



Full Length Article

Improving the gas condensate recovery through wettability alteration to gas-wet during gas recycling via dispersion of nanoparticles in gas

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ABSTRACT

This research investigates the role of dispersion of nanoparticles in gas during gas recycling process to improve the gas condensate recovery via altering the carbonate reservoirs wettability. The nanoparticles were synthesized and analyzed using dynamic light scattering (DLS), energy-dispersive X-ray (EDX), and transmission electron microscopy (TEM). After that, the dispersion of nanoparticles in methane was investigated by cloud point pressures measurement. Also, the effectiveness of methane/nanoparticles solutions was assessed through the contact angle experiments and gas recycling process. Based on the cloud point pressures results, the nanoparticles can be dispersed in methane at pressures commensurate with hydrocarbon reservoirs. Gas/nanoparticles single-phase solutions increased the contact angles of gas condensate and n-decane from 12° to 121° and 135.5°, respectively, for fluorinated silica, and to 100.5° and 108° for fluorinated titania. The shift from oil-wet to gas-wet conditions enhanced the recovery factor from 55% to 76%, marking a 21% improvement in gas condensate recovery during gas recycling. Furthermore, the pressure drop ratio decreased by 60%, due to better surface wettability and reduced condensate blockage. Comparative results indicated that the dispersion of fluorinated silica nanoparticles in gas outperformed fluorinated titania in altering wettability. These results emphasize the potential of current new approach, through dispersion of fluorinated nanoparticles in gas; to improve gas condensate recovery during gas recycling, especially in low-permeability carbonate reservoirs.

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1. Introduction

Most of the gas reservoirs are gas condensate reservoirs, hence, thermodynamically, in these reservoirs, the reverse condensation can occur during the production of gas and consequently, the reservoir pressure will be reduced to less than the dew point pressure [1]. As a result of this phenomenon, a variety of gases have been produced in their liquid form (i.e., condensates). The amount of these gas condensates increases by increasing the production from the reservoirs and consequently further reduction of pressure, [1,2]. Recently, in high-impact research, Fan et al. [1] showed that gas condensate reservoirs can be divided into three areas: (1) the area near the well where into

this area, two phases of gas and condensate are flowing, (2) the condensate production area which into this area both gas and condensate phases are present, but only the gas phase is moving, and (3) the gas single-phase area which in this zone, due to the high gas pressure compared to the dew point pressure, there is a single gas phase, however, this zone is unstable and finally will merge with the second zone [3–5]. In the first and second zones, it is possible to form condensate accumulation, leading to major problems for the production process. In fact, due to the formation of condensate accumulation, a large amount of condensate remains inside the reservoirs and cannot be extracted. Besides, both the effective permeability of the gas and the efficiency of the well have decreased by narrowing the gas flow path [6–8]. It is notable that, the condensate blockage around the near-well area can cause several critical problems, for instance, reducing the relative permeability and decreasing the productivity of the well [9–11]. Hence to overcome these difficulties, up to now, several methods including gas recycling (e.g., CO₂, CH₄, N₂, and natural

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gas), reduction of surface tension utilizing solvents (e.g., alcohols), employing unconventional wells, and wettability alteration have been reported for increasing the efficiency of gas reservoirs [12–15]. Among the different methods, the wettability alteration has attracted the interest of several researchers because it is a permanent method to decrease the formation damage near the wellbore and causes the retrograde moves from wellbore to surface. In this regard, surfactants, nanoparticles, and modified nanoparticles with chemical agents have been applied for wettability alteration to gas-wet [16–18]. Among them, wettability alteration based on the nanoparticles is an attractive and novel field for changing the strong liquid wettability (condensate or water) to medium gas wettability and consequently improving the efficiency of gas condensate reservoirs [19]. In addition, there are two approaches to alter the wettability of the gas condensate reservoirs; 1) using the water-soluble chemicals technique and 2) considering the gas-soluble materials approach. At the first one, the chemicals are dissolved in water and the rock surface is treated with them, which it is not applicable during the gas recycling [20–23]. Moreover, at the second approach, which is considered at the current study, the chemicals are dispersed in gas and after that the modified gas is injected during the gas recycling process [24–26]. In case of water-soluble chemical, various chemicals (fluorinated materials) have been widely used to alter oil-wet to gas-wet in gas reservoirs. For example, Mousavi et al. [27] evaluated the wettability alteration around the well area of the limestone using fluorinated silica nanoparticles. The surface contact angles of the cores after chemical modification were calculated at about 147° and 61° for water and n-decane, in order. On the other hand, the results of injecting these nanoparticles as nanofluids (i.e., nanoparticles dispersed in methanol) into the rock samples exhibited a characteristic change in the contact angle for water and oil from zero to 124°–147° and 50–70°, respectively, improving the pressure drop by about 30% and decreasing the accumulation of gas condensate [27]. In another research, the wettability of gas condensate has been investigated using fluorinated titanium and silicon oxide nanoparticles, and carbon nanotubes, revealing that the contact angle of the samples increases from zero to 144°, 151°, and 147° after treatment with titania, silica, and carbon nanotubes, respectively [28]. Besides, fluoro-modified silica nanoparticles have been utilized for wettability alteration to gas-wet, revealing that the nanofluids of the fluoro-modified silica nanoparticles can efficiently alter the wettability of the rock samples from oil-wet to gas-wet [28]. Moreover, Safaei et al. [29] investigated the wettability alteration of the carbonate core-plugs with the Fe₃O₄ nanofluids. Based on their results, modified Fe₃O₄ nanoparticles significantly improved the wettability of the carbonate rocks from oil-wet to intermediate gas-wetting. In addition, Aguirre et al. [30] synthesized the SiO₂ nanofluid based on anionic surfactant. They reported that the wettability alteration occurred to gas-wet and reduced the formation damage, so it led to increase the gas production in tight gas-condensate reservoirs. In another study, rock treatment was performed via an anionic fluoro-surfactant. Based on the core flooded results, the rock treatment could increase the gas relative permeability by a factor of 1.7 which illustrated the wettability changed to gas-wet [31]. According to the water-soluble chemicals results, there are some technical challenges for its application during the gas recycling in the field scale. For example, the producing wells must be shut-in for chemical injection. Each shut-in time needs to be long enough to perform the surface rock treatment. Also, after well treatment, the early produced fluid must be transported away from the well site. Therefore, it increases the economic costs. Moreover, there is a new alternative method to wettability alteration of gas

condensate reservoirs during gas recycling process via gas-soluble chemical such as nanoparticles which can reduce the technical challenges. To the best of our knowledge, our current study is the first experimental work to change the wettability of gas condensate reservoirs during gas recycling using the gas-soluble chemicals. In the current study, the silica and titania nanoparticles, as well as fluorinated silica and titania nanoparticles, are synthesized and then characterized by DLS, EDX, and TEM imaging methods. Afterward, the dispersion of nanoparticles in methane is investigated by cloud point pressures measurement. Also, the modified methane is prepared and utilized for wettability alteration and core flooding experiments. The contact angles of gas (methane and methane/nanoparticles) and liquid (n-decane, gas condensate, and water) are measured during soaking the carbonate samples with methane/nanoparticles solutions. Furthermore, the effect of wettability alteration to gas-wet is investigated by measuring the condensate recovery during core flooding tests during methane/nanoparticles recycling. However, the wettability alteration of the gas condensate reservoirs to gas-wet via gas-soluble chemicals can be one of the promising approaches to enhance condensate recovery.

2. Experimental

2.1. Chemicals and instrumentations

All materials were purchased from Merck and Sigma Aldrich Companies (Table 1). It is notable that in this work, a magnetic stirrer, a mechanical stirrer, a centrifuge, an ultrasonic bath, a furnace, an oven, a vacuum oven, a Soxhlet, a hot water bath, and a pH meter were used.

2.2. Synthesis of nanoparticles

Titania nanoparticles were synthesized by a sol-gel chemical method [32–35]. In this regard, a certain amount of 30 v/v% of titanium isoperoxide was added to isopropanol, followed by stirring for about 30 min, then 25% hydrochloric acid was introduced to the final solution. After about 20 min, the hydrolysis and condensation were performed to form the titania gel. The resulting gel was allowed to dry at room temperature and then annealed at 400 °C for 6 h.

In addition, silica nanoparticles were synthesized by a sol-gel chemical method [36–38]. In this regard, a certain amount of 50 v/v% of tetraethyl-orthosilicate was added to isopropanol, followed by stirring for about 20 min, then 2 mL of 20 v/v% ammonia solution was introduced to the final solution and the reaction mixture was kept at 40 °C for about 60.0 min. After about 80 min, the hydrolysis and condensation occurred to form the silica gel. The resulting gel was allowed to dry at room temperature and then annealed at 500 °C for 3 h.

2.3. Fluorinated silica and fluorinated titania nanoparticles

To prepare the fluorinated silica nanoparticles [39], the silica nanoparticles were added to 10.0 mL ethanol, stirred for 30 min, and ultrasonicated (400 W/20 kHz) for 45 min. Afterward, a diluted solution of the fluorinated silane (solvent, ethanol) is gradually introduced to the mixture, followed by refluxing the reaction system for 15 h at 50 °C. It should be mentioned that silica nanoparticles were modified with different F: Si ratios. Notably, the fluorinated titania nanoparticles were prepared by a protocol [39].

Table 1
Characteristics of the materials used in this study.

Material	Manufacture	Linear formula	Purity/grade
Methanol	Merck	CH ₃ OH	99.99%
Ethanol	Merck	CH ₃ CH ₂ OH	Absolute ethanol
Isopropanol	Merck	C ₃ H ₈ O	99.9%
Titanium(IV) isopropoxide	Merck	Ti(OCH(CH ₃) ₂) ₄	27.8–28.6 % TiO ₂
Tetraethyl orthogonal silicate	Sigma Aldrich	Si(OC ₂ H ₅) ₄	98%
Methane	Sigma Aldrich	CH ₄	99.99%
n-Decane	Merck	CH ₃ (CH ₂) ₈ CH ₃	99%
Toluene	Merck	C ₆ H ₅ CH ₃	99.9%
Cyclohexane	Merck	C ₆ H ₁₂	99.5%
Fluorinated silane	Sigma Aldrich	(CH ₃) ₃ SiCF	97%

2.4. Preparation of nanofluids

To prepare titania nanofluid [34,40], the as-synthesized titania nanoparticle was gradually added to the base fluid and mixed with a high-speed magnetic stirrer. Then the surfactant was added to the mixture, stirred for 25 min, and then sonicated with a constant power of 300 W for 45. Finally, the mixture was sonicated in an ultrasonic bath (60 W) for 2 h to complete the preparation of titania nanofluid. Moreover, the synthesized silica nanoparticle was gradually added to the base fluid and stirred for about 40 min to prepare a homogenous mixture, followed by adding the surfactant (note that in this study, saponin was a non-ionic surfactant) into the mixture within 10 min and its sonication (250 W/20 min) to complete the preparation of silica nanofluid [41–43]. Furthermore, a one-pot method was applied to prepare fluorinated silica and titania nanofluids. To do this, their synthesis protocol was repeated, but the final step of the synthesis method was ignored. Since the dispensability of the fluorinated silica and titania was much better than the bare ones, the step of sonication was ignored.

