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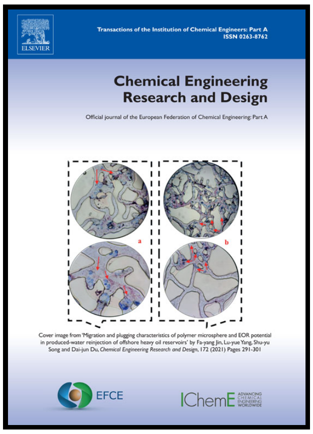

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Effects of hot nanofluid injection on oil recovery from a model porous medium

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Abstract:

In current experimental study a viscous fluid recovery from a transparent two-dimensional porous medium by injecting a fluid was studied. The base oil was used as displaced fluid and porous medium was initially saturated with the base oil. Water, sodium dodecyl sulfate (SDS) solution, and TiO_2 nanofluid were used as displacing fluids. Reduction in water injection flowrate from 0.6 mL/min to 0.08 mL/min, the base oil recovery increased by 22.5%. Also, by increasing the injection temperature from 5 °C to 90 °C, 16.5% more base oil recovery happened. Oil recovery increased by 4.6%, and 5.2% for the SDS solution, and TiO_2 nanofluid. Adding surfactant reduces the interfacial tension between the base oil and the displacing fluid. Besides, presence of nanoparticles reduces interfacial tension and changes wettability of the porous medium. It was observed that the presence of nanoparticles in the displacing fluid always increase base oil recovery compared with water flooding results. However, by comparing the results of 0.1 wt% TiO_2 nanofluid injection with 0.05 wt% TiO_2 nanofluid, it was concluded that an increase in nanoparticles concentration does not always improve oil recovery efficiency. In hot fluid injection with a flowrate of 0.2 mL/min before the breakthrough time, the hot water injection performed better than the hot nanofluid in base oil recovery. After the breakthrough time, the hot nanofluid had a higher efficiency than the hot water. Finally, by adding nanoparticles into the hot SDS solution, oil recovery increased by 7.9%.

Keywords: Hot nanofluid injection; TiO_2; Porous medium; Enhanced oil recovery; Base oil; water

1. Introduction

In fluid-fluid displacement in the porous medium leads to instability at the contact surface between two fluids. This instability appears in the form of a finger penetrating into displaced fluid and reduces the efficiency of fluid extraction from porous medium. So these instabilities must be controlled. To control these instabilities, the fluid flow patterns and reasons that lead to finger instability should be investigated [1]. Generally, fluids flow is not visible through rocks, so artificial porous models are used to understand fluid behaviors in displacement processes. Artificial porous models are a clear version of the porous structure of rocks which are made of glass, polymers, and silicon wafers that are colorless to observe and understand fluids behaviors [2]. In these environments, as fluids develop inside the porous medium, the flow patterns and behaviors are studied and analyzed. In recent decades, a huge number of studies have been conducted in fluid-fluid displacement processes, especially oil recovery, to examine the affection of factors in enhanced oil recovery (EOR) [3]. Therefore, choosing an effective method to achieving the highest level of extraction from a porous medium is essential. Today, many oil recovery methods have been introduced which can be used to recover remaining oil in reservoirs after the end of the primary and secondary recovery methods [3].

EOR processes include a variety of mechanisms such as reducing the interfacial tension (IFT) between the displacing fluid and the displaced fluid, wettability alteration of the porous medium, injecting high-viscose fluid to control the mobility ratio and using thermal methods to reduce the viscosity of oil [4]. Adhesive and negative capillary forces are the reason of trapped oil in the pores of the porous medium, reducing IFT leads to the adhesion reduction and decreases negative capillary force, thus a displacing fluid is easily moved inside the porous medium and dissolves oil in itself. Additionally, trapped oil is directed to the outlet of the porous medium because of IFT reduction. Furthermore, wettability alteration causes the negative capillary force turns into a positive capillary force and leads to easy saturation of displacing fluid inside the porous medium. Hence, it helps to push oil through the pores throat more easily and smoothly [4].

EOR methods are mainly divided into two categories: thermal and non-thermal methods [5]. According to the studies on fluid-fluid displacement processes by injecting hot water into porous medium, it can be concluded that hot water injection results in more oil recovery than cold water injection, because with increasing injection temperature, the viscosity of oil decreases and improves oil mobility and reduces the amount of the saturated oil [6-9]. In non-thermal methods, however, chemicals are used to change the properties of porous medium and fluids. For this reason, these methods of recovery are called chemical enhanced oil recovery. In chemical injection methods, oil recovery is performed by reducing IFT, reducing capillary forces and improving the mobility ratio between injecting fluid and oil, as well as wettability alteration in the porous medium [10]. Nanotechnology is the most widely used method for chemical enhanced oil recovery. According to the researches have been carried out in the past few years, the number of studies related to the use of nanotechnology in the oil industry is growing rapidly [11]. One of the new method of chemical oil recovery is the use of nanofluid flow. In recent years, researchers have tried to use nanoparticles to increase oil recovery efficiency from reservoirs. Nanofluids are obtained by adding nanoparticles with low concentrations to base fluids for increase and improve fluid properties [12], In fact, nanofluids are suspensions with colloidal particles in nanoscale and form a two-phase system consisting of solid phase in liquid phase [13]. Because of nanoparticles high surface energy, the accumulation and deposition of nanoparticles in the nanofluid is possible [14]. To overcome this, surfactants are commonly used to suspend nanoparticles which deposit in nanofluids. [15]. Surfactants have hydrophobic groups (non-polar component or chain of surfactant) and hydrophilic groups (polar component or head of surfactant) [16]. When surfactant is injected as an injection fluid for EOR, the polar head of the surfactant is attached to water and the non-polar chain to the oil, then interfacial tension and capillary pressure are ultimately reduced [17, 18]. As a result, the surfactant can increase oil recovery efficiency by reducing IFT of the two fluids [17, 19]. On the other hand, reducing of interfacial tension in surfactant injection is not the only reason to improve displacement processes ant enhance oil recovery [20].

Literature shows that nanofluid injection results in wettability alteration (surface contact angle reduction) and reduces the surface tensile forces compared to without nanoparticles, thus nanofluids increase oil recovery efficiency [11, 12, 21]. Moreover, studies show that using of nanoparticles improves the rheological properties and also increases the effect of surfactant solution in EOR from the glass micromodel [12]. The main mechanism of nanofluid injection in

EOR is wettability alteration in a porous medium. Nanoparticles, due to their high specific surface area, tend to be hydrophilic after being adsorbed on a solid surface and alter the wettability of porous medium [22]. Ehtesabi et al. have investigated the effect of low concentration titanium dioxide nanoparticles on heavy oil recovery from the porous medium [23]. According to their results, low-concentration nanofluids improved heavy oil recovery from 41% to 55%. They stated that nanoparticles sediment at the inlet part of a porous medium when nanofluids were injected, as the nanofluid flows inside the porous medium the amount of sediment decreased and nanoparticles covered only 1% of the inner surface of the porous medium. By measuring the viscosity, IFT and contact angle, they concluded that because of disjoining pressure, the main mechanism for EOR by nanofluid injection was wettability alteration in porous medium.

Roustaei et al. investigated the effect of nanoparticle concentration on wettability alteration and IFT by injecting silica nanofluid in a porous medium [24]. They reported that with increasing concentration of silica nanoparticles wettability was altered to hydrophilic, and IFT of fluids was reduced up to 15 times. Li and his coworkers studied the possibility of using hydrophilic silica nanofluid for EOR. They could identify the main mechanisms of nanofluid using glass micromodels [25]. The obtained results showed that the nanofluid reduced the IFT between water and oil, and enforced the solid surface to be hydrophilic. They also found that nanofluid recovered trapped oil by the capillary force and ultimately increased oil recovery. In addition, with increasing nanofluid concentration and decreasing nanoparticle size, the contact angle reduces and also the wettability of a porous medium is altered to be more hydrophilic, and so leads to EOR [26]. Furthermore, type of base fluid or surfactants also affect EOR [20, 27, 28,]. Ragab and Hannora used nanoparticles with different sizes to increase oil recovery efficiency in their experiment [29]. Their results indicated that by reducing the size of silica nanoparticles, oil recovery efficiency increased. By combining thermal and chemical propagation methods, the efficiency of fluid extraction from the porous medium can be improved.

In current study, by combining nanofluid injection and thermal oil recovery methods, a viscose fluid (the base oil) recovery efficiency from a two-dimensional porous medium is investigated. We are striving to reach a better perception of fluids displacement within the porous medium. For this purpose, water, titanium dioxide nanofluid, and sodium dodecyl sulfate (SDS) solution are used as displacing (injected) fluids, and the base oil as displaced fluid. Displacing fluids are injected with different rates, temperatures and concentrations to recover the base oil from the designed two-dimensional porous medium. Finally, the effect of each parameter on oil recovery from the porous medium is evaluated.

2- Materials and Methods

The fluid-fluid displacement process was performed inside a two-dimensional transparent glass porous medium with a porosity of 40%. The porous medium was made by placing glass beads (spherical shape) between two square glass plates. In the construction of this porous medium, only one layer of glass beads was placed between two surfaces to ignore the effect of the third dimension. For injecting fluids, an inlet was considered in the corner of the porous medium at an angle of 45 degrees. For discharging fluids, an outlet was considered in the opposite corner of the porous medium at an angle of 45 degrees. A high viscous yellow base oil was injected as a displaced fluid in the porous medium. To extract that yellow base oil from the porous medium, water and sodium dodecyl sulfate (SDS) surfactant and titanium dioxide (TiO_2) nanofluid was injected as a displacing fluid. For fluids injection, a syringe pump with flow and injection speed control capability was used. Before each experiment, the porous medium was saturated by base oil. After 24 h, the base oil was extracted from the porous medium by injecting the displacing fluid. Experiments were carried out in two different injection temperatures, where displacing fluids were injected at 22 °C and 90 °C. For hot injection (90 °C) experiments, the displacing fluid was preheated in hot water bath then was injected inside the porous medium. Effects of each hot fluids injected into the porous medium on the base oil removal rate, and its distribution within the porous medium was investigated.

