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Application of Nanoparticles to Enhanced Oil Recovery

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Abstract: Due to the disadvantages of traditional EOR methods, such as low sweep efficiency, formation damage and poor environmental protection, nanotechnology has attracted great attention in improving oil recovery due to its cost-effectiveness and environmental protection. Common types of nanoparticles that can play an effective role in enhancing oil recovery include oxides of aluminum, zinc, magnesium, iron, zirconium, nickel, tin and silicon. At home and abroad in this paper, the different types of nanomaterials research progress on the reservoir and production technology are introduced in detail, involving nanoparticles in effect on the viscosity of heavy oil and hydraulic fracturing technology, heat recovery technology, low salinity water injection technology and steam foam flooding technology and changing wettability, to reduce the oil/water interfacial tension and so on the basis of theoretical research and application situation. Scholars at home and abroad have carried out a lot of experiments and numerical simulations on the role of nanoparticles in enhancing oil recovery, as well as the required concentration and action conditions, and elaborated on the mechanism of nanoparticle enhanced oil recovery. In this paper, the latest research progress in this field at home and abroad is reviewed, and the key problems and development direction in the application of nanotechnology are pointed out.

Keywords: Oil recovery; Nanoparticles; Oil reservoir; Oil production process.

1. Research background

Nanoparticles have great potential application prospects in energy, environmental protection, chemical industry, catalysis, electronic information, construction and other industries, thus becoming a research hotspot in energy mining, material development, microelectronics manufacturing and other fields. A nanoparticle is defined as a particle size ranging from 1 nm to 100nm. Compared with the injection of gas, water and chemicals in traditional enhanced oil recovery processes, nanoparticles have some special properties and have broad application prospects in enhanced oil recovery.

Extensive research into nanotechnology began in the 1980s, and it has been a modern marvel of scientific discovery ever since. The nanoscale is the boundary between quantum and volume effects. So classical physics and the laws of quantum can only explain the behavior of these nanoparticles to a certain extent. However, the cause of this behavior and most of the details of the nanoparticles' characteristics remain a mystery. At the nanoscale, particles are completely different from their larger-scale counterparts. Scientists have linked the cause of these strange behaviors to quantum effects, or higher atomic densities, at the larger surface areas of these particles. These unique properties of nanoparticles have expanded their application in modern life. With the continuous development of nanotechnology and the emergence of new nanomaterials, the technology has been widely used in the field of oil and gas development in complex formations. Nanotechnology can be integrated with existing Enhanced oil recovery (EOR) technologies to solve many problems that traditional EOR technologies cannot or cannot solve, such as low sweep efficiency, high cost, inadaptability in harsh environments, and potential reservoir damage.

The oil and gas industry have been closely involved in this transformation and is still exploring the benefits of this technology. It is only recently that the high potential of this technology has been discovered in the oil and gas industry. One of the main target areas is to investigate the possibility of improving the application of all conventional EOR methods by injecting nanoparticles. These tiny particles can penetrate into pore Spaces, which traditional oil recovery techniques simply cannot do, resulting in higher recovery rates. Nanoparticles can also be adjusted to change reservoir properties, such as wettability, improve mobility ratios or control the formation of fine particle migration. Since then, a lot of research has gone into the field. However, there is still much to explore and learn. This is followed by a summary of the results of the research conducted to date on the potential application of nanoparticles in the field of EOR.

2. The application of nanoparticles in reservoir engineering

2.1. Reduce interfacial tension

Nanoparticles play an important role in the optimization of oil recovery technology due to their extremely small particle size and physical and chemical properties of silicon oxide and metal oxide nanoparticles. For example, nanoparticles can promote the reduction of oil-water interfacial tension, thereby improving the efficiency of chemical flooding.

In recent years, foreign scholars have conducted in-depth research on the application of nanoparticles in heavy oil exploitation, and some of them have conducted a large number of experimental investigations on the effect of nanoparticles on reducing interfacial tension. The experimental contents and methods are shown in Table 1.