2.5. Dispersion of nanoparticles into gas

The dispersion of nanoparticles in methane was performed at different nanoparticles concentrations. It measured using visual techniques by a high-pressure, high-temperature windowed cell that has been explained in our previous studies in details [24,26,44]. The highest pressure at which the solutions were no longer a clear single-phase mixture, but rather a slightly foggy solution in which a haze of nanoparticles-rich droplets were suspended in the methane-rich system was illustrated to be the cloud point pressure. All subsequent experimentation (contact angle and core flooding tests) was performed at a pressure and temperature conditions that were above the cloud point pressures of the corresponding methane/nanoparticles solutions to ensure that the methane/nanoparticles solutions were in a single phase state and that no nanoparticles would come out of the solutions [45].

2.6. Contact angle measurements

To measure the contact angle of samples including n-decane, gas condensate, and methane/nanoparticles solutions an IFT400 device with the ability to measure contact angles at room

Table 2
Properties of carbonate rock.

Properties of carbonate rock		
Minerals	Formula	Composition (%)
Calcite	CaCO ₃	74
Anhydrite	CaSO ₄	5
Dolomite	CaMg(CO ₃) ₂	13
Quartz	SiO ₂	5
Clay	–	3

temperature up to 180 °C was applied. Notably, although in this study, n-decane was used as a simplified model for gas condensate, the real gas condensate was also tested to enhance the applicability and reliability of the findings. In addition, the carbonate substrates were prepared to measure the contact angles. Moreover, the aging process was performed for carbonate substrates to provide the strongly oil-wet condition using the gas condensate fluid [44,45]. The statistical analysis was carried out to ensure repeatability of data. In this regard, all data in each plot are reported as the mean value of 3 replicate measurements. The measurements was revealed the very good repeatability of experiments [46].

2.7. Core flooding experiments

Table 2 describes the properties of the carbonate rock used in this study. Notably, the properties of the carbonate cores used in this study were as follows; a diameter of 5 in., a total length of about 29.42 in. The core plug was 1.5 in. in diameter with a porosity of over 10%–14%. The carbonate cores were saturated (connate water and condensate) to provide the initial conditions of gas condensate reservoir at the near well bore. After that, all saturated cores were put in the cylinder to set the oil-wet condition during the aging process. The core flooding test including aging process has been described in our previous studies in details [24,26,44]. Finally, the aged core put into the core holder to investigate the effect of methane/nanoparticles injection on condensate recovery during gas recycling process, Fig. 1 [47].

3. Results and discussion

3.1. Characterization of the as-synthesized nanoparticles

3.1.1. Optimization of fluorination process of silica and titania nanoparticles

The fluorination process of fluorination process of silica and titania nanoparticles was optimized for effective factors including reaction time, temperature, and fluorinated silane concentration. As an index for finding the best experimental conditions for the synthesis of the fluorinated silica and titania nanoparticles, the effect of reaction time, temperature, and fluorinated silane concentration on the performances of the final products on the wettability

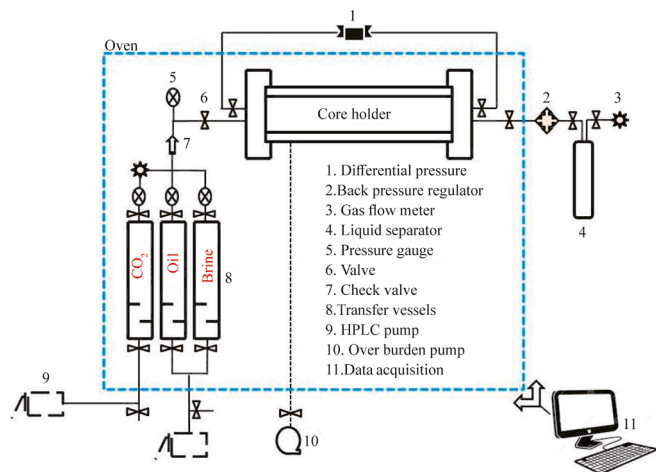


Fig. 1. The schematic of the Core-flooding apparatus.

alternation to gas-wet was assessed. The results are shown in Fig. 2. As can be seen in Fig. 2(a), the contact angle of n-decane as a model molecule was increased by increasing the synthesis time of both functions of the fluorinated silica and titania nanoparticles, reached its maximal value after 15 h and then leveled off which may be attributed to saturation of the nanoparticles active sites with the fluorine group after 15 h. Fluorinated silica and titania nanoparticles have been synthesized at 50 °C and increasing the synthesis temperature can significantly reduce their performances toward wettability alternation to gas-wet, hence, the synthesis was carried at 50 °C as Fig. 2(b). Finally, the F: Si/Ti ratio of the prepared fluorinated silica/titania nanofluid was optimized as Fig. 2(c), revealing that by increasing the fluorine content of the nanofluid, the contact angles for all samples increase and reach their maximum values when fluorinated silica nanoparticles with an F:Si ratio of 0.25: 1.00 or fluorinated titania nanofluid with a constant F:Ti ratio of 0.1:1 (F: Ti) was utilized for treating the samples.

3.1.2. Morphological properties

The as-synthesized nanoparticles were characterized using transmission electron microscope imaging for evaluation of their morphological properties and calculation of their average particle size. The TEM images of silica and titania nanoparticles are shown in Fig. 3. According to this figure, both silica and titania nanoparticles have semi-spherical morphology with uniform particles. The average size of silica and titania nanoparticles according to TEM images was estimated at 51 nm and 55 nm, respectively. In addition, fluorinated silica and titania nanoparticles were also examined by transmission electron microscope imaging method to determine the size and morphology. The results are shown in Fig. 4, according to this figure, both nanoparticles have spherical morphology and are almost uniform in size. Notably, the average size of fluorinated silica and titania nanoparticles was calculated at about 200 nm and 300 nm, in order [32–35].

3.1.3. Size distribution

The DLS analysis was performed to estimate the size distribution of the as-prepared nanoparticles. The results are shown in Fig. 5. Regarding Fig. 5(a)(b), silica, and titania nanoparticles reveal a size distribution over 36–75 nm (mode size of 46.5 nm) and 32.8–680 nm (mode size of 47.3 nm), in turn, which is close to the results of TEM imaging method. Besides, the size of fluorinated silica as Fig. 5(c) and fluorinated titania nanoparticles as Fig. 5(d)

was found to be over 154–218 nm (mode size of 193 nm) and 245–310 nm (mode size of 305 nm), in turn [36].

3.1.4. Elemental composition and crystalline properties

The elemental composition of the as-prepared nanoparticles was investigated using EDX analysis as a reliable way. The results are shown in Fig. 6, as shown in this figure, in the EDX pattern of silica nanoparticles, the lines of O and Si can be observed as shown in Fig. 6(a) while in the EDX pattern of the fluorinated silica nanoparticles, the new line of F can be observed, revealing the successful coating of fluorine functionalities on the surface of nanoparticles as shown in Fig. 6(b). Regarding titania nanoparticles, the EDX pattern of unmodified nanoparticles showed only the lines of Ti and O, see Fig. 6(c) while after their modification with F groups, the new lines of Si and F are observable in the EDX pattern, revealing the successful coating of fluorinated silane on the surface of titania nanoparticles as Fig. 6(d). Moreover, SiO₂ nanoparticles have an amorphous structure with a broad band at 20°–30°, however, after its modification with fluorine functionalities, the broad peak was shifted to higher diffraction angles while the amorphous structure of SiO₂ was saved. Hence, it can be concluded that fluorine functionalities did not affect the crystalline structure of SiO₂. Besides, regarding the bare and fluorinated TiO₂, the characteristic peaks of TiO₂ structure related to the anatase phase while after its modification with fluorine functionalities, the second rutile phase was also observed in the XRD pattern [48].

3.1.5. Cost efficiency and scalability

Since the cost efficiency is one of the most important factors for practical applications of the nanofluids, the synthesis cost of fluorinated nanoparticles (e.g., fluorosilane usage) and scalability for field applications were assessed. The cost of materials used for the synthesis of fluorinated nanoparticles is summarized in Table 3, as can be seen, the fluorinated nanoparticles were synthesized from available materials at a low cost. Moreover, trace amounts of the fluorosilane which are diluted with a green abundant solvent, ethanol, were used for the synthesis of the fluorinated nanoparticles, making the method cost-effective from an economic point of view. Besides, comparing the traditional water-based nanofluid methods which need high-cost polymeric materials or surfactants in large amounts, this method only used small portions of hydrophobic agents for achieving the highly efficient nanofluids. Considering the cost-effectiveness of the synthesis method, this approach can be proposed in the field scale conditions.

3.1.6. Environmental risks of fluorinated system and disposal protocols

Fluorinated nanoparticles may pose environmental risks (e.g., bioaccumulation), hence, it is necessary to address the nanoparticle toxicity and disposal protocols. It is well-known that titania is considered a safe compound even for use as a food additive. However, the nanoparticles of titania are known as potential carcinogenic materials to humans (by inhalation). In contrast, from a safety point of view, silica nanoparticles are considered non-toxic materials. Moreover, although, the fluorinated titania nanoparticles are generally safe, there are some safety concerns about them for instance, their potential for accumulation in the human body [5]. However, fluorinated nanoparticles generally show good biocompatibility in industrial applications which is in demand in this work. Hence, considering some safety concerns, some disposal protocols including filtration and adsorption methods should be included in the industrial protocols involving the fluorinated nanoparticles [6].