Figure 1 shows the porous medium saturated with base oil and used in this study. Also, table 1 lists the physical characteristics of glass porous medium. Besides, table 2 shows the list of the material sources. Additionally, table 3 shows the properties of the fluids at 22 °C.

A two-step method was used to produce titanium dioxide nanofluid. Sodium dodecyl sulfate (SDS) as surfactant was used to stabilize the nanoparticles in the solvent (distilled water). The SDS surfactant has a great ability to reduce the surface tension of base fluid [30]. Table 4 presents the specifications of the chemicals used in the preparation of the nanofluid. To prepare

TiO_2 nanofluid with different weight percentages, a certain weight of TiO_2 nanoparticles and SDS were dissolved in 100 mL of distilled water using magnetic stirrer for 45 minutes. The resulting solution was then subjected to ultrasound for 45 minutes inside an ultrasonic homogenizer. The prepared nanofluid had white color and remained stable at least for 4 hours, which was sufficient for performing base oil extraction tests by injecting nanofluid. Figure 2 shows the nanofluid image with different weight percentages.

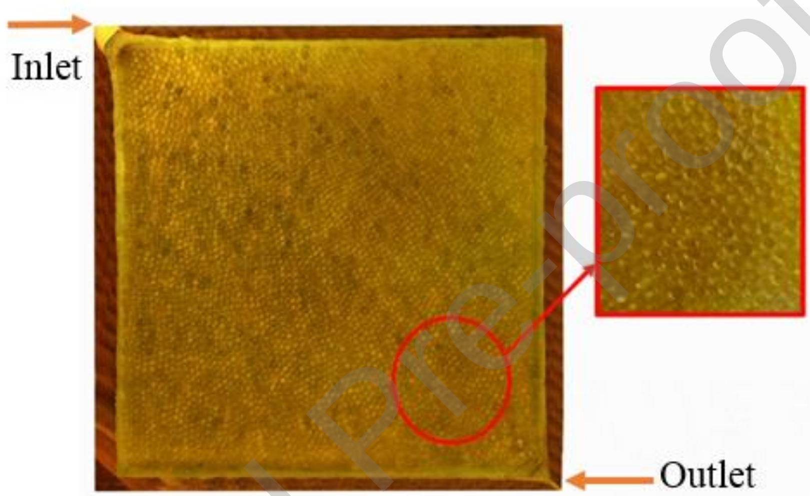


Figure 1. 2D Porous medium saturated with yellow base oil. Inlet and outlet have been shown at the corners.

Table 1- Physical characteristics of glass porous medium.

Pattern characteristic	Amount
Length (cm)	20
Wide (cm)	20
Depth (cm)	3
Pore volume (cm^3)	48
Porosity (%)	40

Table 2- Source of materials used in the experiment.

Material	Substance and color	Source
Base oil	Yellow liquid	Poyan Saial Azar, Iran
Titanium dioxide	White powder	Merck, Germany
Sodium dodecyl sulfate	White powder	Merck, Germany

Table 3- Fluid properties at room temprature (22°C).

Fluid	Density (gr/ml)	viscosity (cP)	viscosity (cSt)	Interfacial Tension (mN/m)	Thermal conductivity (W/m.k)
Viscous oil	0.895	134.936	150.766	---	---
Water	0.998	0.94	0.942	45.03	0.599
SDS solution 0.2 wt%	1.00194	1.05	1.048	28.9	0.59
Tio_2 Nanofluid 0.05 wt%	1.00254	1.09	1.087	28.3	0.62

Table 4- Chemicals used in preparation of the nanofluids.

Chemical	Name	Weight fraction in this study %	Density (gr/mL)	Particle size (nm)	Purity	Type of nanoparticle
Titanium dioxide	TiO_2	0.01, 0.05, 0.1	3.89	25	%99.6	anatase
Sodium dodecyl sulfate	SDS	0.2	1.1	---	% 85	---

Figure 2. Prepared TiO_2 nanofluids with different weight percentages.

During the experiments, to extract the base oil from the porous medium, displacing fluids were injected into the porous medium under different conditions. Table 5 shows the injection conditions of the displacing fluid during the test.

The tests were completed after 4 hours of intermittent injection so that the injection time to remove the base oil was the same in all tests. To investigate the effect of existence of nanoparticles on the base oil extraction process, in another test, a base solution containing SDS and distilled water (SDS solution) was injected as displacing fluid under the same conditions.

Figure 3 shows the image of the experimental setup of the present study. Depending on the injection temperature a hot water bath was used to heat the injected (displacing) fluid or an ice bucket was used to keep the displacing fluid cold. In all tests to prevent heat loss during the fluid-fluid displacement, the porous medium was covered with fiberglass.

Table 5 . Fluids injection conditions.

Injected Fluid	**Condition**
Water injection	1- Water injected at room temperature with different flow rates 0.08 ml/min, 0.2 ml/min, 0.4ml/min and 0.6 ml/min. 2- Water injected at different temperatures 5°C, 22°C, 60°C and 90°C with flow rate 0.4ml/min. 3- Water injected at high temperature 90°C with different flow rates 0.08 ml/min, 0.2 ml/min, 0.4ml/min and 0.6 ml/min.
SDS injection	1- SDS 0.2wt% injected at room temperature with flow rate 0.2 ml/min. 2- SDS 0.2wt% injected at high temperature 90°C with flow rate 0.2 ml/min.
Tio_2 nanofluid injection	1- The nanofluid with different weight fractions 0.01wt%, 0.05wt% and 0.1wt% injected at room temperature with flow rate 0.2 ml/min. 2- The nanofluid 0.05wt% injected at room temperature with flow rate 0.2 ml/min and 0.4ml/min. 3- The nanofluid 0.05wt% injected at high temperature 90°C with flow rate 0.2 ml/min and 0.4ml/min.

To study the composition and crystal structure of TiO_2 nanoparticles, Fourier transform infrared (FTIR) and X-ray diffraction (XRD) spectroscopy were performed. Meanwhile to determine the morphological properties of nanofluid and the stability of TiO_2 nanoparticles inside the nanofluid, Field Emission Scanning Electron Microscopy (FESEM) analyses were performed. For FTIR and XRD analyzes, TiO_2 powder nanoparticles were used as sample for analysis, but for FESEM analysis, dried nanofluid was used.

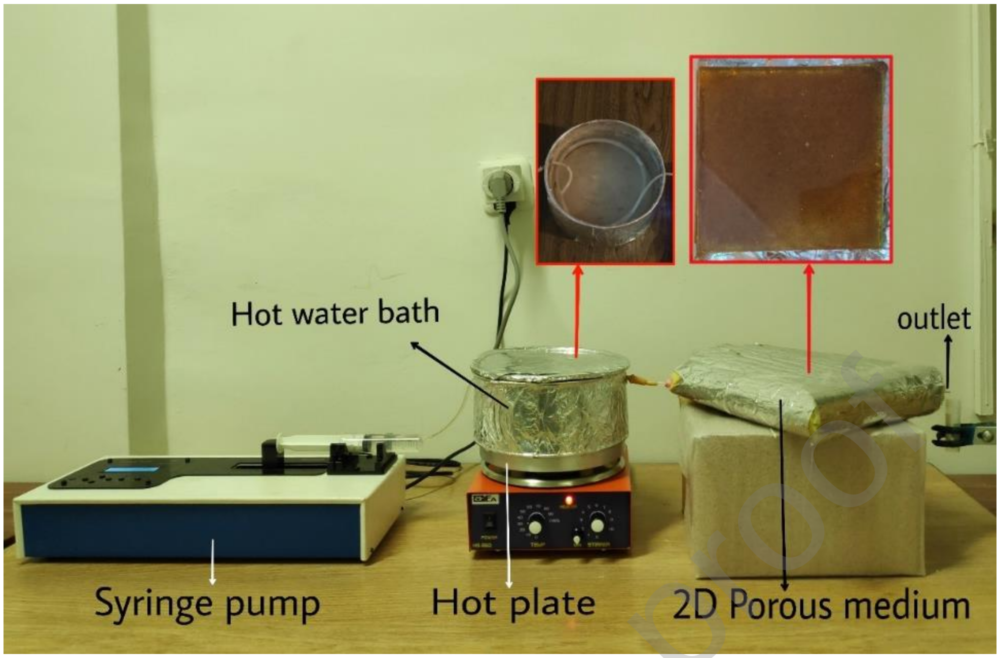


Figure 3. Experimental setup used for oil recovery from the constructed porous medium.

3- Results and discussion

3-1- TiO_2 nanoparticles characterization

Figure 4 shows the results of the Fourier transform infrared spectroscopy (FTIR) analysis of TiO_2 nanoparticles as a graph. Due to the vibrational excitation, downward peaks appear which indicate the type of chemical bonds. At 809 cm^{-1}, there is a strong metal oxide bond that is related to TiO_2. Also, the peak of 809 cm^{-1} wavelength is the largest peak shown in Figure 4, indicating that the chemical bond of TiO_2 is the most effective bond in the sample.

Figure 5 shows the results of X-ray diffraction (XRD) analysis of TiO_2. XRD results indicate that the powder sample of TiO_2 nanoparticles has a crystalline structure. The sharpness of the peaks indicates that the crystal plates are wider, and that the crystal plates have become smaller as the peaks become shorter. Note that the XRD pattern in Figure 5 is in match with the standard reference XRD of anatase phase TiO_2 nanoparticles (JCPDS Card 21-1272). Peaks are also observed at 25.36 °, 37.84 ° and 48.09 °, which are consistent with the characteristics of anatase phase TiO_2 nanoparticles.

