). Numerous research have been carried out to investigate the applicability of nanotechnology in oil and gas industry and numerous are going as nanotechnology has ability to improve the key features which effects the oil recovery. Recently the full potential of ‘nanotech’ in the upstream sector of oil and gas industry has been revealed (Hendraningrat & Torsæter, 2015).

The major area of interest is to examine the potency of this technology to upgrade the present conventional EOR methods to improve the oil production. Nanotechnology in the form of nanoparticle stabilized nanofluid has proved its potential in enhancing oil in past few years. The nano-sized particle provide higher density compare to their counterparts and large surface area which helps in interfacial tension reduction at the oil-aqueous interface(Sharma et al., 2016). The small sized nanoparticles (NPs) can pass through the small pore of reservoir which are left behind by the conventional recovery methods. Nanoparticles can also be tailored to modify the reservoir characteristics like wettability alteration of rock surfaces, improvement of mobility ratio etc. Improvement in oil production is also achieved by the application of structural disjoining pressure by nanoparticles on spreading of liquid film on the rock surfaces containing these nanoparticles (Zhang et al., 2016). The nanoparticles in the nanofluids tends to form self-assembled wedge-shaped film on contact with oil droplets thereby extracting more oil from the walls of the pore channels than with conventional water flooding(Mcelfresh et al., 2012).

Present study focusses to use nanotechnology concepts to improve oil production using silica nanoparticle based nanofluid. Silica nanoparticles of hydrophilic nature having good dispersibility in aqueous medium was used to synthetize the nanofluid. Silica was also selected because it is the main constituent of a sandstone reservoir.

Nanofluids prepared by Ultrasonication process (Figure 1) has enhanced kinetic stability due to nanosize particles Brownian motion, slow aggregation of nanoparticles with water. The Nanofluids exhibit enhanced rheological properties which is favourable for mobility control, easy passage through porous media with long distance travelling ability is an advantage for EOR. (Ju et al., 2006) The brine was selected for the mimic the reservoir salinity and the sandpack flooding performed at the reservoir temperature in this it was 90°C.

![Figure 1. Formation of silica based nanofluid by high energy method (ultrasoundication process). A homogenized nanofluid with uniform particle size is obtained.](image-url)
Method and Theory

In present study silica nanoparticles of 15 nm were used to prepare nanofluids in two steps. First, silica NPs were mixed with brine (1 wt. %) with the help of magnetic stirrer for 1 hour. In second step the stirred mixture was homogenized using Hielscher Ultrasonics UP200ht, a hand held ultra sound for 2 hours obtaining a homogenous dispersed suspension of nanoparticles that is Silica-based Nanofluids of different concentration 0.04 wt%, 0.08 wt% and 0.12 wt%. The formed nanofluid was characterized by dynamic light scattering (DLS) for particle size and surface charge by zeta potential measurement using Litesizer 500 (Anton Par) respectively. The wetting behavior of nanofluid on sandstone rock surface was analyzed by sessile drop method measuring the dynamic contact angle via Kruss DSA 25 Drop shape analyzer. The potency of synthesized nanofluid was tested by performing sand-pack flooding experiment. The optimized concentration of Silica was found to be 0.08 wt.%, the average particle size for optimized concentration was found to be 420.6 ± 8 nm with zeta potential value of -35.9±1.4 mV (Table 1).

**Table 1** The Average diameter and Zeta potential values of prepared nanofluids at different Silica NPs Concentrations.

<table>
<thead>
<tr>
<th>Concentration of Silica NPs (wt. %)</th>
<th>Average Diameter (nm)</th>
<th>Zeta Potential (mV)</th>
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</thead>
<tbody>
<tr>
<td>0.04</td>
<td>415.4 ± 6.0</td>
<td>-33.0 ± 1.3</td>
</tr>
<tr>
<td>0.08</td>
<td>420.6 ± 8.0</td>
<td>-35.9 ± 1.4</td>
</tr>
<tr>
<td>0.12</td>
<td>514.2 ± 10.5</td>
<td>-32.3 ± 1.3</td>
</tr>
</tbody>
</table>

Wettability alteration of oil saturated sandstone rock was analyzed using contact angle measurement of different silica nanofluids. The test were performed in two phase condition where contact angle of nanofluid drop on an oil aged sandstone rock was measured in the presence of air. The contact angle was measured with time and compared with those of simple brine solution. In the measured time, end contact angle for brine on rock sample was 81.1°; however presence of nanoparticle in solution made them more water wet and contact angle decreased rapidly too much lower values. From figure 2, the optimized silica NPs concentration of 0.08 wt. % was obtained due to its reducing ability of contact angle from 119.1° to 10.3° in 18 minutes. This shows the wettability from mix oil wet to preferably water wet condition is gained which is good for high recovery of oil (Hendraningrat & Torsæter, 2014).