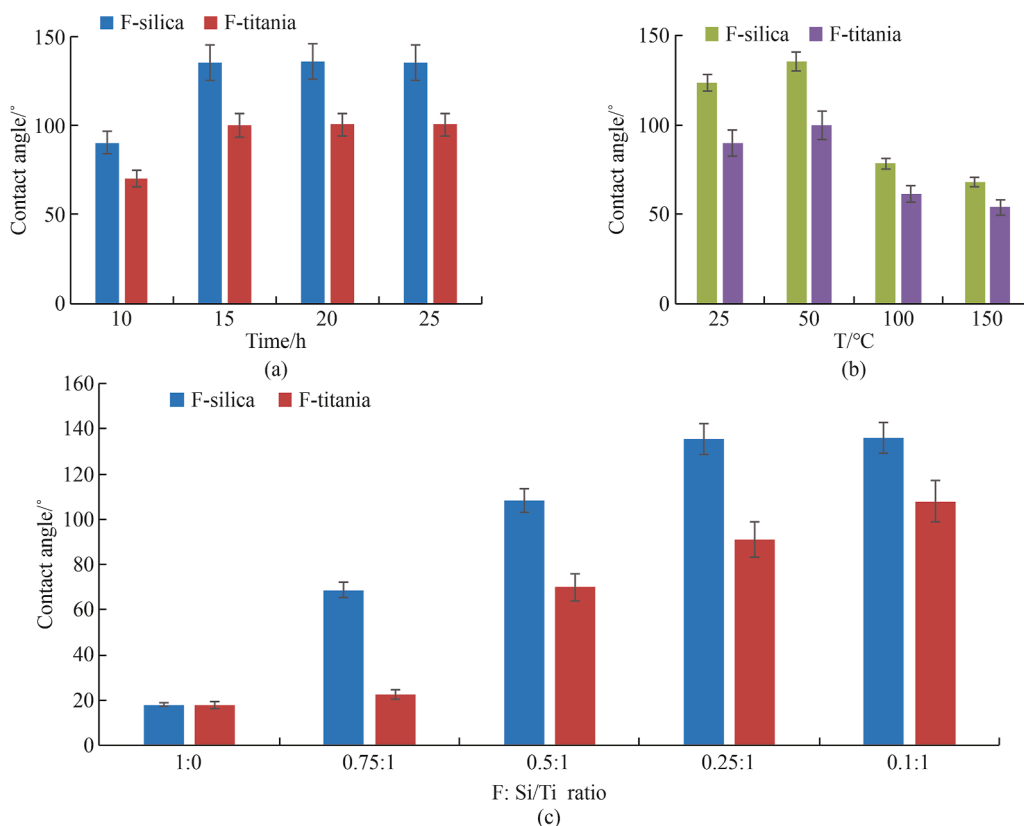


Fig. 2. Optimization of fluorination process of silica and titania nanoparticles, the effect of (a) time, (b) temperature, and (c) F: Si/Ti ratio.

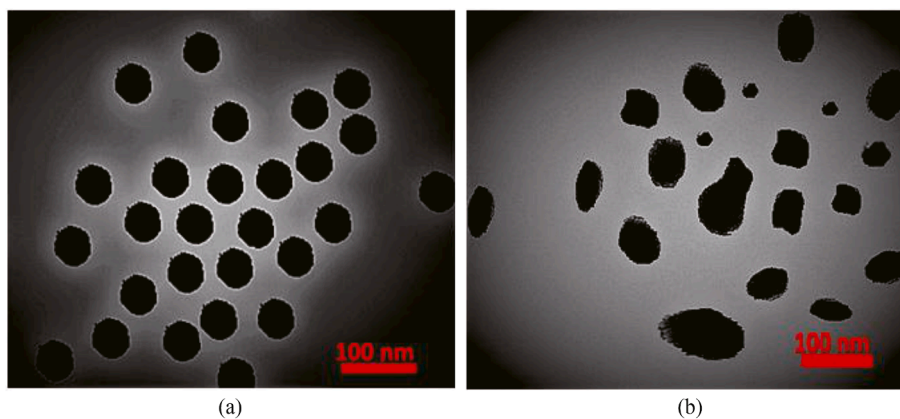


Fig. 3. TEM image of (a) titania nanoparticles; (b) silica nanoparticles.

3.2. Dispersion nanoparticles in methane

Based on the cloud point pressures all nanoparticles can be dispersed in methane at pressures ranging from 1800 to 2000 psi at reservoir temperature. Also, the nanoparticle dispersion was investigated for different nanoparticle concentrations. It illustrated that when the nanoparticle concentration increased, the dispersion process occurred at higher pressure. According to the cloud point pressures, the methane/nanoparticle solutions were in the single-phase state at reservoir conditions. Also, our current results have a good consistency with the literature [49]. Therefore, during the methane/nanoparticle recycling process, no nanoparticles come out from the solution. Also, during the wettability

alteration, the methane/nanoparticle solutions are used to investigate the effect of modified methane on the reservoir rock wettability.

3.3. Contact angle measurements

In this regard, both fluorinated silica and titania nanoparticles were utilized for preparing the methane/nanoparticle solutions and then the sample treatment was performed by soaking the carbonate substrates with methane/nanoparticle solutions. Afterward, the contact angles of gas condensate, methane/nanoparticle, water, and n-decane on the carbonated surfaces were measured before and after exposure to methane/nanoparticle solutions. The

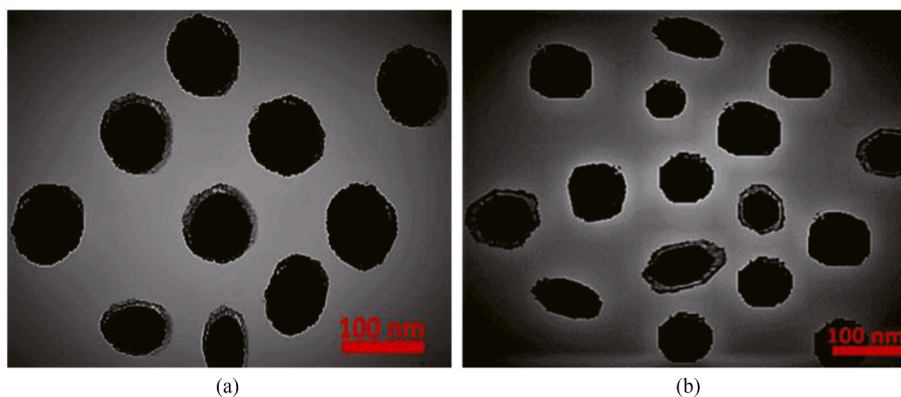


Fig. 4. TEM image of fluorinated silica nanoparticles (right) and fluorinated (a) titania nanoparticles; (b) fluorinated silica nanoparticles.

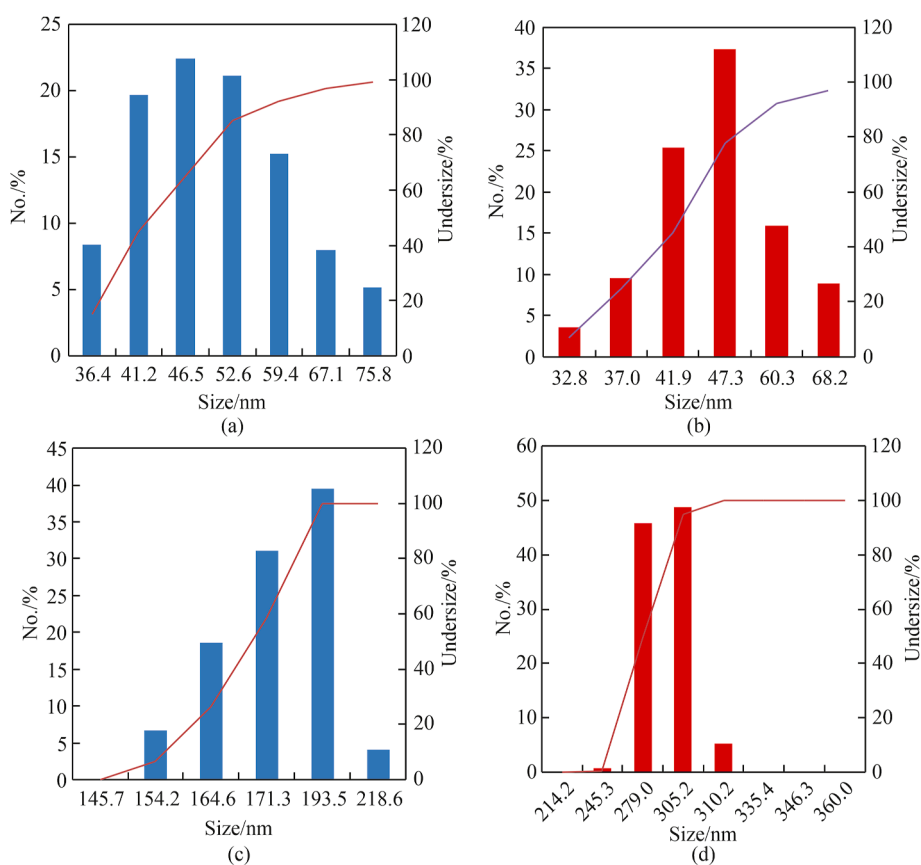


Fig. 5. DLS results of (a) silica nanoparticles; (b) titania nanoparticles; (c) fluorinated silica nanoparticles; (d) fluorinated titania nanoparticles.

n-decane was used as a traditional and common condensate simplified model for performing experiments. Besides, the concentrations and ratios of fluorinated nanoparticles were selected based on the one-factor optimization and experimental screening method for finding the best concentrations and ratios of fluorinated nanoparticles.

3.3.1. Evaluating the effect of methane/silica and methane/fluorinated silica solutions on contact angle

To evaluate the effect of the silica amount on the contact of gas condensate, water, and n-decane on the carbonated surfaces, their contact angle was measured before and after sample treatment

with methane/silica solutions. In this regard, the alter of the contact angles of n-decane, water, and condensate as a function of silica concentration was investigated. The results of this experiment are shown in Fig. 7 after soaking the carbonate substrates with methane/nanoparticle solutions. The results showed that the initial contact angle for both n-decane and gas condensate was 12° for all samples while regarding water, this value was found to be about 33°. The low value of the contact angles of n-decane and gas condensate before treatment with methane/nanoparticle solutions indicates the strong liquid wetting (oil wetting) before the treatment process. However, after treating the samples with methane/silica solution, the corresponding value of water

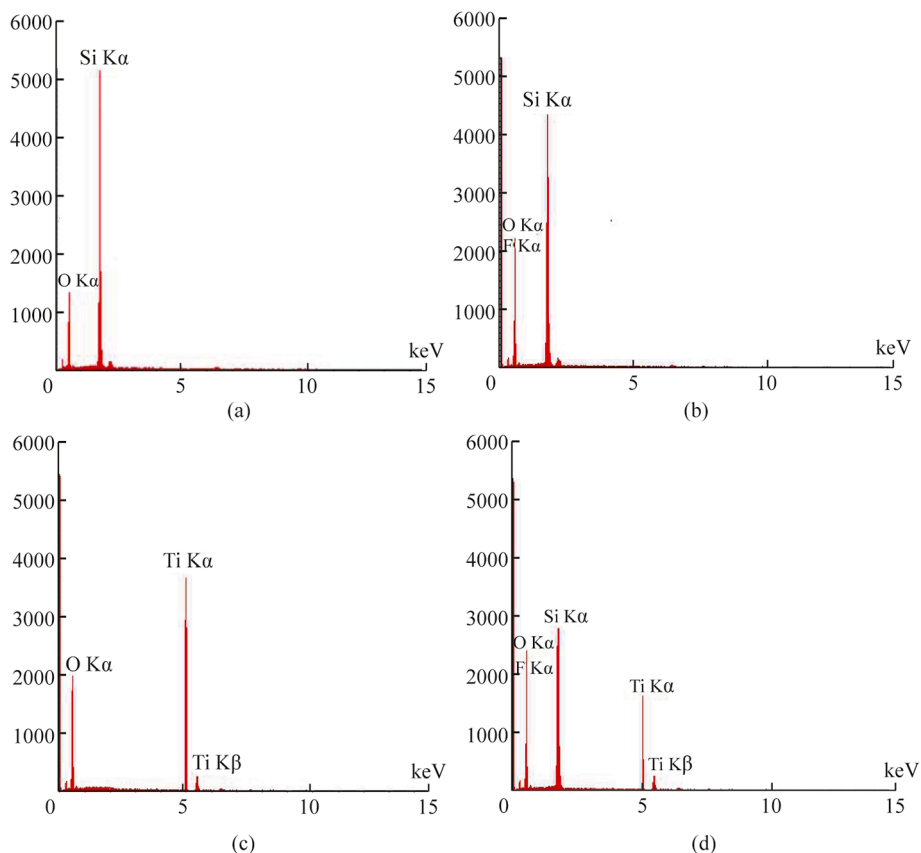


Fig. 6. EDX pattern of (a) silica nanoparticles, (b) fluorinated silica nanoparticles, (c) titania nanoparticles, and (d) fluorinated titania nanoparticles.