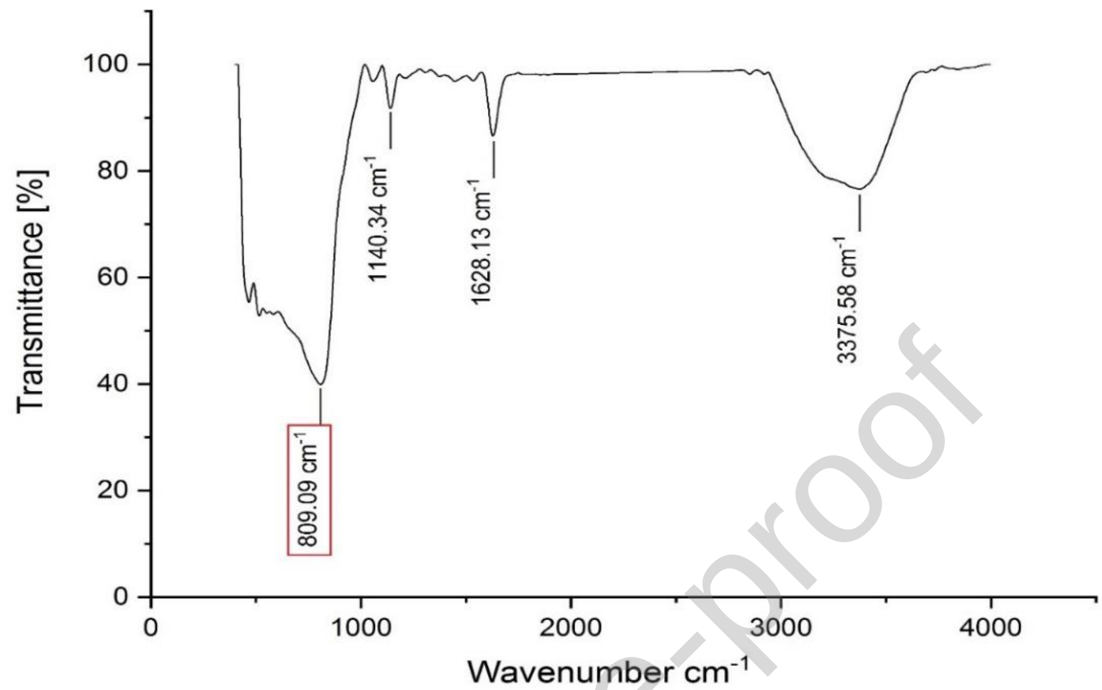


Figure 4. Fourier transform infrared spectroscopy (FTIR) of TiO_2 nanoparticles sample.

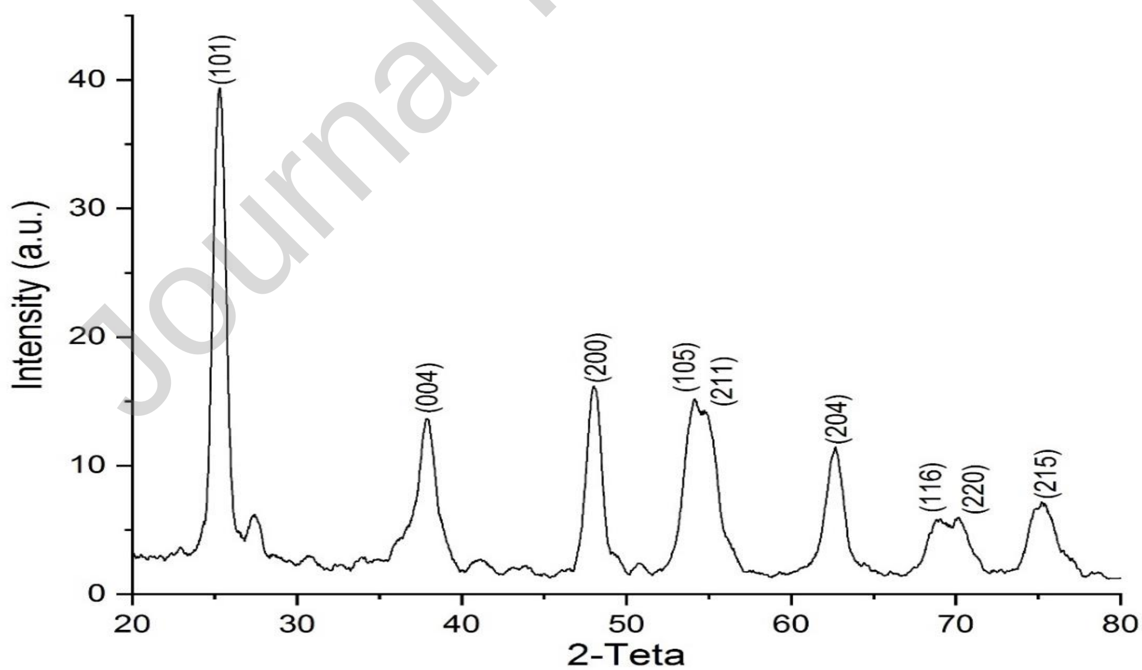


Figure 5. Results of X-ray diffraction (XRD) analysis of TiO_2 nanoparticles.

Figure 6 shows a field emission scanning electron microscopy (FESEM) image of TiO_2 nanofluid 0.05 wt%. The FESEM image was prepared after the nanofluid was dried. In Figure 6, the spherical nanoparticles, the distribution of the nanoparticles within the base fluid, and the stability of the nanoparticles are clearly visible. Size of the nanoparticles in the FESEM image was also calculated using *Image J* software. The nanoparticle size distribution diagram was plotted in Figure 7. According to Figure 7, it can be concluded that the particle size of TiO_2 nanoparticles used in this research was not uniform and was stable in different sizes of 20 to 120 nm inside the nanofluid. The average size of TiO_2 nanoparticles was 55 nanometers.

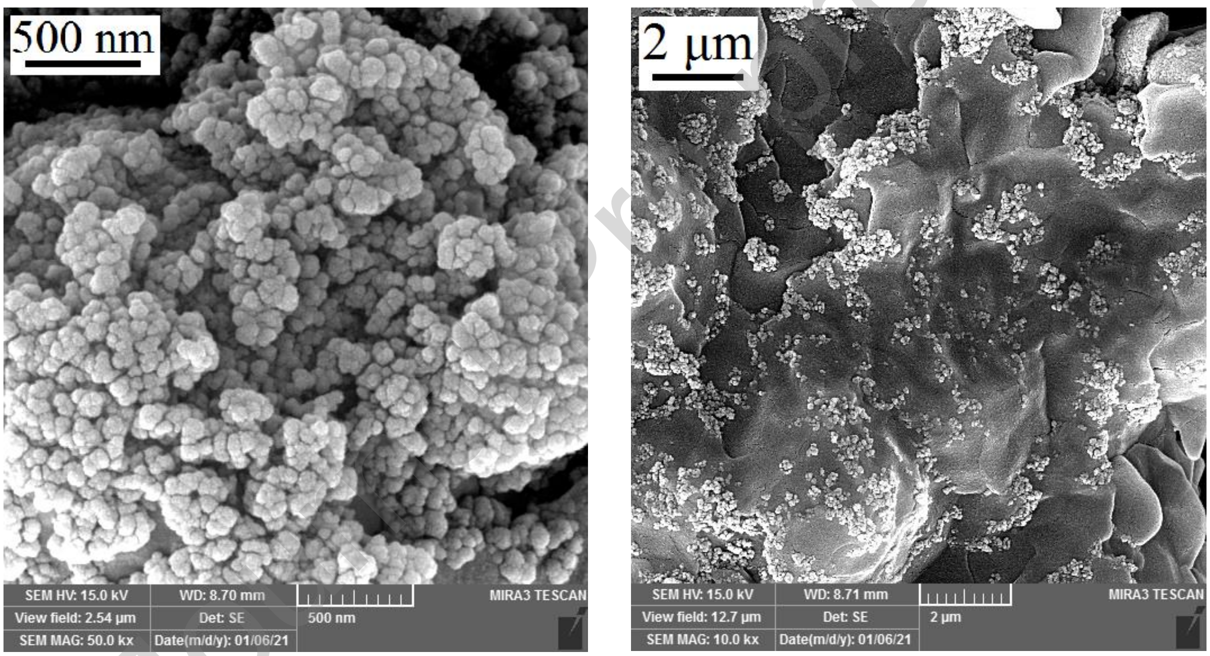


Figure 6. FESEM images of TiO_2 nanofluid with a concentration of 0.05 wt%.

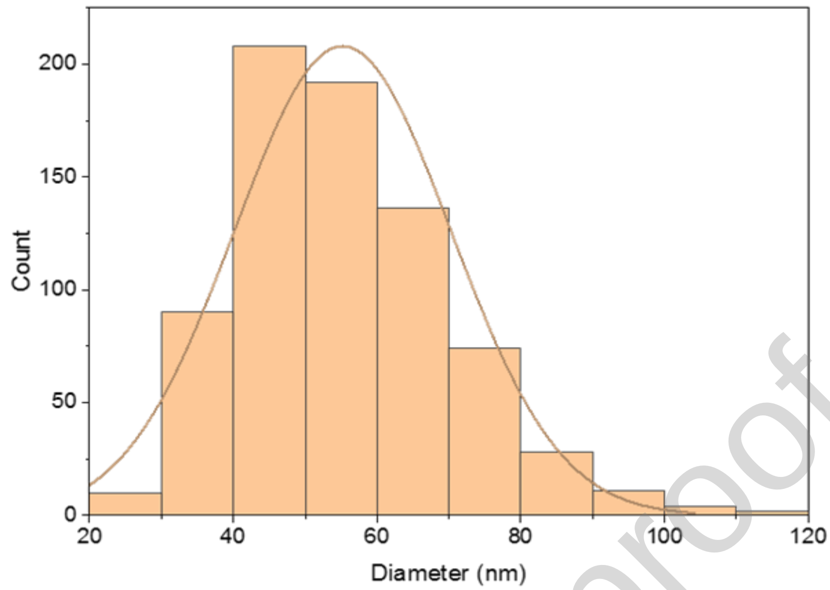


Figure 7. Size distribution of TiO_2 spherical nanoparticles.