2.2. Surface modified NPs improve polymer flooding performance

Laura Corredor, Brij Maini, and Maen Husein [5] prepared nano-polymer sols by mixing different types of surface modified silica nanoparticles with hydrolyzed polyacrylamide (HPAM) or xanthan gum (XG) solutions. In order to produce different interfacial interactions, silica nanoparticles were chemically grafted with carboxylic acid and silane.

The properties of modified silica nanoparticles were characterized by Fourier transform infrared spectroscopy

(FTIR), and the properties of nano-polymer sol were studied by viscosity test and ζ potential test. The non-Newtonian behavior of nano polymer sol is expressed by Oswald-de Waele model. The experiments showed that adding any type of nanoparticles could not improve the area sweep efficiency of HPAM polymer solution, because the viscosity of the polymer solution was reduced and the interfacial tension between the injected solution and the oil was decreased. However, the addition of 1.0 wt% and 2.0 wt% NP modified XG polymer solutions significantly improved the sweep efficiency.

Table 1. Reagents, nanoparticles and their methods used in interfacial tension experiment

Scholar	Heavy oil type	Nanoparticles	Experimental method
Arab [1]	Luseland Heavy Oil (14,850 mPa.s, 14.6 wt% asphaltene)	Two types of colloidal silica nanoparticles. They were EOR-5XS and Ludox CL, respectively.	Firstly, nanoparticle dispersion and surfactant mixed solution were treated with ultrasonic bath and eddy current for 25 minutes. The surface tension and surface tension were then measured using the Wilhelmy plate technique.
Giraldo [2]	Light crude oil with API of 38° was obtained from a reser-voir in Colombia.	SiO_2 nanoparticles were synthesized with tetraethyl orthosilicate and ethanol (99.9%). The average particle size was 94 nm±4 nm.	By means of interfacial tension (IFT) experiments, the minimum nanoparticle concentration required for injection in displacement tests of quarter-point micromodels was determined.
Mashat and Fattah [3]	Filtered crude with a density of 0.8171 g/cm^3 and a viscosity of 12.1 cp.	Three nano-surfactants (NS) formulations (STRX-NS, WIT-NS and SUG-NS) were prepared from petroleum sulfonates and three co-surfactants from Chemtura.	Interfacial tension between crude oil and nano-surfactant solution was measured using a rotating droplet interfacial tensimeter at 90°C compared with high salinity water alone or cosurfactant solution of the same concentration.
Junin and Agi [4]	A heavy oil sample from the Sarawak field (asphaltene content of 14.6 wt%, viscosity of 10 mP.s at 25°C).	CSNP nanoparticles (starch extracted from cassava tubers, dispersed with vinegar to form a solution, which is then dripped into alcohol).	The ring technique was used to determine the IFT of CSNF at different concentrations (0.05-0.2wt%). Measure with KRUSS EasyDyne K20 tensiometer.

2.3. Changing wettability to improve oil recovery

Li Yuyang, Wang Xinke, Zhao Mingwei[6] revealed the mechanism of enhanced oil recovery by the mixed solution through the imbibition experiments of water-based nano-fluid, alkaline aqueous solution (pH equal to water-based nano-fluid) and brine on ultra-low permeability sandstone cores pre-saturated with oil.

In their study, trimethoxy-silane and sodium p-styrene sulfonate were alternately assembled on the surface of silica nanoparticles. The results show that the recovery rate of the nano-fluid leached core is significantly higher than that of the core leached with alkaline water (pH=9) and 3% NaCl solution. In order to measure the wetting contact Angle of the oil - wetting surface before and after nano - fluid treatment. The results show that the wettability of the core changes from oil-wet to water-wet after nano-fluid treatment.

Masoumeh Tajmiri and Mohammad Reza Ehsani[7] determined the absorption and wettability potential of CuO nanoparticles through experimental and numerical calculations. Two laboratory tests were conducted on two cylindrical core samples from heavy oil reservoirs in Iran. The experimental results show that the oil recovery rate of sandstone cores increases from 20.74% without the addition of nanoparticles to 31.77% with the addition of CuO nanoparticles. In the absence of nanoparticles, the oil recovery of carbonate cores was 0, while the recovery of cores with nano-CuO was 6.92 percent. Through the analysis of the relative permeability curve, the intersection points were shifted to the right by the addition of nano-CuO nanoparticles, which means that the nanoparticles successfully changed the wettability of sandstone and even carbonate cores, making them more hydrophilic.