Table 3
Cost of material used in preparation of the fluorinated silica/titania nanoparticles.

Material	Amount	Price (USD)
Ethanol	1.0 L	73.5
Titanium(IV) isopropoxide	100.0 mL	49.5
Tetraethyl orthogonal silicate	0.5 L	42.0
Fluorinated silane	5.0 g	200

increased and reached its maximum value (78.5°) at a concentration of 0.075 w/w% of the silica nanofluid while the contact angles of n-decane and gas condensate did not change and remained zero after treatment with silica nanofluid containing nanoparticles.

The bare silica nanoparticles are not effective for the wettability alteration to gas-wet and increasing the gas condensate recovery, Fig. 7. To overcome these difficulties, silica nanoparticles were initially modified with fluorine functional groups as the active agent to prepare the fluorinated silica nanoparticles with different F: Si ratios. Thereafter, the methane/fluorinated silica solutions were used to treat the above-mentioned samples. The contact angles of water, n-decane, and gas condensate were measured after the treatment with them. The contact angles of different samples after treatment with methane/fluorinated silica solutions with different F: Si ratios are shown in Table 4. The results revealed that at a constant nanoparticle concentration, by increasing the fluorine content, the contact angles of all samples were increased.

To explore more precisely, the plot of the variation of the contact angle by variation of the F: Si ratio of the methane/fluorinated silica solutions was constructed. The plots of contact angle of water, n-decane, and condensate as a function of the F:Si ratio of

the prepared fluorinated silica nanofluid are shown in Fig. 8(a). Also, as can be seen in Fig. 8(a), by increasing the fluorine content of the nanofluid, the contact angles for all samples increase and reach their maximum values in 0.075 W/W fluorinated silica nanofluids prepared by fluorinated silica nanoparticles with an F: Si ratio of 0.25: 1.00. Based on Fig. 8(b), the contact angles of water, n-decane and gas condensate altered from 78.5° to 146.3°, from 12° to 135.5° and from 12° to 121°, respectively. The change in the contact angles can be explained by the adsorption of methane/nanoparticles, which brings the wettability of the surface from oil-wet to intermediate gas-wet. However, the contact angle variations were found to vary from sample to sample, and these differences may be related to the kinetics of the reactions. Due to the higher methane/nanoparticles adsorption, the contact angles of the gas condensate and the n-decane also increased, confirming that the surface wettability was altered to oleophobic or hydrophobic for all samples.

There are no reports in the literature on the case of the dispersion of nanoparticles in methane to investigate the wettability alteration in gas condensate reservoirs. However, in the case of water bas nanoparticle, Mousavi et al. [27] prepared the fluorinated silica nanoparticles and used them to alter the rock wettability to gas-wet in the gas condensate reservoirs. They synthesized the fluorinated silica nanoparticles (mean size of about 80 nm) and utilized them to alter limestone core wettability to intermediate gas-wet state from highly liquid-wet. The results of their research revealed that water and n-decane contact angles for the rock samples were found to be 147° and 61° for water and n-decane on the core surface, in order. Hence, they concluded that before treatment with fluorinated silica nanoparticles nanofluids, the rock surface cannot support the formation of water or n-

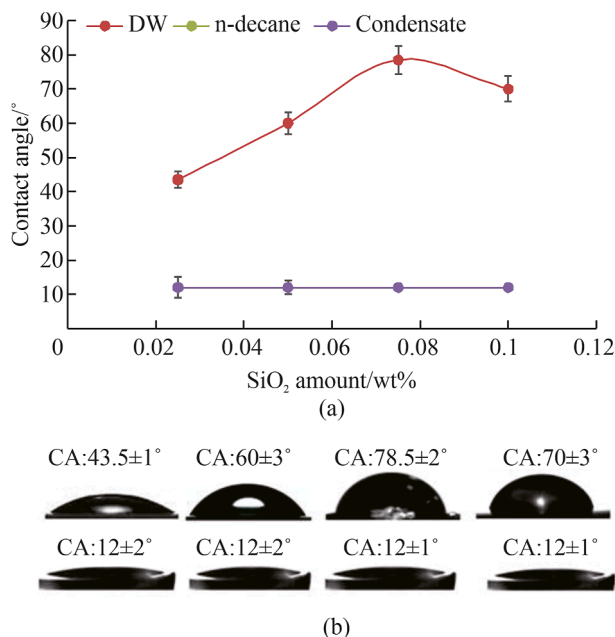


Fig. 7. The effect of silica amount on the contact angles of water, n-decane, and condensate upon sample treatment with methane/silica solutions: (a) plot of contact angle as a function of silica amount, (b) corresponding contact angle images.

decane droplets [27]. In another study, Binshan et al. [50] synthesized and characterized the polysilicon-based nanofluids with different sizes over 10–500 nm, thereafter they used the nanofluids for changing the wettability of porous media in the oil field. According to the discussion and the results obtained in the current study, the methane/fluorinated silica solutions have successfully changed the wettability of gas condensate reservoirs to intermediate gas-wet. However, the current approach can be an alternative method compared to the common water-based nanoparticles technique due to the improvement of gas condensate recovery.

3.3.2. Investigation of the effect of methane/titania and methane/fluorinated titania solutions on contact angle

The rock samples were treated by soaking the methane/titania solutions and the contact angles were measured after their treatment. In this regard, the change of the contact angles of n-decane, water, and condensate as a function of titania concentration was investigated to evaluate the effect of the titania amount on the contact angles of different samples. The results of this experiment are shown in Fig. 9(a). Besides, the optical image of the contact angle measurements is presented in Fig. 9(b). According to this figure, after treating the samples with methane/titania solutions, the corresponding values for water contact angle increased and reached their maximum value (61.5°) when 0.1 w/w% of nanofluid was used for sample treatment. While the contact angles of n-decane and gas condensate did not change and remained equal to 21° after treatment with methane/titania solutions. The

Table 4
Contact angles of water, n-decane, and gas condensate after sample treatment with Methane/fluorinated silica solutions.

Treated rock sample by methane/fluorinated silica solutions					
Scenarios	Contact angle (°)				
SiO ₂ : Fluor group ratio	1:0	0.75:1	0.5:1	0.25:1	0.1:1
Water	78.5	90.4	123.7	146.3	149.2
n-decane	12	68.6	108.4	135.5	136
Condensate	12	50.2	97.5	121	122.5

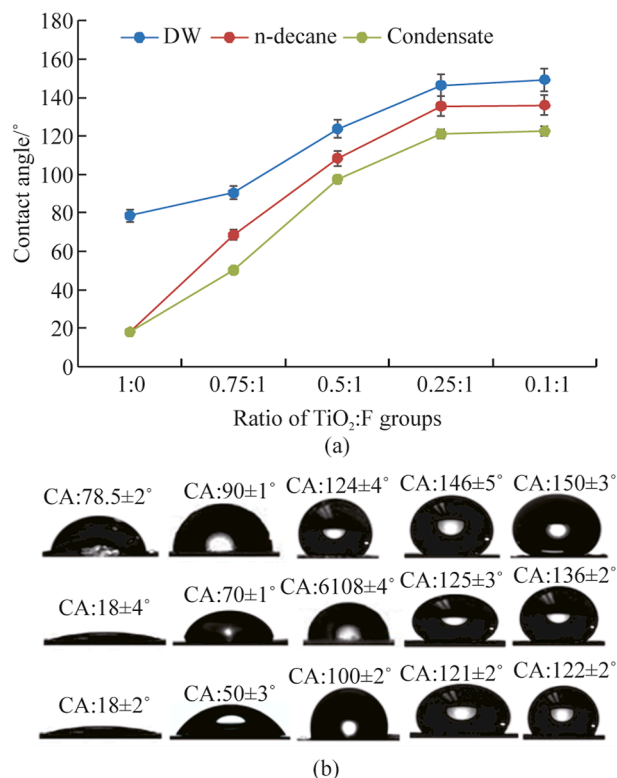


Fig. 8. The effect of F: Si ratio on the contact angles of water, n-decane, and condensate upon sample treatment with methane/fluorinated silica solutions: (a) plot of contact angle as a function of silica amount; (b) corresponding contact angle images.

unmodified titania nanofluids are not effective for wettability alteration to gas-wet and increasing the gas condensate recovery. To overcome these difficulties, titania nanoparticles were initially modified with fluorine functional groups as the active agents to prepare the fluorinated titania nanoparticles with different F: Ti ratios. Thereafter, the fluorinated titania nanoparticles were used to prepare the nanofluids and were then applied for sample treatment by methane/fluorinated titania solutions. The results revealed that at a constant nanoparticle concentration by increasing the fluorine content of the nanofluid, the contact angles of all samples were increased functional groups (Table 5). To explore more precisely, the plot of the variation of the contact angle by variation of the F: Ti ratio of the as-prepared fluorinated titania nanofluid was constructed. The plots of the contact angles of water, n-decane, and condensate as a function of the F:Ti ratio of the as-prepared fluorinated titania nanofluid are shown in Fig. 10 (a). Besides, the optical image of the contact angle measurements is presented in Fig. 10(b). As can be seen in this figure, increasing the fluorine content of the nanofluid leads to increasing the contact angles of all samples. The contact angles meet their maximum values when 0.1 w/w% of fluorinated titania nanofluid with a

constant F:Ti ratio of 0.1:1 was utilized for treating the samples. The variations of the contact angles can be explained by methane/nanoparticles adsorption which leads to wettability alteration from oil wettability to intermediate gas wettability.