One of the mechanisms to increase the fluid-fluid displacement efficiency is to increase viscosity of the displacing fluid. Because with increasing the viscosity of the displacing fluid, the viscosity ratio (viscosity of the displacing fluid/viscosity of the displaced fluid) in the displacement process increases and the distribution of the displacing fluid within the displaced fluid becomes wider and more stable (stable displacement). According to the table 3, presence of SDS surfactant in water increases the base fluid dynamic viscosity from 0.94 cp to 1.05 cp, and presence of TiO_2 nanoparticles in the SDS solution, increases the viscosity from 1.05 cp to 1.09 cp. Also, the presence of SDS reduced the interfacial tension of water and the base oil from 45.03 mN/m to 28.9 mN/m as the main effect of the surfactants and by adding TiO_2 nanoparticles to the SDS solution, the interfacial tension is slightly reduced from 28.9 mN/m to 28.3 mN/m. Moreover, by using droplet technique, this was proved adding TiO_2 nanoparticles and SDS change the glass wettability. Three droplets including the nanofluid droplet, the SDS solution droplet and water droplet were placed on the surface of the glass used in the construction of the porous medium, and then their images were recorded. The contact angle of the droplets with the glass surface was calculated by using *Image J* software. According to Figure 8, by adding SDS to water, the contact angle between the droplet and the glass surface was reduced from 52.1° to 39.8°, and also by adding TiO_2 nanoparticles to the SDS solution, the contact angle between the droplet and the surface of the glass was decreased to 29.7°. Therefore, the nanofluid has made the glass surface more water-friendly. As a result, by nanofluid injection, the contact angle is reduced, and the hydrophobic porous medium changes to hydrophilic medium. Consequently, the nanoparticles injection leads to an increase in the extraction of the base oil.

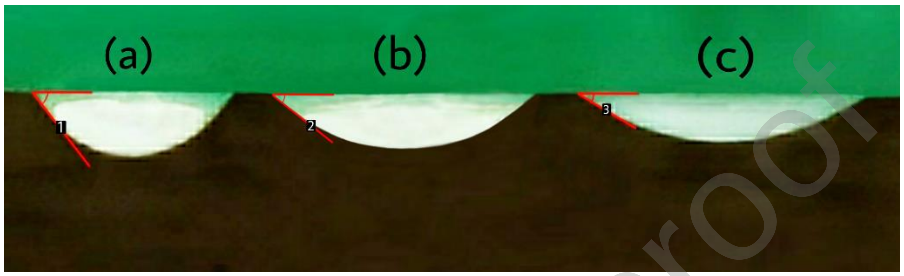


Figure 8. Contact angle of (a) Water, (b) SDS, and (c) TiO_2 nanofluid droplet with solid surface.

3-2. Effects of flow rate and temperature on base oil extraction

To investigate the effect of injected fluid temperature on the extraction of the base oil, water was injected as the displacing fluid with a constant flow rate 0.4 mL/min at temperatures of 5 °C, 22 °C, 60 °C, and 90 °C into the porous medium that filled with the base oil. Extracted base oil volume during water injection at different temperatures has been shown in Figure 9. According to the Figure 9, with increasing the temperature from 5 °C to 90 °C, the total extracted oil volume has increased from 26.9% to 43.4%. Also, with increasing temperature, more time was required for water to reach the outlet. Actually, due to the heat transfer the viscosity of the base oil decreases and the base oil mobility improves. Then the displacing fluid extracts the base oil easily with a wider path. Thus the amount of the trapped base oil reduces and the base oil recovery increases.

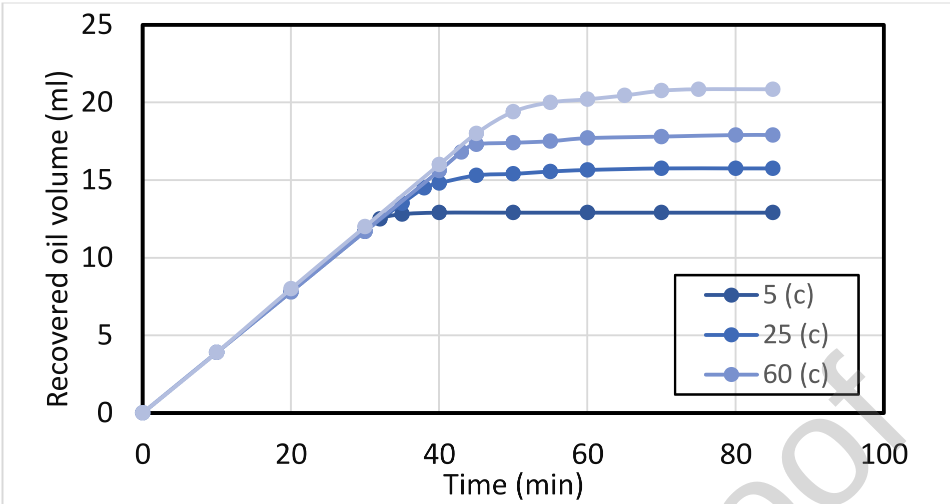


Figure 9. Recovered oil volume from the porous medium during water injection at different injection temperatures.

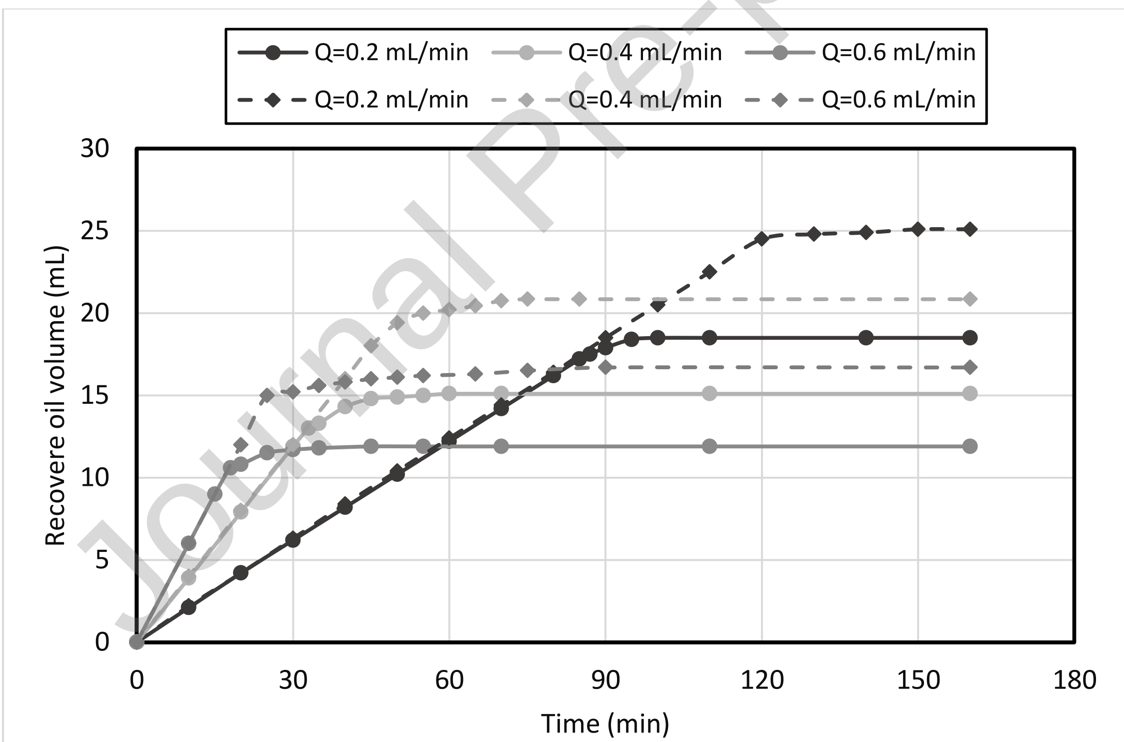


Figure 10. Recovered oil volume from the porous medium at different flow rates when injecting water temperaturs is 22 °C (solid lines) and hot water's is 90 °C (dashed lines).

For further investigation, hot water of 90 °C was injected at 0.2 ml/min, 0.4 ml/min, and 0.6 ml/min flowrates, and the results were presented in Figure 10 and Table 6. Figure 10 shows the recovered oil volume from the porous medium by injecting water at T = 22 °C, and T = 90 °C at different rates. According to Table 6 and Figure 10, by reducing the injection flow rate due to increasing the residence time of the injected fluid and increasing the contact surface between displacing and displaced fluids, hot water transfers more heat energy to the viscous oil and reduces the viscosity of the oil. In addition, as known at low flow rates fingering phenomena reduces. Thus, hot water distributes widely during the porous medium and extracts more base oil from the porous medium. In fact, by decreasing flowrate hot water injection has a greater and more positive effect on the base oil recovery. In spite of this, at very low flow rate, 0.08 ml/min, increasing the injection time causes heat losses to the environment, so base oil recovery efficiency decreases slightly.

Table 6. Oil recovery efficiencies by injecting water at T= 22 °C and hot water at T=90 °C with different flow rates.