2.4. Improve the stability of emulsion

Oil/water emulsions are common in oil production operations because water is almost always produced with oil and the water cut increases as the reservoir matures. The presence of two insoluble liquid phases (oil and water) and the shearing of the produced liquid as it passes through various constraints (e.g., downhole safety valves, pumps, orifices, throttling) are sufficient to disperse one phase into the other.

Nanoparticle stabilized emulsions are used in research enhanced oil recovery (EOR) operations as an alternative to traditional surfactant stabilized emulsions. I. Gavrielatos, R.D abirian, R.M ohan[8] from atmospheric pressure under the condition of nanoparticles (SiO2, size of 20 nm) stability of emulsion and surfactants counterparts separation dynamics in the preliminary experimental results it is concluded that under the condition of the moisture content of 25%, Nanoparticle stabilized emulsions exhibit separation kinetics similar to that of surfactants. For high water content (50 and 75%), the surfactant will not only form a larger emulsion volume, but also a denser emulsion. Compared with nanoparticles, the separation kinetics of surfactant stabilized emulsions is significantly hindered. In the case of 75% water content, the emulsion formed by the higher nanoparticle concentration (20 times) was as dense as the emulsion formed by the lower surfactant concentration under certain conditions.

At different salinified levels, the aqueous nanoparticles and the pentane or butane oil phase produce an oil-in-water emulsion with a volume ratio of 1:1. Nicholas Griffith [9] et al. observed the properties of several emulsions and investigated the influence of salinity on the stability of nano silica dispersions and liquid natural emulsions. In core displacement experiments, injection of 0.50 PV pentane emulsion followed by saline flushing was performed, and increased recovery was observed at higher flow rates. The core flooding test shows that the nanoparticle stabilized natural gas water-in-water emulsion has the potential to produce the remaining oil phase with higher consistency.

Ayman. MAlmohsin[10] studied through experiments whether the combination of surfactant and nanoparticles can form a stable emulsion better than the simple surfactant. The results show that the stability of non-ionic emulsion can be improved by adding Al2O3 and SiO2 nanoparticles into the emulsion. Emulsion stability can be formed by adding Al2O3 and SiO2 nanoparticles to anions and cations at different water-oil ratios.

Zhenjie Wang [11] screened effective emulsifiers of oil-water emulsions from a wide range of solid nanoparticles, and selected suitable Pickering emulsifiers. Five kinds of nanoparticles, including cellulose nanocrystals (CNCs), silica, alumina, magnetite and zirconia, were tested for the stability of the oil-water emulsion. The screening results showed that CNC could be an effective emulsifier by adjusting pH value or salinity. In addition, the influence of particle concentration on the stability of emulsion was quantitatively studied by using the particle size distribution calculated by ImageJ software. The results show that the particle size decreases sharply with the increase of particle concentration and then changes gently. For the WOR effect, a phase transition from oil-in-water (O/W) to oil-in-water (W/O) emulsions occurs when the oil content is greater than 0.6. The thermal stability of the emulsion was studied from macroscopic and microscopic aspects. The results showed that the thermal stability of the emulsion stabilized by CNC could reach 100℃.

2.5. Improve water drive sweep coefficient

Polymer flooding has significant tertiary oil recovery potential. It is suitable for reservoirs with heavy oil viscosity above 150 mPa.s. As the viscosity of injected water increases, the polymer injection volume decreases significantly, and so does the polymer pumping efficiency. To overcome this limitation, Cenk Temizel [12] proposed the use of supramolecular assemblers (SMA) with adjustable viscosity properties. They propose the use of polymer gel technology, polymer injection during polymer flooding can improve the viscosity of water, improve the efficiency of oil displacement. Therefore, the objective of enhanced oil recovery with polymer flooding is to improve the oil mobility ratio.