**Figure 2** (a) Plot of contact angle with time in minutes for nanofluids at different silica NPs concentrations. (b) Silica nanofluids with optimized silica NPs concentration of 0.08 wt. % on sandstone rock at t= 0, 3, 7, 12, 15 and 18 minutes after drop was placed on rock.

Figure 3 shows the apparatus used for EOR experiment. This setup consists of a dual syringe pump, fluid cylinders (Brine, Crude oil and Nanofluid) and a sandpack core holder encased in hot air oven. The dual syringe pump is a displacement pump (Teledyne Isco, model 500D, USA), used for fluid injection with a constant flow rate in the sand pack. The dimensions of the sand pack holder are 3.75 cm diameter and 41 cm length. The sand holder housed for the sand pack, which was prepared by
compact packing of dry sand together with brine. The fluid which used for perflush i.e. brine at 15 mL/h was injected in the sand pack to reach the initial saturation of water in the sand pack. Brine injected at constant flow rate will creates a pressure difference (Δp) across the sand pack, and its value was measured a pressure gauge as shown in Figure 2. Flow rate at the fluid collect through the sand pack was also verified manually (volume /min) and with help of Δp to determine the absolute permeability (k_{abs}) of the sand pack using Darcy’s law.

The sand pack imitates a reservoir condition of porosity and permeability. Subsequently, crude oil was injected (at 15 mL/h) into the water saturated sand pack until water production stopped. The amount of water produced at this stage is equal to the amount of oil in the sand pack referred to as original oil in place (OOIP). OOIP was used to determine the initial oil saturation (S_{oi}) in the sand pack by volume balance and thus, the amount of irreducible water saturation (S_{wi}) was calculated. The effective permeability of oil (k_o) at S_{wi} was also measured using Darcy’s law and by measuring the pressure drop of the oil and the oil flow rate at S_{wi}. Sand pack was aged for 7 Days with crude oil at S_{wi} and test temperature of 90°C to achieve 100 % oil saturation. Later, brine was injected at a constant injection rate (15 mL/h), to establish the residual oil saturation (S_{or}) state and the associated oil recovery under water flooding conditions (until a water cut of more than 95% was reached). The sand pack at S_{or} was now targeted for EOR by injecting 1 PV of optimized nanofluid (silica NPs 0.08wt. %). Finally, 2 PV of chase brine was injected until oil production from the sand pack ceased. The results of conducted flooding experiment are tabulated in table 2.

Figure 3 (a) The schematic diagram of flooding setup consisting of displacement pump, 3 cylinders (Brine, Crude oil and Nanofluid), sand-pack holder enclosed in hot air oven with fluid collector and (b) Plot of cumulative oil recovery and pressure differential as function of fluid pore volumes injected at 90°C.
Table 2 Petro physical properties of the sand pack flooding system.

<table>
<thead>
<tr>
<th>Porosity (%)</th>
<th>Permeability, $k$ (mD)</th>
<th>Design of chemical slug</th>
<th>Secondary recovery (% OOIP)</th>
<th>Additional recovery (% OOIP)</th>
<th>Cumulative Oil recovery (% OOIP)</th>
<th>% Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_w$ ($S_w=1$)</td>
<td>$k_o$ ($S_{wi}$)</td>
<td></td>
<td></td>
<td></td>
<td>$S_{wi}$</td>
</tr>
<tr>
<td>32.50</td>
<td>1361.8</td>
<td>121.7</td>
<td>Silica NPs 0.08 wt. %</td>
<td>56.94</td>
<td>16.21</td>
<td>73.15</td>
</tr>
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</table>

Conclusion

The small size of nanoparticles helps in forming a stable dispersion as confirmed from dynamic light scattering (DLS) study. Small size also helps to create greater disjoining pressure for removing trapped oil from the rock pores. Zeta potential also showed increase in magnitude with increasing nanoparticle concentration which is a good indicator of stability. Contact angle results showed that the nanofluids has the ability to significantly change the rock nature from oil-wet to strongly water-wet state, which is a desirable condition for oil production. The optimized silica-based enhanced nanofluids exhibit superior rock-wetting characteristics and good stability which are desirable for functional application in enhanced oil recovery (EOR) processes which was confirmed by the result of EOR sandpack core nanofluid flooding with incremental oil recovery of 16.21% after water flooding.

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References