Step	Flow rate (mL/min)	Oil recovery efficiency by water	Oil recovery efficiency by hot water	Difference between efficiencies
1	0.08	% 47.3	% 49.8	% 2.5
2	0.2	% 38.5	% 52.3	% 13.8
3	0.4	% 31.5	% 43.4	% 12
4	0.6	% 24.8	% 34.8	% 10

3-2. Effects of nanofluid injection on base oil extraction

Figure 11 shows the recovered volume of the base oil during the injection time of the nanofluid in different concentrations. As shown, with increasing the nanofluid concentration from 0.01 wt% to 0.05 wt%, the amount of base oil extraction increases. Because increasing the nanofluid concentration increases the viscosity of the injected fluid and decreases the interfacial tension between the nanofluid and oil [31]. It is predicted due to the accumulation of nanoparticles and clogging of the pores with increasing the nanofluid concentration, the amount of base oil extraction decreased. Table 7 presents the extraction information of the base oil by injecting the nanofluid in different concentrations. According to the Table 7, the total amount of base oil extraction by injection of the nanofluid 0.1 wt% was reduced to 45.4%. But this amount is higher than result of the nanofluid 0.01 wt% injection. Moreover, injection the nanofluid 0.05 wt% leads to the higher breakthrough time of injected fluid and higher oil recovery from the porous medium. According to the table 3 and figure 8, presence of nanoparticles in the displacing fluid not only reduces the interfacial tension but also changes the wettability of the porous medium significantly, hence the nanofluid injection results in base oil recovery increment. Actually, interfacial tension reduction and wettability alteration increase the capillarity number and decrease saturation of the base oil inside the porous medium. So the displacing fluid pushes the base oil through the throats more easily and smoothly, hence more base oil move away from inside of the pores, and oil recovery efficiency improves.

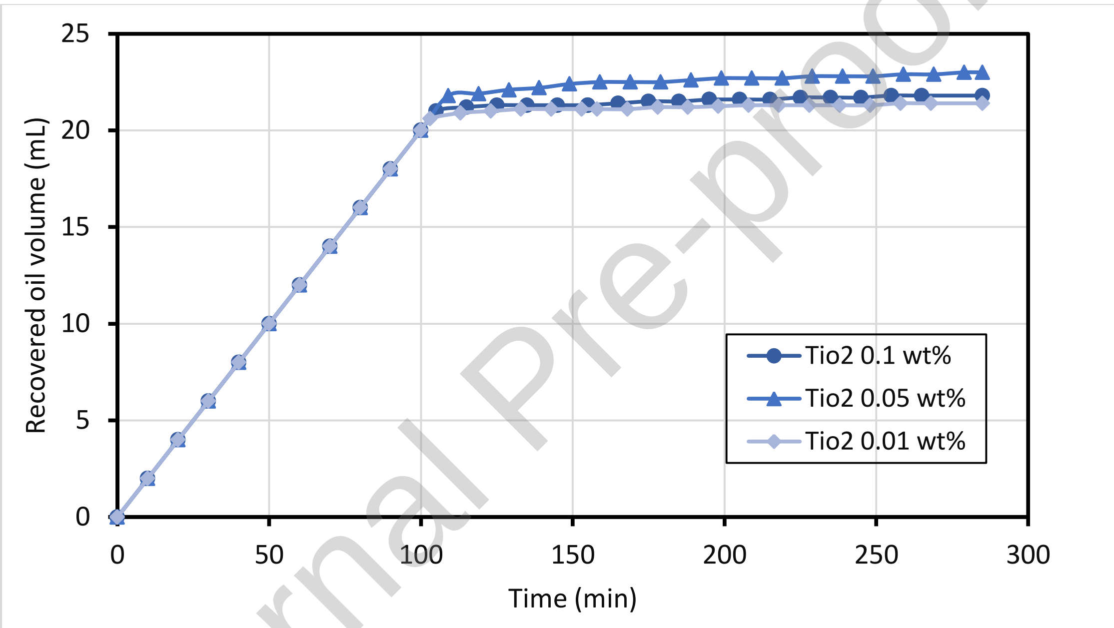


Figure 11- Recovered oil volume from the porous medium when the nanofluid injected with different concentrations.

Table 7- oil recovery efficiencies by injecting nanofluid with different concentrations.

Step	Nanofluid wt.%	Total oil recovery efficiency	Oil recovery efficiency before breakthrough	Breakthrough time (min)
1	0.01	% 44.6	% 42.9	103
2	0.05	% 47.9	% 45.4	109
3	0.1	% 45.4	% 43.8	105

3-3. Comparison among different fluids injection

In Figures 12 and 13 the results of different fluids injection at T = 22 °C and T = 90 °C have been presented. By adding surfactant to water, 2.3% more base oil is extracted than water injection before the breakthrough time. Also the base oil extraction amount has increased by 4% after the breakthrough time. By adding SDS to water, the breakthrough time increases from 87 minutes to 93 minutes and by adding TiO_2 nanoparticles to the SDS solution (base fluid), the breakthrough time increases from 93 minutes to 109 minutes, hence that the nanofluid has performed better than the surfactant solution in base oil recovery. It is worth mentioning that, by adding nanoparticles to the surfactant solution, before the breakthrough time, base oil recovery increased by 6.6% compared to the injection of the SDS solution. On the other hand, after the breakthrough time, SDS injection leads to higher base oil recovery. In fact, the presence of TiO_2 nanoparticles has affected the extraction of the base oil before the breakthrough time and surfactant has increased the extraction of the base oil after breakthrough time. Comparing the results of water injection, the SDS solution injection and nanofluid 0.05 wt%, it is concluded that the presence of SDS surfactant and TiO_2 nanoparticles has a positive effect on increasing oil recovery. Overall, presence of SDS in water leads to a significant reduction in the interfacial tension between the base oil and water, and presence of TiO_2 nanoparticles in the SDS solution results a particular reduction in the contact angle between water and the glass surface. As mentioned earlier, increasing the viscosity of the displacing fluid increases the viscosity ratio and decreases the mobility ratio, thereby increasing the oil recovery from the porous medium. Nonetheless, significant reducing interfacial tension and wettability alteration increase the capillary number. Thus, the displacing fluid easily moves inside the porous medium and then dissolves the base oil in itself and extracts more base oil smoothly. Indeed, change in viscosity and interfacial tension in presence of nanoparticles is very small, and the most effective reason to increase the oil extraction in injection of the nanofluid is the alteration of the porous medium wettability.

In hot water injection, 6.9% more base oil is recovered from the porous medium compared whit the hot SDS solution injection. However, in the hot SDS solution injection, more base oil is recovered compared with the hot water injection after the breakthrough time but in overall, hot water injection extracts higher base oil recovery rather than the hot SDS solution injection. This is in accordance with literature [32]. Xia and coworkers investigated the effect of the concentration of SDS on the ratio of conductive heat transfer coefficient [32]. They reported that with increasing SDS concentration in water, the ratio of the SDS solution heat transfer coefficient to the pure water heat transfer coefficient decreased, so the thermal resistance of the SDS solution increased. As a result, hot water injection has better performance in base oil recovery rather than the hot SDS solution injection because the SDS solution has higher thermal resistance and has a poorer performance in reducing viscosity of the base oil.

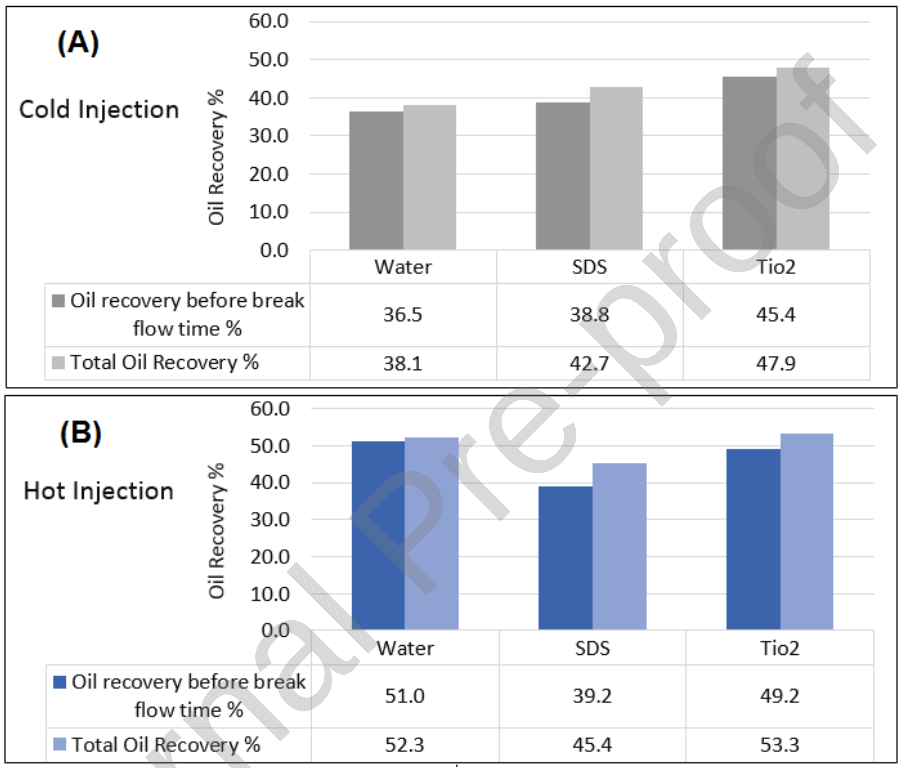


Figure 12. Base oil recovery from the porous medium by injection of different fluids; (A) at 22 °C, and (B) at 90 °C.

On the other hand, in the hot water injection, 1.2% more base oil is recovered from the porous medium compared to the hot nanofluid injection before the breakthrough time. But after breakthrough time (at ~230 minute of injection), 7.9% more base oil is recovered rather than hot water injection. Das and his coworkers reported that the addition of TiO_2 nanoparticles to the SDS solution increased the heat transfer coefficient of the nanofluid [33]. They also reported that increasing the temperature reduced the nanofluid interfacial tension more than the SDS solution's. So it is concluded that adding TiO_2 nanoparticles to the base fluid (the SDS solution) increases the conductive heat transfer coefficient and reduces the thermal resistance. So the presence of the nanoparticles in the hot nanofluid improves the performance of the hot nanofluid in the oil recovery.