In addition to these advantages, SMA systems also have potential applications in highly enclosed environments, such as thin layers and permafrost conditions, where traditional polymer treatments are difficult to apply. As a result, salinitic-resistant, heat-resistant, ph-responsive supramolecular assembled solutions demonstrate the potential for more efficient global applications than conventional polymer treatment systems.

2.6. Nanoparticle dispersion technology

In 2016 and 2017, several Wolfcamp and Bone Springs target Wells in the northern Delaware Basin were fractured and successfully completed using a new method that used a relatively small pre-filled shot volume of nanoparticle dispersion prior to each fracturing stage. These neutral, wet, solid nanoparticles imbibition by countercurrent, breaking the separated oil into smaller oil droplets, thereby increasing hydrocarbon recovery and allowing it to flow more efficiently back into the support fracture network and back into the wellbore. The advantage of this method and mechanical process is the ability to reach outside the reservoir where the proppant can be placed, thereby increasing the effective reservoir volume. Because the average diameter of individual particles is 12 nanometers, silica nanodispersion (SDND) particles can easily penetrate natural fracture networks at the nanoscale. The advantage of this method and mechanical process is the ability to access the reservoir beyond the proppant location, thereby creating a more efficient stimulation reservoir volume (ESRV)[13].

2.7. Magnetic effect of magnetic nanoparticles to enhance oil recovery

Ningyu Wang [14] demonstrated the enhanced oil recovery (EOR) potential of hydrophilic magnetic nanoparticles in oil production through direct observation of microfluidics. They studied the mobilization of oil droplets by ferrofluid (a suspension of hydrophilic magnetic nanoparticles in water) in a poly-dispersive channel at different depths (the so-called 2.5D micromodel). The initial oil displacement experiment of MHD was carried out under static magnetic field. This magnetic field deforms the oil droplets and dynamically breaks them into smaller droplets, reducing residual oil saturation.

Significant oil droplet displacement was observed within 2h after the magnetic field was applied. In the process of oil displacement, the oil saturation in the observation area of the microscopic model decreased from 27.4% to 12.0%, which may be due to the synergistic effect of hydrodynamic and magnetic forces. Further experiments confirmed that magnetic forces can deform and rotate oil droplets trapped in a water-based ferrofluid.

3. Application of nanoparticles in oil recovery technology

3.1. Viscosity reduction effect on heavy oil

Heavy oil and bitumen account for nearly 70% of the remaining oil reserves. Reducing heavy oil viscosity is the most important problem in improving heavy oil recovery. Thermal recovery is the most effective method in reducing heavy oil viscosity. Thermal recovery can effectively reduce the viscosity of heavy oil and increase the fluidity of heavy oil, so as to improve the recovery efficiency of heavy oil.

Mohamed Elshawaf [15] measured heavy oil samples (API=21.9, asphaltene content 8.28 wt%) from the Baraime field in South Sinai, Egypt, using the RBV700 vissimeter. In addition, the RBV700 viscometer was used to measure the influence of a certain concentration of GO nanoparticles on the viscosity of heavy oil at a certain temperature [16]. At the temperature of 40~90℃, GO can reduce the viscosity of heavy oil to 20~60% of the original value. In addition, the optimal viscosity reduction concentration of GO is between 0.02 and 0.08%. When the mass fraction of GO is 0.05%, the viscosity reduction effect will be improved compared with that at 0.5%wt. The cost reduction of Fe2O3 nanomaterials can reach 40~50 % of the total cost.

C.A. Franco [17] adopted 1 wt% nickel palladium oxide as functional group of vapor phase silica nanoparticles (average size of 61nm) as the catalyst for the steam flooding process. The bath adsorption experiment was carried out by adding a certain number of nanoparticles into the model solution of heavy oil and mixing. Experiments show that once the nanoparticles interact with the crude oil, the asphaltene is adsorbed more and more. This is because the asphaltene/asphaltene interaction is smaller than the asphaltene/nanoparticle interaction. Therefore, the asphaltene is separated from the aggregation system in the oil matrix and diffused through the bulk phase to the surface of the nanoparticle until the maximum adsorption capacity is reached. The asphaltene remaining in the bulk phase will form smaller aggregates, and the reduction of asphaltene aggregates will directly lead to the decrease of oil viscosity.