Notably, in case of water-based nanoparticles approach, Moghaddam et al. [47] investigated the effect of the different nanofluids including zirconium dioxide, magnesium oxide (MgO), calcium carbonate (CaCO₃), silicon dioxide (SiO₂), titanium dioxide (TiO₂), cerium oxide (CeO₂), aluminum oxide (Al₂O₃), and carbon nanotube (CNT) on the alteration of the wettability of carbonate rocks to gas-wet state from the liquid-wet state. They performed a series of experiments for the evaluation of contact angle to screen the effect of different nanoparticles on the wettability alteration. Afterward, they investigated the performances of the nanofluids on the alteration of the wettability of carbonate rocks to a gas-wet state using the spontaneous imbibition and core flooding experiments, revealing the active roles of CaCO₃ and SiO₂ nanoparticles for enhancing oil recovery. Considering the above explanation, it can be deduced that the results of the current work are in line with the results of the previously reported works, but there are fewer technical challenges compared to the water-based nanoparticles approach.

3.3.3. Effect of operating temperature on contact angle

Initially, the effect of operating temperature on the contact angles after treatment with the methane/fluorinated silica solutions was evaluated by measuring the contact angles of n-decane and condensate as a function of operating temperature. The results are shown in Fig. 11, as can be seen in this figure, the contact angles of n-decane were increased from 135.5° to 153° by increasing the operating temperature from 25 °C to 70 °C respectively. Besides, the contact angles of condensate were increased from 121° to 142° by increasing the operating temperature from 25 to 70 °C. These results revealed that increasing the operating temperature has a

positive effect on the wettability alteration to gas-wet upon applying the methane/fluorinated silica solutions, resulting in a significant increase in the gas condensate recovery. The effect of operating temperature on the wettability alteration to gas-wet after treatment with the methane/fluorinated titania solutions was checked by calculating the contact angles of n-decane and condensate as a function of the operating temperature. The results of this investigation are shown in Fig. 12(a)–(b), as can be seen in this figure, the contact angles of n-decane were increased by increasing the operating temperature; from 108° at 25 °C to 127° at 70 °C. Besides, the contact angles of condensate were increased from 100.5° to 120° by increasing the operating temperature from 25 to 70 °C. These results revealed that increasing the operating temperature has a positive effect on the wettability alteration to gas-wet utilizing methane/fluorinated titania solutions, leading to a characteristic increase in the gas condensate recovery. Recently authors of a high-impact published work investigated the effect of operating temperature on the contact angles of the gas condensate and then reported that the contact angle between gas condensate and the carbonate rock surface after their treatment with the nanofluids prepared by the Fe₃O₄-PVA/DW nanoparticles altered from the initial value of 25° at 25 °C to the final value of 38° at 80 °C in the presence of air [29]. Additionally, they reported that the contact angles of the water altered from its initial value of 104° at 25 °C to 125° at 80 °C after treatment of the rock surface with the nanofluids prepared by the Fe₃O₄-PVA/DW nanoparticles [29]. It must be mentioned that the results of this investigation about the effect of operating temperature on the contact angles of n-decane and condensate are in line with the results of the reported works in the literature.

To obtain a better view of the applicability of the methane/nanoparticles solutions toward wettability alteration to gas-wet and increasing the gas condensate recovery, the methane/fluorinated silica solutions were compared to the methane/fluorinated titania solutions. In this regard, the variation of the contact angles of n-decane, and gas condensate upon treatment with both solutions were measured and used as a reliable index for understanding the ability of the methane/nanoparticles solutions for wettability alteration. The results are shown in Fig. 13(a)–(b). As can be seen in the figure, upon sample treatment with the methane/fluorinated silica solutions, the increase in the contact angles of n-decane was found to be 1.25-fold higher than that of the methane/fluorinated titania case. Besides, the contact angles of the condensate after treatment with methane/fluorinated silica solutions were estimated about 1.2 orders higher than that of the methane/fluorinated titania solutions. According to the results of this research, it seems that the methane/fluorinated silica solutions act better than the other cases regarding the wettability alteration to a gas-wet state and can be more efficient for increasing the gas condensate recovery. The enhancement of the gas recovery using silica nanoparticles compared to titania nanoparticles can be attributed to the porous structure of silica, obtaining a large surface area, improving the availability of surface area for more efficient interactions with condensate, higher surface acidity and self-cleaning properties of the silica nanoparticles compared of the titania nanoparticles. It is important to note that silica nanoparticles are safer than titania nanoparticles and show lower degrees of cytotoxicity which is one of their important advantages from a green chemistry point of view. Hence, considering the above-mentioned facts, it can be concluded that the methane/fluorinated silica solutions are more appropriate for the wettability alteration to a gas-wet state. However, it is well-known that if SiO₂ and TiO₂ were used simultaneously in a mixture, a SiO₂-TiO₂ interface can form which improves the availability of the surface area and provides a more suitable porous structure which

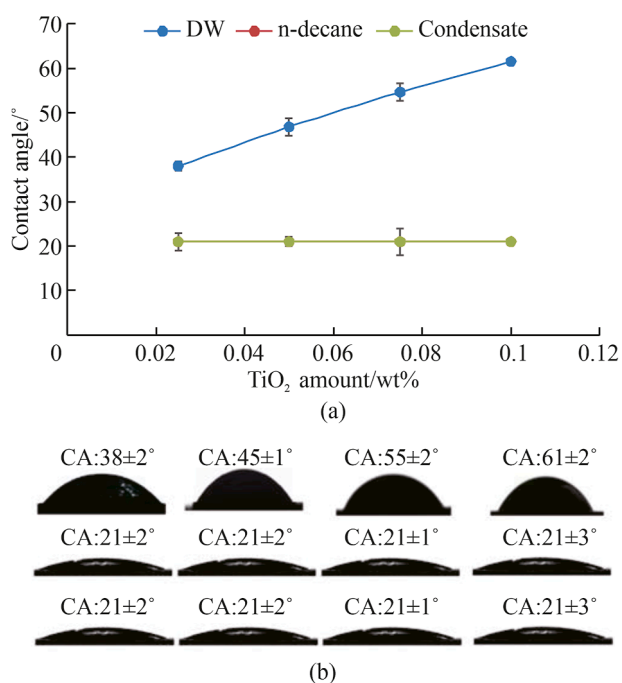


Fig. 9. The effect of titania amount on the contact angles of water, n-decane, and condensate upon sample treatment with methane/titania solutions: (a) plot of contact angle as a function of titania amount, (b) corresponding contact angle images.

Table 5
Contact angles of n-decane and gas condensate after sample treatment with Methane/fluorinated titania solutions.

Treated rock sample by methane/fluorinated titania solutions					
Scenarios	Contact angle (°)				
TiO ₂ : fluor group ratio	1:0	0.75:1	0.5:1	0.25:1	0.1:1
n-decane	21	22.5	70	91	108
Condensate	21	18.3	68	83.8	100.5

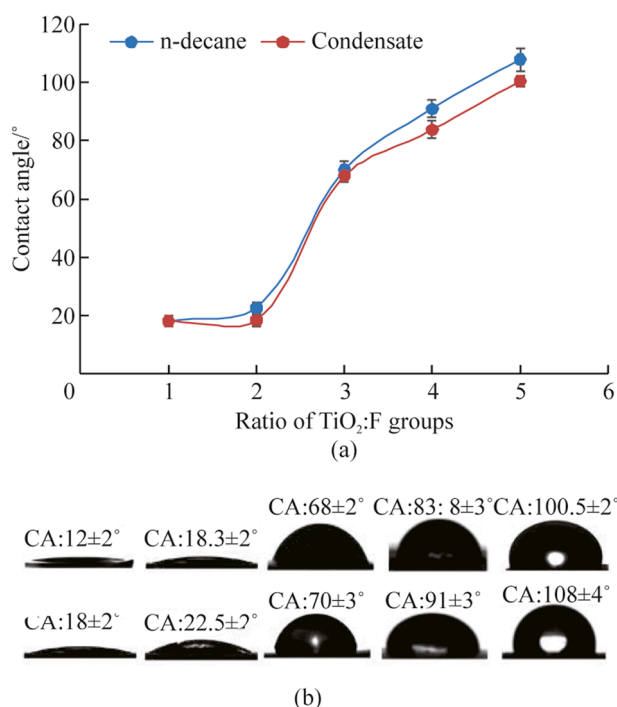


Fig. 10. The effect of F: Si ratio on the contact angles of n-decane, and condensate upon sample treatment with methane/fluorinated titania solutions: (a) plot of contact angle as a function of fluorinated titania, (b) corresponding contact angle images.

may help to enhance the efficiency of gas condensate reservoirs. Hence, it is proposed to use a fluorinated silica-titania interface nanofluid for the wettability alteration to a gas-friendly state.

3.4. Long-term stability of the system

The long-term stability of the fluorinated nanoparticles under cyclic pressure/temperature fluctuations was tested by investigation of the stability of the contact angles of both gas condensates treated by fluorinated silica/titania methane/nanoparticles system over long reaction times over 60 h (aging assessments). The results are shown in Fig. 14, as can be seen from this figure, the tolerance of the contact angle of the treated samples with both fluorinated silica/titania nanoparticles over a long time of 60 h is very negligible, revealing long-term stability (colloidal stability) of the fluorinated silica/titania methane/nanoparticles system. Also, the absolute values of zeta potential were 48 and 56 mV for methane/fluorinated silica and methane/fluorinated titania solutions respectively at 70 °C and 2000 psi. Generally, a suspension with a measured zeta-potential above 30 mV (absolute value) is considered to have good stability [51]. Moreover, the long-term stability of the fluorinated nanoparticles results illustrated that both methods had a good consistency.

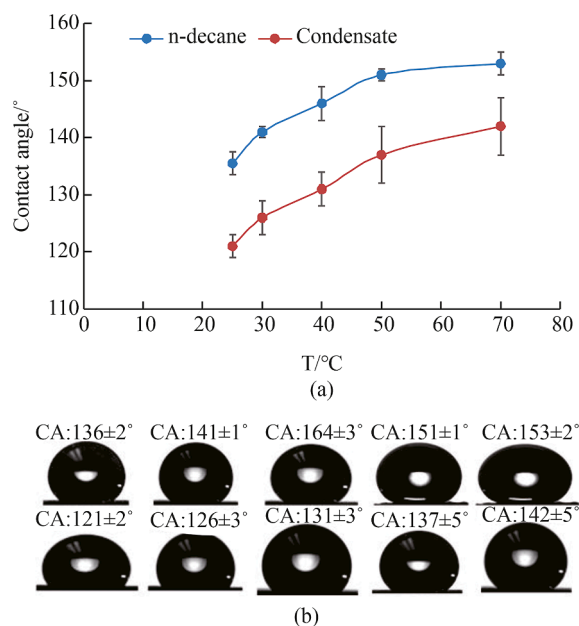


Fig. 11. The effect of operating temperature on the contact angles of n-decane and condensate upon sample treatment with methane/fluorinated silica solutions: (a) plot of contact angle as a function of silica amount; (b) corresponding contact angle images.