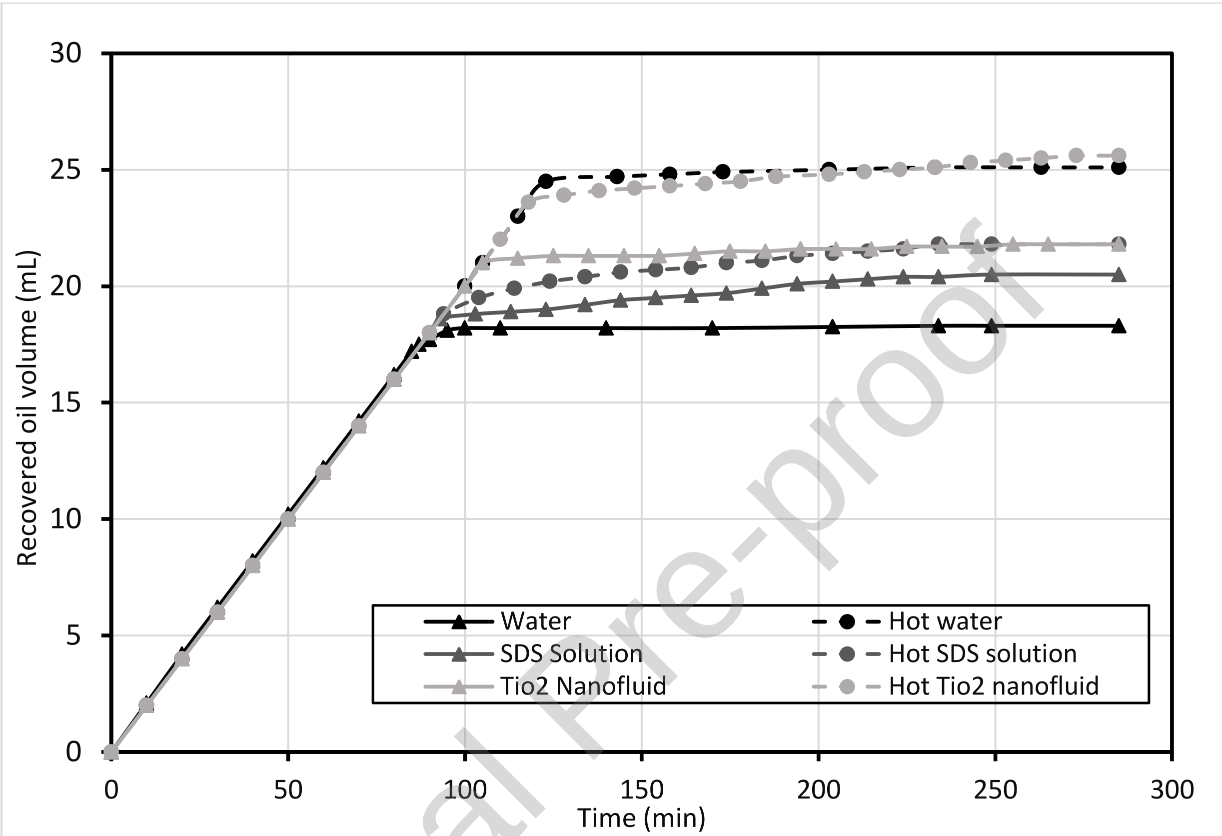


Figure 13. Recovered oil volume from the porous medium by injection of different fluids at T= 22 °C, (solid lines), and hot fluid at T=90 °C (dashed lines).

According to Figure 14, in the hot SDS solution injection with a different flow rates, until the breakthrough time, an increase temperature injection of the SDS solution has no significant effect on increasing base oil recovery due to the SDS solution has higher thermal resistance. On the other hand, after the breakthrough time, the hot SDS solution injection increases base oil recovery slightly rather than the SDS solution injection at T=22 °C and total base oil recovery is increased during the two- phase extraction as an emulsion. This is due to reduction in interfacial tension by increasing temperature. As a result, trapped oil is recovered as an emulsion.

In addition, the nanofluid 0.05 wt% injection with flow rates 0.2 ml/min and 0.4 ml/min extract 5.2% and 4% more base oil from the porous medium in comparison base fluid (the SDS solution) injection. Also the hot nanofluid 0.05 wt% injection with flow rates 0.2 ml/min and 0.4 ml/min recover 7.9% and 5.7% more oil recovery from the porous medium. These results have been shown in Table 8. It is resulted that by reducing the injection flow, the effect of nanoparticles on an increase base oil recovery becomes effective. Because lower flow rate increases the resident time of nanofluid, so nanoparticles play effectively their role in viscosity reduction of base oil by heat transfer.

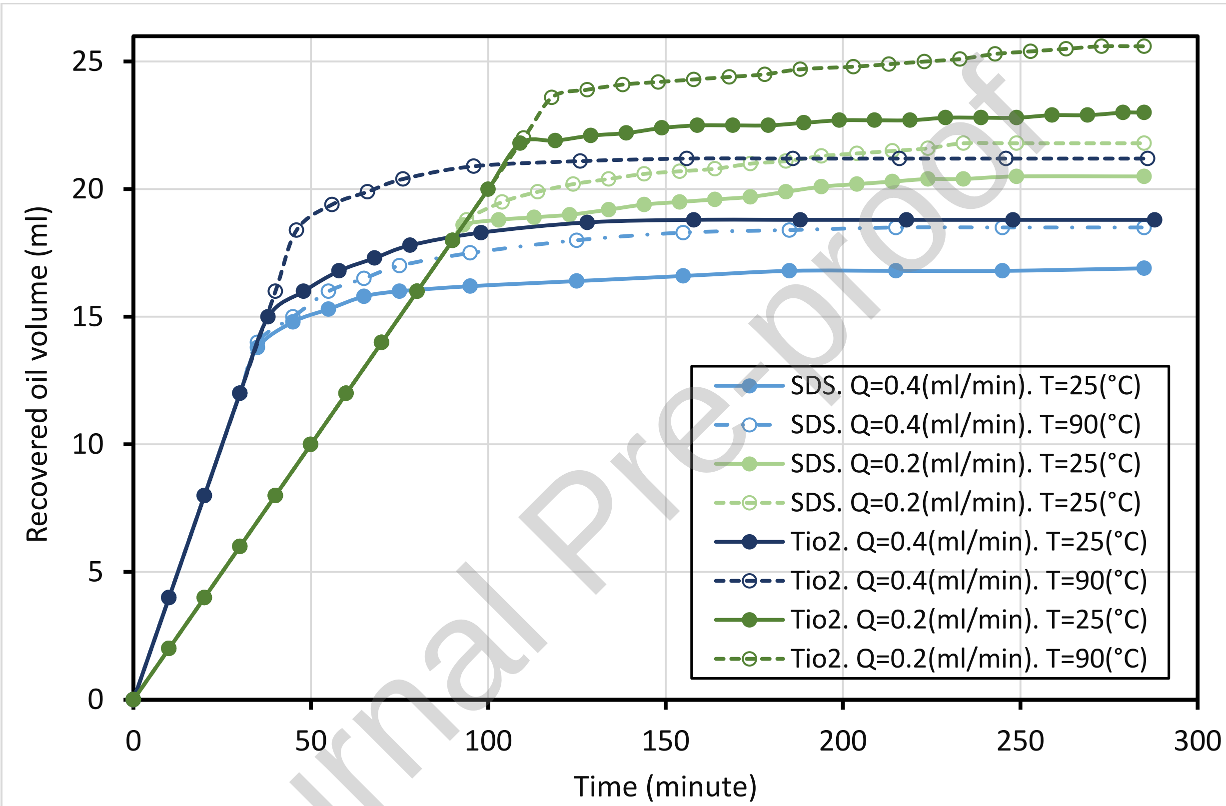


Figure 14. Recovered oil volume from the porous medium using cold and hot nanofluid injection.

Table 8. Oil recovery effienciey by injecting cold and hot nanofluid.

Injected fluid	Injection flow rate (ml/min)	Injection temperature (°C)	Oil recovery efficiency before breakthrough	Breakthrough time (min)	Total oil recovery efficiency
SDS solution	0.2	22	% 38.8	93	% 42.7
TiO_2 nanofluid	0.2	22	% 45.4	109	% 47.9
SDS solution	0.2	90	% 39.2	94	% 45.4
TiO_2 nanofluid	0.2	90	% 49.2	118	% 53.3
SDS solution	0.4	22	% 28.8	35	% 35.2
TiO_2 nanofluid	0.4	22	% 31.2	35	% 39.2
SDS solution	0.4	90	% 29.1	38	% 38.5
TiO_2 nanofluid	0.4	90	% 38.3	46	% 44.2

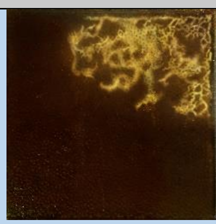
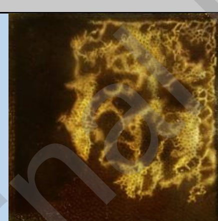
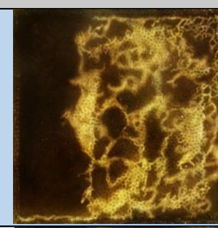
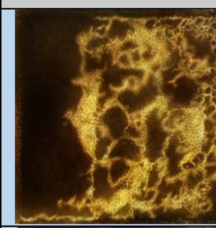
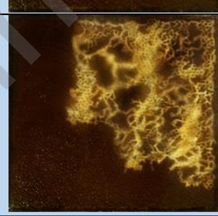
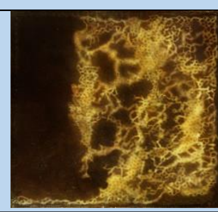
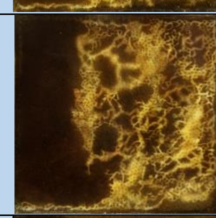
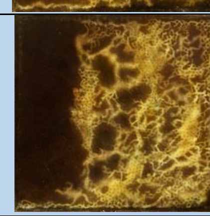
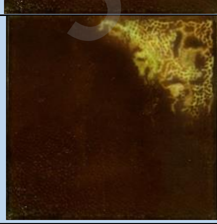
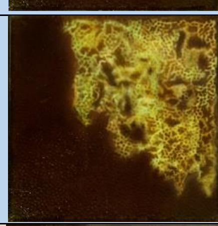
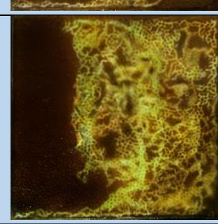
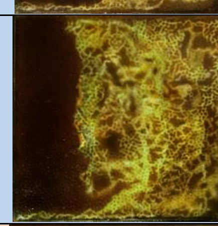
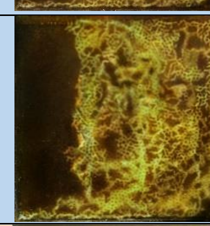
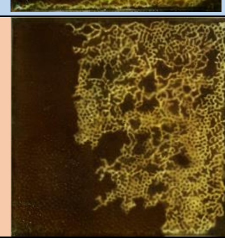
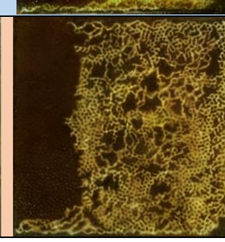
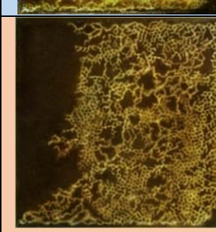
3-4. Fluid flow pattern study

Table 9 shows the distribution patterns of displacing fluids (injected fluids) in the porous medium until 280 minutes of fluids injection at flow rate 0.2 ml/min. by comparing SDS solution injection with water injection at T=22 °C, the part of the porous medium where the base oil is surrounded by the SDS solution paths are smaller than water paths, and the SDS solution has stable displacement at fluid interface. Also, in water injection trapped base oil spots are larger and fingering pattern is observed compared to the SDS solution injection. Moreover, for the nanofluid injection at T = 22°C the trapped base oil parts are the smallest, and the distribution of the nanofluid flow looks vastest and most stable compared to the other fluids' injections. In fact, presence of nanoparticles alters wettability of the porous medium and decrease contact angle. So trapped base oils are directed to the outlet of the porous medium as negative capillary force turns into positive capillary force by wettability alteration. Thus, the nanofluid injection reduces fingering pattern, and is distributed in a wide path inside the porous medium compared to the other fluids' injections. So the nanofluid extracts more base oil.

Similar story can be stated for three fluids injection at T=90 °C. Moreover, by increasing the injection temperature due to the heat transfer, the viscosity of the base oil decreases and the displacing fluid extracts the base oil easily and with a wider path. In contrast to this similarity, the breakthrough time for each displacing fluids are different. This difference is pronounced because of an increased residence time of the displacing fluid, difference in interfacial tensions, wettability alteration, and viscosity of the base oil changes.

Table 10 shows the distribution patterns of the displacing fluids (injected fluids) in the porous medium from beginning to 200 minutes of fluid injection at flow rate 0.4 ml/min. The effect of the hot nanofluid injection in stabilizing the fluid-fluid interface is clearly seen. Again, oil trapped regions during the nanofluid injection is less than that of in the SDS solution injection. By comparing table 9 with table 10, it is resulted that at lower flow rate (0.2 ml/min) wall effect on the distribution pattern is significant compared to its effect in higher flow rate (0.4 ml/min). At low flow rates and at a given injection temperature, for the same displacing fluid and same injection time, viscose fingering decreases. So, the breakthrough time at lower flow rates is longer compared to the higher flow rates.

Table 9. Injected fluids pattern in the porous medium for injection flowrate of 0.2 ml/min at T= 22 °C and T = 90 °C.

Injection time	30 min	75 min	110 min	Breakthrough time	280 min
Water T = 22 °C			--------		
SDS solution T = 22 °C					
TiO_2 Nanofluid T = 22 °C					
Water T = 90 °C					

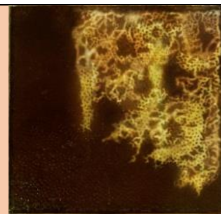
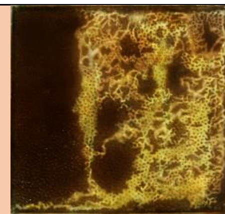
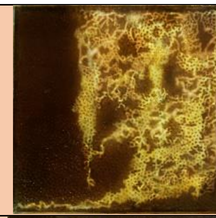
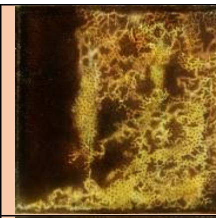
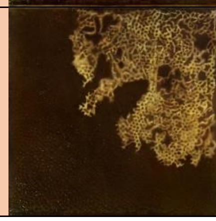
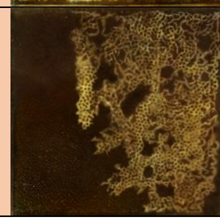
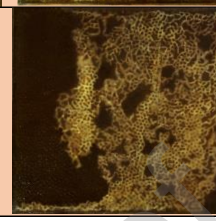
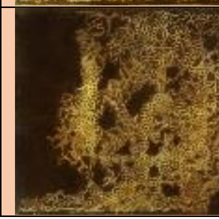
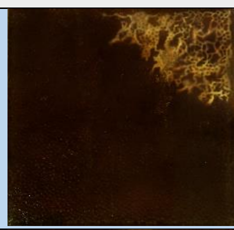
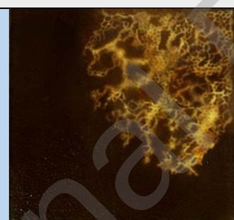
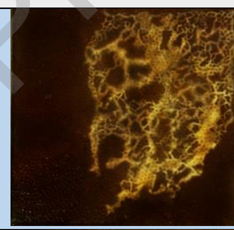
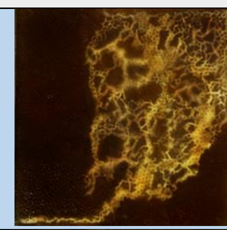
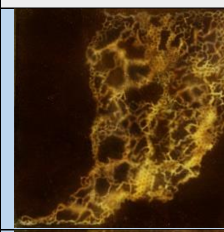
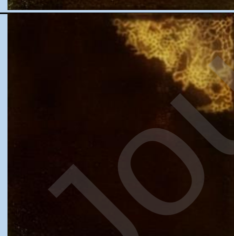
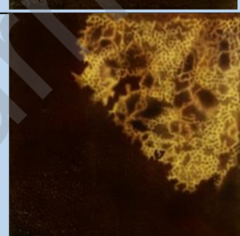
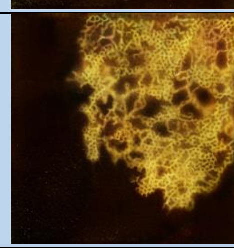
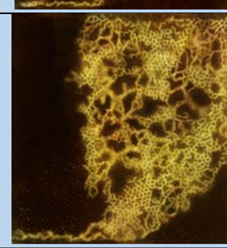
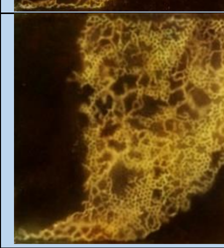
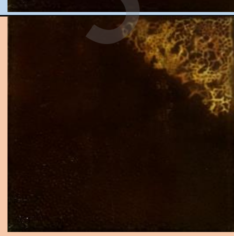
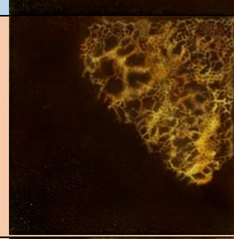
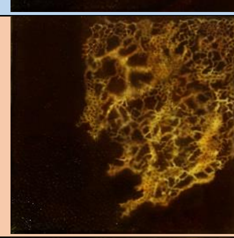
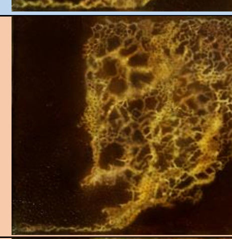
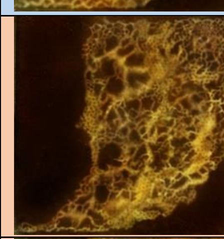
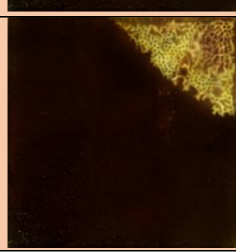
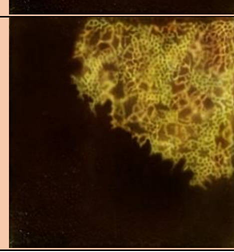
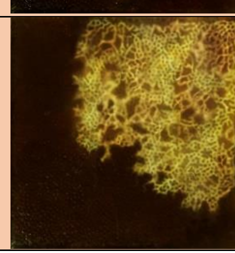
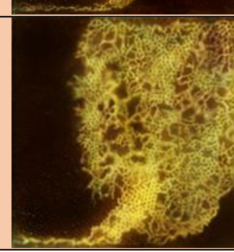
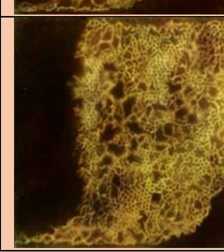
SDS solution T = 90 °C					
TiO_2 Nanofluid T = 90 °C					

Table 10. Injected fluids pattern in the porous medium for injection flowrate of 0.4 ml/min at T= 22 °C and T = 90 °C.