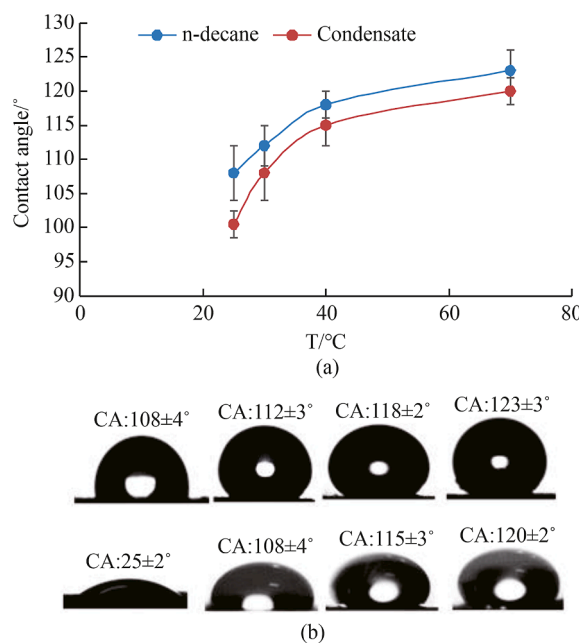


Fig. 12. The effect of operating temperature on the contact angles of n-decane and condensate upon sample treatment with methane/fluorinated titania solutions: (a) plot of contact angle as a function of titania amount; (b) corresponding contact angle images.

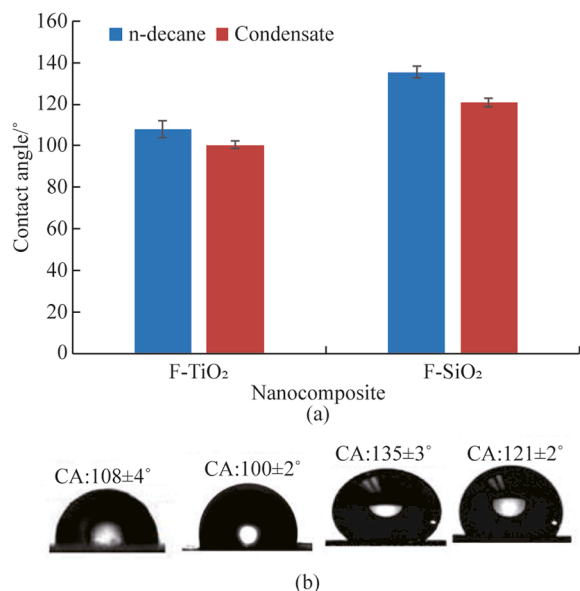


Fig. 13. Comparing the results of methane/fluorinated silica and methane/fluorinated titania solutions: (a) histogram for comparing F-TiO₂ and F-SiO₂; (b) corresponding contact angle images.

3.5. Improvement of gas condensate recovery during gas recycling

Fig. 15 shows the pressure gradient and the recovery factor as a function of the pore volume of methane/nanoparticles injected during gas recycling in gas condensate reservoirs before and after sample treatment with methane/nanoparticles solutions. For this aim, the pressure gradient was recorded, the pressure gradient was increased, reached its maximum value, and then it was decreased by increasing the PV, following a downward trend to reach a final steady state condition, as can be seen in Fig. 15. The decrease of the pressure drop can be assigned to the fluid generation and can be proved by the single-phase flow through the porous medium. Before the sample treatment with the methane/nanoparticles, the experimental investigations exhibited that the pressure gradient reached its maximum value of about 193 psi at 0.3 PV, and then a significant decrease can be observed in the plot which leads to a constant value of 120 psi at 1.4 PV.

After sample treatment with methane/nanoparticles solutions, the pressure gradient reached its maximum value of 153 psi at 0.2 PV, followed by a decreasing trend to reach a final steady-state condition with a constant value of 75 psi at 1.4 PV. It should be mentioned that the ratios of pressure drop after and before the wettability alteration were found to be as high as 1.6, revealing that the sample treatment with the methane/nanoparticles solutions reduced the pressure drop of steady-state two-phase flow by about 60%. This reduction of the pressure drop can be related to the ability of methane/fluorinated nanoparticles solutions to improve the wettability of surfaces and consequently produce more gas and condensate. In fact, methane/nanoparticles adsorption occurred on the rock surface via forming van der Waals bonds as well as by electrostatic interactions, which eventually help to separate the trapped liquid from the surface. On the other hand, the polar parts of the surface interact with the polar groups on the fluorinated nanofluids, leading to significant improvement of the recovery factor after sample treatment with methane/nanoparticle solutions [52]. To investigate this hypothesis, the recovery factor was measured before and after sample treatment by methane/

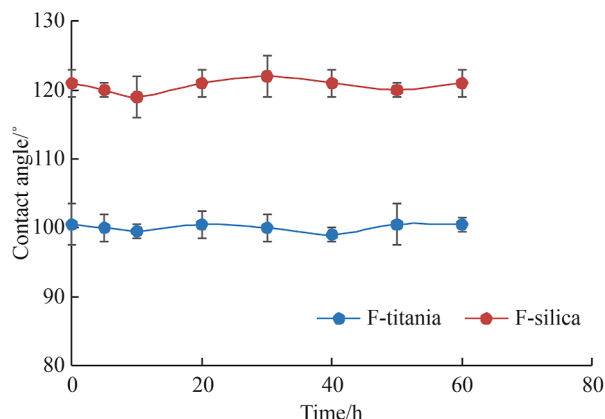


Fig. 14. The stability of the contact angles of both gas condensate treated by fluorinated silica/titania methane/nanoparticles system over long reaction times over 60 h (aging assessments).

nanoparticle solutions. The results shown in Fig. 15 indicated that the recovery factor before sample treatment has a maximum value of about 55%. In contrast, upon sample treatment, the recovery factor increases significantly and reaches its maximum value of about 76%, indicating that by the sample treatment with the methane/nanoparticle solutions, the wettability alters from oil-wet to gas-wet resulting in an improvement of the productivity of gas reservoirs by 21% (Fig. 15).

Moreover, the core flooding experiments were also conducted using heterogeneous (fractured) core plugs to assess the applicability of this method in actual reservoirs. The results revealed a recovery factor of about 81.3% for the core treated with fluorinated methane/nanoparticle system which was found to be 5.3 % higher than the recovery factor of the homogeneous carbonate cores which can be attributed to the changing the chemical interactions between gas and rock surface in the heterogeneous (fractured) core plugs. Due to the good agreement of the recovery factor of the heterogeneous (fractured) core plugs treated with fluorinated methane/nanoparticle system with that of the homogeneous carbonate cores, it can be concluded that the fluorinated methane/nanoparticle system can be practically applied for boosting the gas recovery from the actual reservoirs.

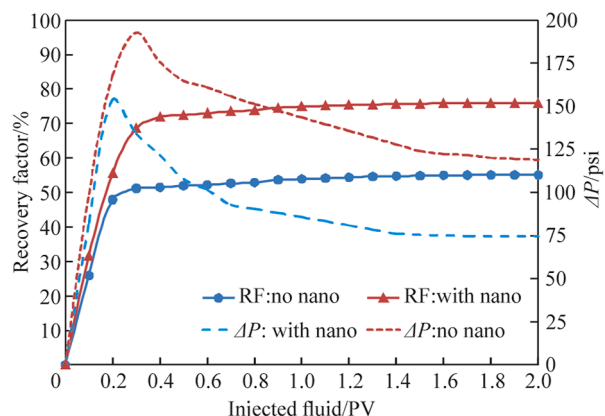


Fig. 15. The effect of sample treatment with the methane/nanoparticles solutions on the condensate recovery factor and pressure gradient during the gas recycling process.

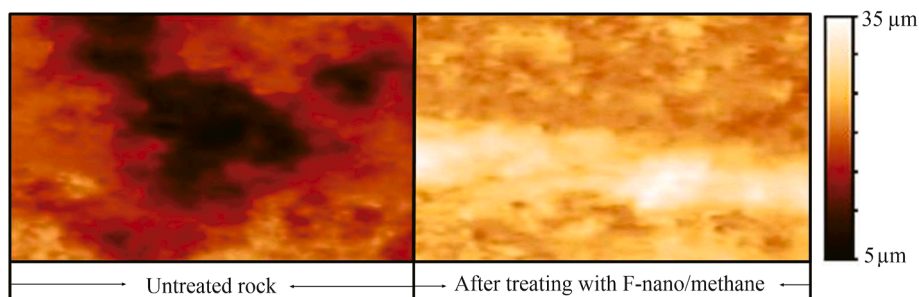


Fig. 16. The SP micrographs for the as-prepared untreated and treated core substrate using the fluorinated titania/methane system.

3.6. Mechanism of adsorption and wettability alternation

To assess the mechanisms of the wettability alternation, the SEM imaging method and SP topography were utilized for probing the adsorption of the nanoparticles on the surface of the carbonate rocks. The micro-scale visualization was assessed using recording the SP micrographs for the as-prepared untreated and treated core substrate using the fluorinated methane/titania system. The SP topography image for both untreated and treated core plugs is shown in Fig. 16. As it is evident from this figure, the core surface provides a primary roughness inherently and the original core plug reveals a superoleophilic and superhydrophilic nature with a contact angle of water of 12° and a same contact angle of n-decane. This may correspond to the presence of different valleys throughout the roughness, in contrast upon treating the rock samples with the fluorinated methane/nanoparticle system, the fluorinated nanoparticle can be adsorbed on the core surface via different interactions such as wander Vales or hydrogen binding for developing a new roughness on the surface, resulting a dual-roughened surface of micro-scaled core asperities and a nanotextured layer which make the rock capable of arising its superhydrophobicity thanks to the presence of a lot of methane gas get trapped into the cavities between the protrusions. These results

emphasize the potential of the current new approach, through the dispersion of fluorinated nanoparticles in gas; to improve gas condensate recovery during gas recycling, especially in low-permeability carbonate reservoirs.