Injection Time	10 min	20 min	30 min	Breakthrough time	200 min
SDS solution T = 22°C					
TiO_2 Nanofluid T = 22 °C					
SDS solution T = 90 °C					
TiO_2 Nanofluid T = 90 °C					

4. Conclusion

In this experimental research, a base oil recovery from a two-dimensional porous medium was studied. The porous medium was made by placing glass beads (spherical shape) with an approximate diameter of 3 mm between two square glass plates with a size of 20 cm and a thickness of 6 mm. In the construction of this the porous medium, only one layer of glass beads was placed between two surfaces to ignore the effect of the third dimension. TiO_2 with concentrations of 0.01, 0.05 and 0.1% by weight were injected as the displacing fluid. To investigate the process of increasing base oil, injection flowrates of 0.2, 0.4, and 0.6 ml/min were considered. The Base oil was used as the displaced fluid. Distilled water, sodium dodecyl sulfate (SDS) in distilled water, and the nanofluid containing water, SDS and titanium dioxide nanoparticles were used as displacing fluids. By injecting displacing fluids at different flowrates and temperatures as well as different concentrations, an attempt was made to increase the recovery efficiency of the base oil from the porous medium. By decreasing the water injection flowrate from 0.6 mL/min to 0.08 mL/min, base oil recovery increased by 22.5%. Also, by increasing the injection temperature from 5 °C to 90 °C, due to the heat transfer, the viscosity of the base oil decreases and the displacing fluid extracts the base oil easily and with a wider path and 16.5% more base oil recovery happened.

By adding surfactant to the displacing fluid, the interfacial tension between the base oil and the displacing fluid reduces. Also, the presence of nanoparticles in the displacing fluid not only reduces the interfacial tension but also changes significantly the wettability of the porous medium. Base oil recovery increases by injection of the SDS solution by 4.6%, and 5.2% by injection of the nanofluid. This is due to the wettability alteration and low interfacial tension between oil and injected fluid. It was also observed an increase in the nanofluid concentrations does not always improves the oil recovery efficiency. Because injection of the nanoparticles with high concentration causes nanoparticles sedimentation inside the porous medium and so pores collapse. On the other hand, it is resulted by adding nanoparticles into the displacing fluid always an increase in base oil recovery is observed.

In hot fluid injection with a flow rate of 0.2 mL/min before the breakthrough time, the hot water injection performed better than the hot nanofluid in the extraction of oil, but after the breakthrough time, the hot nanofluid had a higher efficiency than the hot water. Adding nanoparticles to the hot SDS solution increases the thermal conductivity coefficient of the displacing fluid and reduces the interfacial tension. So nanoparticles improve the performance of the hot nanofluid in the oil recovery. Finally, adding nanoparticles to the hot SDS solution, the oil recovery increased by 7.9%.

5- References

1. Lenormand R. Flow through porous media: limits of fractal patterns. Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences, 1989; 423(1864): p. 159-168.

2. Karadimitriou N, Hassanizadeh S. A review of micromodels and their use in two-phase flow studies. Vadose Zone Journal, 2012; 11(3): p. vzj2011.0072.

3. Bashir, A., A.S. Haddad, and R. Rafati, A review of fluid displacement mechanisms in surfactant-based chemical enhanced oil recovery processes: Analyses of key influencing factors. Petroleum Science, 2021.

4. Deng X, Tariq Z, Murtaza M, Patil Sh, Mahmoud M, Kamal MS. Relative contribution of wettability Alteration and interfacial tension reduction in EOR: A critical review. Journal of Molecular Liquids, 2021; 325: p. 115175.

5. Kirk R. E., Othmer DF., Encyclopedia of chemical technology. Vol. 23. 1983: Wiley.

6. Lv M, Wang S., Pore-scale modeling of a water/oil two-phase flow in hot water flooding for enhanced oil recovery. RSC advances, 2015; 5(104): p. 85373-85382.

7. Kenzhekhanov S., Chemical EOR process visualization using NOA81 micromodels. 2016, Colorado School of Mines.

8. Prats M., Thermal recovery. 1982. SPE Monograph Series Vol. 7. ISBN: 978-1-61399-548-8

9. Babadagli T., Evaluation of EOR methods for heavy-oil recovery in naturally fractured reservoirs. Journal of Petroleum Science and Engineering, 2003; 37(1-2): p. 25-37.

10. Gbadamosi A. O., Junin R., Manan M. A., Agi A., Yusuff A. S., An overview of chemical enhanced oil recovery: recent advances and prospects. International Nano Letters, 2019; 9(3): p. 171-202.

11. Agista M. N., Guo K., Yu Z., A state-of-the-art review of nanoparticles application in petroleum with a focus on enhanced oil recovery. Applied Sciences, 2018; 8(6): p. 871.

12. Suleimanov B. A., Ismailov F., Veliyev E., Nanofluid for enhanced oil recovery. Journal of Petroleum Science and Engineering, 2011; 78(2): p. 431-437.

13. El-Diasty A. I., Ragab A. M., Applications of nanotechnology in the oil & gas industry: Latest trends worldwide & future challenges in Egypt. in North Africa Technical Conference and Exhibition. 2013. Society of Petroleum Engineers.

14. Li Y., Tung S., Schneider E., Xi S., A review on development of nanofluid preparation and characterization. Powder technology, 2009; 196(2): p. 89-101.

15. Jehhef K. A., Siba M. A. A. S., Effect of surfactant addition on the nanofluids properties: a review. Acta Mechanica Malaysia, 2019; 2(2): p. 1-19.

16. Rosen M. J., Kunjappu J. T., Surfactants and interfacial phenomena. 2012. John Wiley & Sons.

17. Yarveicy, H. and A. Javaheri, Application of Lauryl Betaine in enhanced oil recovery: A comparative study in micromodel. Petroleum, 2019. 5(2): p. 123-127.

18. Negin, C., S. Ali, and Q. Xie, Most common surfactants employed in chemical enhanced oil recovery. Petroleum, 2017. 3(2): p. 197-211.

19. Chen P., Mohanty K. K., Surfactant-enhanced oil recovery from fractured oil-wet carbonates: effects of low ift and wettability alteration. in SPE International Symposium on Oilfield Chemistry. 2015. OnePetro.

20. Yarveicy, H. and A. Haghtalab, Effect of amphoteric surfactant on phase behavior of hydrocarbon-electrolyte-water system-an application in enhanced oil recovery. Journal of Dispersion Science and Technology, 2018. 39(4): p. 522-530.

21. Sun X., Zhang Y., Chen G., Gai Z., Application of nanoparticles in enhanced oil recovery: a critical review of recent progress. Energies, 2017; 10(3): p. 345.

22. Yan C., Kan A. T., Wang W., Wang L., Tomson M. B., Synthesis and size control of monodispersed Al-sulfonated polycarboxylic acid nanoparticles and their transport in porous medium. Spe Journal, 2013; 18(04): p. 610-619.

23. Ehtesabi H., Ahadian M. M., Taghikhani V., Enhanced heavy oil recovery using TiO2 nanoparticles: investigation of deposition during transport in core plug. Energy & Fuels, 2015; 29(1): p. 1-8.

24. Roustaei A., Saffarzadeh S., Mohammadi M., An evaluation of modified silica nanoparticles' efficiency in enhancing oil recovery of light and intermediate oil reservoirs. Egyptian Journal of Petroleum, 2013; 22(3): p. 427-433.

25. Li S., Hendraningrat L., Torsaeter O., Improved oil recovery by hydrophilic silica nanoparticles suspension: 2 phase flow experimental studies. in IPTC 2013: International Petroleum Technology Conference. 2013. European Association of Geoscientists & Engineers.

26. Jiang R., Li K., Horne R., A mechanism study of wettability and interfacial tension for EOR using silica nanoparticles. in SPE Annual Technical Conference and Exhibition. 2017. Society of Petroleum Engineers.

27. Ogolo N., Olafuyi O., Onyekonwu M., Enhanced oil recovery using nanoparticles. in SPE Saudi Arabia section technical symposium and exhibition. 2012. Society of Petroleum Engineers.

28. Yarveicy, H., et al. Enhancing oil recovery by adding surfactants in fracturing water: A Montney case study. in SPE Canada Unconventional Resources Conference. 2018. OnePetro.

29. Ragab A. M., Hannora A. E., An experimental investigation of silica nano particles for enhanced oil recovery applications. in SPE North Africa technical conference and exhibition. 2015. Society of Petroleum Engineers.

30. Mohajeri M., Hemmati M., Shekarabi A. S., An experimental study on using a nanosurfactant in an EOR process of heavy oil in a fractured micromodel. Journal of petroleum Science and engineering, 2015; 126: p. 162-173.

31. Das P. K., Mallik A. K., Ganguly R., Santra A. K., Synthesis and characterization of TiO2–water nanofluids with different surfactants. International Communications in Heat and Mass Transfer, 2016; 75: p. 341-348.

32. Xia G., Jiang H., Liu R., Zhai Y., Effects of surfactant on the stability and thermal conductivity of Al2O3/de-ionized water nanofluids. International Journal of Thermal Sciences, 2014; 84: p. 118-124.

33. Das P. K., Mallik A. K, Ganguly R., Santra A. K., Stability and thermophysical measurements of TiO2 (anatase) nanofluids with different surfactants. Journal of Molecular liquids, 2018; 254: p. 98-107.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights:

- Enhancing Oil Recovery (EOR) from two-dimensional porous medium by cold and hot fluids injection was studied.
- TiO_2 nanofluid, SDS solution, and water with different rates considered as injected fluids.
- Oil recovery by nanofluid injection was more than SDS solution injection because of wettability alteration.
- Oil recovery by hot nanofluid injection was more than hot SDS solution injection due to the presence of nanoparticle.
- Hot water in EOR acts better than hot nanofluid before breakthrough time.
- Hot nanofluid injection overtake hot water result after breakthrough time.