Besides, the SEM images of untreated cores and the cores treated with fluorinated methane/nanoparticle solution were recorded (Fig. 17). As can be seen from this figure, in comparison with the surface of the untreated native carbonate core plug, the surface morphology of the carbonate core aged in the fluorinated methane/nanoparticle solution reveals the formation of sphere-like nanotextures on the microstructure core surface after the treatment. Hence, it can be concluded that the wettability alternation to gas-wet is a result of roughness creation on surface rock by the nanoparticles and the reduction of surface free energy by the fluorine groups presented on the surface of the fluorinated nanoparticles, as previously reported in the literature [53]. It should be mentioned that the silica nanoparticles can increase the surface roughness of the core plugs which consequently leads to increasing the area fraction of air and decreasing the area fraction of liquid, as reported [54]. Besides, the fluorine groups on the surface of the fluorinated nanoparticles can reduce the free energy [55–57], leading to liquid repellency of the surface, or more precisely causing the wettability alteration by creating roughness and

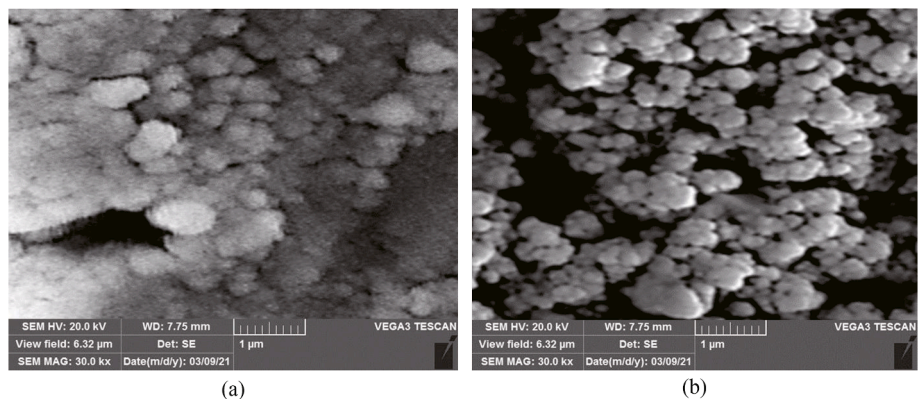


Fig. 17. The SEM images of (a) untreated cores; (b) cores treated with fluorinated nanoparticle/methane nanofluid.

Table 6
Comparing the fluorinated methane/nanoparticles system with the traditional water-based nanofluids for improving gas recovery.

Nanofluid system	Enhancement of gas recovery (%)	Core samples	Ref.
Fluorinated SiO ₂ /water	30%	Limestone core	[27]
Fe ₃ O ₄ - PVA/DW/water	34%	Carbonate rocks	[29]
Fe ₃ O ₄ - HAp/DW/water	32%	Carbonate rocks	[29]
CaCO ₃ and SiO ₂ /water	8%–9%	Carbonate rocks	[47]
Methane/nanoparticles	21%	Carbonate rocks	Current work

surface free energy reduction thanks to the presence of fluorine groups such as $-CF_2$ in the structure and coated on nanoparticles, as previously reported [53,57].

3.7. Potential practical hurdles

Generally, the methods developed for boosting the condensate recovery from gas reservoirs may be affected and challenged with some practical hurdles for example nanoparticle retention, and injectivity loss, and in the case of this system, methane emissions may also be considerable. The injectivity reduction [58], especially in tight and deep gas formations can be challenging and may contribute to near-wellbore damage, however, there are several techniques for instance, abrasive jet perforations, acid squeeze treatment conveyed by coiled tubing, and bullhead acid spearhead stage at lowest pumping rate in addressing low injectivity in tight gas wells to minimize delays in operations and associated risks [58]. Besides, the potential methane emissions can also be addressed by recycling the methane and minimizing its ratio in the nanofluid composition. Moreover, regarding nanoparticle retention, it was found that several methods including surface modification, utilizing intelligent materials, and applying optimized injection techniques can be used as model mitigation strategies for solving the challenges contributed to nanoparticle retention [59].

In addition, our current study were compared with the water-based traditional methods in terms of condensate recovery factor which has been used the carbonate reservoir rocks. The results are shown in Table 6. As can be seen in this table, in some cases the condensate recovery factor is higher than compared to our current study. It is worth mentioning that, during the water-soluble chemicals results, there are some technical challenges for its application during the gas recycling in the field scale. For example, the producing wells must be shut-in for chemical injection. Each shut-in time needs to be long enough to perform the surface rock treatment. Also, after well treatment, the early produced fluid must be transported away from the well site. Moreover, a large amount of brine is needed to prepare the nanofluid. Therefore, it increases the economic costs. Furthermore, there is a new alternative method to wettability alteration of gas condensate reservoirs during gas recycling process via gas-soluble chemical such as nanoparticles which can reduce the technical challenges. Hence, it can be concluded that in this study, a permanent pathway increases the gas condensate recovery by using the methane/fluorinated nanoparticles scenarios as a new alternative to the water-based nanofluids.

4. Conclusions

In this contribution, experimental evaluation of wettability alteration to gas-wet for increasing the gas condensate recovery utilizing fluorinated silica and fluorinated titania nanoparticles was performed. In this regard, the fluorinated silica and titania nanoparticles were synthesized and then characterized by DLS, EDX, and TEM imaging methods. Afterward, the methane/nanoparticles single phase solutions were prepared by measurement of cloud point pressures for wettability alteration and gas recycling experiments. The contact angles of n-decane and gas condensate changed from about 12° to 135.5° and 121° , in order, after treatment with methane/fluorinated silica solutions. Besides, after treatment with solutions containing methane/fluorinated titania, the contact angles of n-decane and gas condensate were found to be about 108° and 100.5° , respectively. However, treatment with bare methane/titania and methane/silica solutions did not affect the contact angles of gas condensate. The ratio of pressure drop after and before wettability alteration was estimated as about 1.6,

revealing that upon the pressure drop of steady-state two-phase flow developed process has reduced by about 60%. The recovery factor before treatment was found to have a maximum value of 55% which enhanced to 76% after treatment with methane/nanoparticles solutions, exhibiting that the alteration of the wettability from oil-wet to intermediate gas-wet leads to an increase in the efficiency of the gas condensate recovery by 21%. However, the wettability alteration of the gas condensate reservoirs to gas-wet via gas-soluble chemicals can be one of the permanent promising approaches to enhance condensate recovery.

CRediT authorship contribution statement

Naser Namdari Garaghani: Methodology, Writing – original draft, Data curation, Investigation, Validation, Formal analysis, Writing – review & editing, Conceptualization. **Asghar Gandomkar:** Visualization, Software, Data curation, Formal analysis, Methodology, Funding acquisition, Validation, Resources, Supervision, Project administration, Investigation, Conceptualization, Writing – review & editing, Writing – original draft. **Amin Azdarpour:** Writing – review & editing, Data curation, Supervision, Conceptualization, Methodology, Writing – original draft, Investigation.

Declaration of competing interest

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.

References

- [1] L. Fan, B.W. Harris, A. Jamaluddin, J. Kamath, R. Mott, G.A. Pope, ..., C. H. Whitson, Understanding gas-condensate reservoirs, *Oilfield Rev.* 17 (4) (2005) 14–27.
- [2] J. Kamath, Deliverability of gas-condensate reservoirs—field experiences and prediction techniques, *J. Petrol. Technol.* 59 (4) (2007) 94–99.
- [3] W. Lei, D. Chen, Q. Wang, Combined use of petroleum inclusion analysis, PVT simulation, and basin modeling for reconstruction of deep fluid phase evolution in condensate gas reservoirs, *Mar. Petrol. Geol.* 171 (2025) 107210.
- [4] J. Kamath, Deliverability of gas-condensate reservoirs—field experiences and prediction techniques, *J. Petrol. Technol.* 59 (4) (2007) 94–99.
- [5] A. Naghizadeh, R. Azin, S. Osfouri, R. Fatehi, Wettability alteration of calcite and dolomite carbonates using silica nanoparticles coated with fluorine groups, *J. Petrol. Sci. Eng.* 188 (2020) 106915.
- [6] F. Kazemi, A. Khlyupin, R. Azin, S. Osfouri, A. Khosravi, M. Sedaghat, ..., M. V. Karsanina, Wettability alteration in gas condensate reservoirs: a critical review of the opportunities and challenges, *Energy Fuels* 38 (3) (2024) 1539–1565.
- [7] X. Meng, Z. Meng, J. Ma, T. Wang, Performance evaluation of CO₂ huff-n-puff gas injection in shale gas condensate reservoirs, *Energies* 12 (1) (2018) 42.
- [8] M. Mohammed, T. Babadagli, Wettability alteration: a comprehensive review of materials/methods and testing the selected ones on heavy-oil containing oil-wet systems, *Adv. Colloid Interface Sci.* 220 (2015) 54–77.
- [9] D.B. Dorhjie, T. Aminev, K. Maerle, Impact of depletion rate on the thermodynamics of gas condensates: experimental insights and analysis, *Gas Sci. Eng.* 134 (2025) 205534.
- [10] G.R. Karandish, M.R. Rahimpour, S. Sharifzadeh, A.A. Dadkhah, Wettability alteration in gas-condensate carbonate reservoir using anionic fluorinated treatment, *Chem. Eng. Res. Des.* 93 (2015) 554–564.
- [11] M. Fahes, A. Firoozabadi, Wettability alteration to intermediate gas-wetting in gas-condensate reservoirs at high temperatures, *SPE J.* 12 (4) (2007) 397–407.
- [12] A. Seethepalli, B. Adibhatla, K.K. Mohanty, Wettability alteration during surfactant flooding of carbonate reservoirs, in: *SPE Improved Oil Recovery Conference?*, SPE, 2004. SPE-89423.
- [13] J. Zong, Ch Zhang, X. Yan, Synthesis and evaluation of poly (imidazole olefin-co-olefin-octadecyl maleate) as flow improvers for waxy gas condensate, *Colloids Surf. A Physicochem. Eng. Asp.* 715 (2025) 136662.
- [14] X. Wei, K. Liu, X. Ding, Evolution of the Dibe condensate gas reservoirs in the northern Kuqa Foreland Basin, western China: insight for hydrocarbon in-reservoir alteration, *Mar. Petrol. Geol.* 174 (2025) 107306.
- [15] A. Hosseinzadegan, H. Mahdiyar, A. Raouf, J. Qajar, The pore-network modeling of gas-condensate flow: elucidating the effect of pore morphology,

- wettability, interfacial tension, and flow rate, *Geoenergy Sci. Eng.* 229 (2023) 211937.
- [16] M.M. Baghmolaei, Z. Sakhaei, S. Zendejboudi, Modeling of well productivity enhancement in a gas-condensate reservoir through wettability alteration: a comparison between smart optimization strategies, *J. Nat. Gas Sci. Eng.* 94 (2021) 104059.
- [17] O. Ajagbe, M. Fahes, Establishing screening criteria for field application of wettability alteration in gas-condensate reservoirs, *J. Petrol. Sci. Eng.* 193 (2020) 107342.
- [18] N.E. Ali, B. Zoghbi, M. Fahes, The impact of near-wellbore wettability on the production of gas and condensate: insights from experiments and simulations, *J. Petrol. Sci. Eng.* 175 (2019) 215–223.
- [19] R. Ahmadi, Z. Farmani, Sh Osfour, Condensate blockage remediation in a gas reservoir through wettability alteration using natural CaCO₃ nanoparticles, *Colloids Surf. A Physicochem. Eng. Asp.* 579 (2019) 123702.
- [20] S.A. Hoseinpour, N. Norouzi, A.H. Mohammadi, Condensate blockage alleviation around gas-condensate producing wells using wettability alteration, *J. Nat. Gas Sci. Eng.* 62 (2019) 214–223.
- [21] H.R. Erfani, M.H. Ghazanfari, Toward a hydrocarbon-based chemical for wettability alteration of reservoir rocks to gas wetting condition: implications to gas condensate reservoirs, *J. Mol. Liq.* 248 (2017) 100–111.
- [22] M. Sheydaemehr, B. Sedaesola, Vatani, A., gas-condensate production improvement using wettability alteration: a giant gas condensate field case study, *J. Nat. Gas Sci. Eng.* 21 (2014) 201–208.
- [23] Z. Sakhaei, M.M. Baghmolaei, R. Azin, Study of production enhancement through wettability alteration in a super-giant gas-condensate reservoir, *J. Mol. Liq.* 233 (2017) 64–74.
- [24] F. Torabi, A. Gandomkar, The application of CO₂-soluble non-ionic surfactants for wettability alteration to intermediate CO₂-oil wet during immiscible gas injection, *SPE J (SPE-221487-PA)* 29 (09) (2024) 5071–5086.
- [25] F. Haeri, L.C. Burrows, P. Lemaire, P.G. Shah, R.M. Enick, A. Goodman, Improving CO₂-EOR in shale reservoirs using dilute concentrations of wettability-altering CO₂-Soluble nonionic surfactants, in: Presentation at the Unconventional Resources Technology Conference, 2020, p. 2774. USA, URTEC.
- [26] A. Gandomkar, M. Sharif, Nano composites performance as direct thickeners for gas based enhanced oil recovery, a new approach, *J. Pet. Sci. Eng.* 194 (2020) 107491.
- [27] M.A. Mousavi, S. Hassanajili, M.R. Rahimpour, Synthesis of fluorinated nanosilica and its application in wettability alteration near-wellbore region in gas condensate reservoirs, *Appl. Surf. Sci.* 273 (2013) 205–214.
- [28] P. Esmaeilzadeh, M.T. Sadeghi, Z. Fakhroueian, A. Bahramian, R. Norouzbeigi, Wettability alteration of carbonate rocks from liquid-wetting to ultra gas-wetting using TiO₂, SiO₂ and CNT nanofluids containing fluorochemicals, for enhanced gas recovery, *J. Nat. Gas Sci. Eng.* 26 (2015) 1294–1305.
- [29] A. Safaei, F. Esmaeilzadeh, X. Wang, Experimental investigation of wettability alteration of carbonate gas-condensate reservoirs from oil-wetting to gas-wetting using Fe₃O₄ nanoparticles coated with Poly (vinyl alcohol), (PVA) or Hydroxyapatite (HAp), *J. Petrol. Sci. Eng.* 184 (2020) 106530.
- [30] M.F. Aguirre, R.D. Zabala, F.B. Cortés, Interaction of anionic surfactant-nanoparticles for gas-wettability alteration of sandstone in tight gas-condensate reservoirs, *J. Nat. Gas Sci. Eng.* (2018) 53–64.
- [31] G.R. Karandish, M.R. Rahimpour, S. Sharifzadeh, Wettability alteration in gas-condensate carbonate reservoir using anionic fluorinated treatment, *Chem. Eng. Res. Des.* 93 (2015) 554–564.
- [32] S.R.H. Jangi, M. Akhond, Synthesis and characterization of a novel metal-organic framework called nanosized electroactive quasi-coral-340 (NEQC-340) and its application for constructing a reusable nanozyme-based sensor for selective and sensitive glutathione quantification, *Microchem. J.* 158 (2020) 105328.
- [33] R.E. McMahon, L. Wang, R. Skoracki, A.B. Mathur, Development of nanomaterials for bone repair and regeneration, *J. Biomed. Mater. Res. B Appl. Biomater.* 101 (2) (2013) 387–397.
- [34] Y. Lai, J. Huang, Z. Cui, M. Ge, K.Q. Zhang, Z. Chen, L. Chi, Recent advances in TiO₂ based nanostructured surfaces with controllable wettability and adhesion, *Small* 12 (16) (2016) 2203–2224.
- [35] Y. Chen, N. Bahadori, K. Saxena, Investigating the impact of nanoparticles and surfactants on the surface wettability, *Bull. Am. Phys. Soc. Int. Mech. Eng. Congr. Exposition* (2023).
- [36] P. Esmaeilzadeh, M.T. Sadeghi, A. Bahramian, Wettability alteration in near-wellbore regions of gas reservoirs to mitigate liquid blockage using super water-and oil-repellent ZnO/SiO₂ Nanofluid treatment, *Journal of Gas Technology* 2 (1) (2017) 16–30.
- [37] H.S. Nalwa (Ed.), *Nanostructured Materials and Nanotechnology*, concise edition, Elsevier, 2001.
- [38] X. Zhang, H. Liu, L. Jiang, Wettability and applications of nanochannels, *Adv. Mater.* 31 (5) (2019) 1804508.
- [39] E.K. Kim, C.S. Lee, S.S. Kim, Superhydrophobicity of electrospray-synthesized fluorinated silica layers, *J. Colloid Interface Sci.* 368 (1) (2012) 599–602.
- [40] J. Xu, Y. Ao, D. Fu, C. Yuan, Low-temperature preparation of F-doped TiO₂ film and its photocatalytic activity under solar light, *Appl. Surf. Sci.* 254 (10) (2008) 3033–3038.
- [41] J. Jin, J. Sun, K. Rong, K. Lv, T.A. Nguyen, R. Wang, J. Wang, Gas-wetting alteration by fluorochemicals and its application for enhancing gas recovery in gas-condensate reservoirs: a review, *Energies* 13 (18) (2020) 4591.
- [42] J. Chang, L. Zhang, P. Wang, Intelligent environmental nanomaterials, *Environ. Sci. Nano* 5 (4) (2018) 811–836.
- [43] J.A. Ali, K. Kolo, A.K. Manshad, A.H. Mohammadi, Recent advances in application of nanotechnology in chemical enhanced oil recovery: effects of nanoparticles on wettability alteration, interfacial tension reduction, and flooding, *Egyptian journal of petroleum* 27 (4) (2018) 1371–1383.
- [44] A. Gandomkar, F. Torabi, R.M. Enick, Enhanced oil recovery via dissolution of low molecular weight PDMS in CO₂ during immiscible gas injection in matrix-fracture system, *Chem. Eng. Res. Des.* 203 (2024) 18–28.
- [45] L.C. Burrows, F. Haeri, D. Tapriyal, M.E. Enick, A. Goodman, Dissolving nonionic surfactants in CO₂ to improve oil recovery in unconventional reservoirs via wettability alteration, *Energy Fuels* 36 (2022) 11913–11929.
- [46] J.A. Medina, E.C. Obasi, T. Elshehabi, S. Saraji, Wettability alteration and interface tension modification for enhanced oil recovery in oil-wet carbonates: a comparative study of different surfactants, *Geoenergy Sci. Eng.* 225 (2023) 211637.
- [47] R.N. Moghaddam, A. Bahramian, Z. Fakhroueian, A. Karimi, S. Arya, Comparative study of using nanoparticles for enhanced oil recovery: wettability alteration of carbonate rocks, *Energy Fuels* 29 (4) (2015) 2111–2119.
- [48] H. Wang, J. Fang, T. Cheng, J. Ding, L. Qu, L. Dai, T. Lin, One-step coating of fluoro-containing silica nanoparticles for universal generation of surface superhydrophobicity, *Chem. Commun.* (7) (2008) 877–879.
- [49] A. Gandomkar, A. Azizkhani, A novel method for application of nanoparticles as direct asphaltene inhibitors during miscible CO₂ injection, *J. Petrol. Sci. Eng.* 185 (2020) 106661.
- [50] J. Binshan, D. Shugao, L. Zhian, Z. Tiangao, S. Xiantao, Q. Xiaofeng, A study of wettability and permeability change caused by adsorption of nanometer structured polysilicon on the surface of porous media, in: SPE Asia Pacific Oil and Gas Conference and Exhibition, SPE, 2002, October. SPE-77938.
- [51] Saidur Ghadimi, H.S.C.R.A. Metselaar, A review of nanofluid stability properties and characterization in stationary conditions, *Int. J. Heat Mass Tran.* 54 (2011) 4051–4068.
- [52] E. Hajibolouri, S. Kord, A. Hashemi, Y. Tamsilian, Improving fluid flow capacity in gas-condensate reservoirs through condensate blockage remediation using nanofluid wettability alteration, *J. Dispersion Sci. Technol.* (2025) 1–14.
- [53] R. Saboori, R. Azin, S. Osfour, S. Sabbaghi, A. Bahramian, Synthesis of fluorine-doped silica-coating by fluorosilane nanofluid to ultrahydrophobic and ultraoleophobic surface, *Mater. Res. Express* 4 (10) (2017) 105010.
- [54] D. Wang, X. Wang, X. Liu, F. Zhou, Engineering a titanium surface with controllable oleophobicity and switchable oil adhesion, *J. Phys. Chem. C* 114 (21) (2010) 9938–9944.
- [55] J.D. Brassard, D.K. Sarkar, J. Perron, Synthesis of monodisperse fluorinated silica nanoparticles and their superhydrophobic thin films, *ACS Appl. Mater. Interfaces* 3 (9) (2011) 3583–3588.
- [56] M. Ramezani, M.R. Vaezi, A. Kazemzadeh, Preparation of silane-functionalized silica films via two-step dip coating sol-gel and evaluation of their superhydrophobic properties, *Appl. Surf. Sci.* 317 (2014) 147–153.
- [57] Y. Zheng, Y. He, Y. Qing, Z. Zhuo, Q. Mo, Formation of SiO₂/polytetrafluoroethylene hybrid superhydrophobic coating, *Appl. Surf. Sci.* 258 (24) (2012) 9859–9863.
- [58] A. Yudin, N. Nurlybayev, Z. Al-Jalal, Solving the low injectivity challenges in hydraulic fracturing tight gas reservoirs-case histories review, in: SPE Middle East Oil and Gas Show and Conference, SPE, 2023, March D011S018R002.
- [59] E.O. Yusuf, I. Amber, S. Officer, G.F. Oluyemi, Controlled application of nanoparticles for remediation in oil and gas application: strategies, challenges, and innovations, *Energies* 18 (4) (2025) 991.