Daniel Montes Pinzon [18] promoted the conversion of crude oil heavy compounds (asphaltenes) to lepton components by using a new cracking reaction method, namely ultrasonic crystallization and nickel oxide nanoparticle functionalization technology, assisted silica nanoparticles as catalysts and water as hydrogen donors. The heavy oil with asphaltene content of 17.02% was used for the experiment. NiO nanoparticles were functionalized on 7 nm silica carrier using 1% metal oxide. The study found that the adsorption of SiNi nanoparticles on the asphaltene surface of crude oil will affect the internal structure of the fluid, and the asphaltene of crude oil will be converted into light components, reducing the content of asphaltene of crude oil, and thus reducing the viscosity of crude oil.

Hajir al-Farsi and Peyman Pourafshary[19] also studied the influence of nanoparticles on heavy oil recovery by microwave-assisted gravity flooding (MWAGD) process. The results show that in MWAGD process, nano-Al2O3 and nano-TiO2 have the greatest impact on the recovery, with low concentrations of 0.1 and 0.05 wt%, respectively. The addition of nanoparticles to water can improve the thermal conductivity of water, increase the thermal adsorption, reduce the viscosity of heavy oil, and enhance the oil recovery through MWAGD.

3.2. Improve water flooding efficiency

Compared with conventional waterflooding, low-salinity waterflooding technology can effectively improve heavy oil recovery in the presence of nanoparticles. In addition, the addition of nanoparticles to LSHW (low salinity hot water) promotes a synergistic effect of thermal energy, wettability changes, and interfacial tension (IFT) reduction, resulting in increased water flooding efficiency and thus enhanced oil recovery.

Yanan Ding [20] prepared 0.05wt% nano-Al2O3 (particle size 20-30nm) dispersed LSW (low salinity water) and 0.05wt% nano-Al2O3 (particle size 20-30nm) dispersed LSW, and designed and implemented 10 experimental scenarios. The oil displacement properties of salt water flooding, LSW water flooding, nano-SiO2 assisted LSW and nano-Al2O3 assisted LSW at different temperatures were evaluated.

Compared with brine flooding, the oil recovery performance of LSW flooding at room temperature is better, and the performance of LSW dispersed with 0.05wt% nano-SiO2 is better than that of pure brine and LSW. In particular, at 70°C, when the nano-Al2O3 content is 0.05wt%, the ultimate oil recovery of LSW flooding is up to 40.2%. These results indicate that the nanoparticles have a good synergistic effect in LSW flooding. In addition, the appropriate temperature has a significant impact on the production performance of heavy oil, the final recovery efficiency is obviously improved, and the oil recovery period is prolonged. The nanoparticle assist can also enhance the delay of water intrusion, and the effect is much gentler, while the increased temperature can effectively inhibit the sharp rise of water content in the early stage and then reduce its value in the later stage.

Chemical modification of injected water using nanofluids (including nano-silicon polymers) is an effective method for enhanced oil recovery (EOR). Mohamed Omran[21] conducted an experimental study on this. Nanofluid injection was performed on the core and the recovery was compared with synthetic seawater injection (SSW). Both nanofluids and SSWS were injected in a secondary mode. Five clean and dry Berea sandstone cores were used for core displacement experiments.

The properties of the four nanoparticles are shown in Table 2.

Table 2. Properties of nanoparticles suspended in distilled water

Nanofluid type	Bases	mass fraction (wt%)	Size(nm)
NF02-3	silicon dioxide	38.6	32.9
NF02-4	silicon dioxide	26.0	81.9
NF02-6	A mixture of silica and alumina	21.6	130.4
NF02-8	A mixture of silica and alumina	25.5	155.5

Core flooding experiments have demonstrated that polymer-coated silica nanoparticles in hydrophilic Berea sandstones can enhance oil recovery. In the secondary oil recovery process, the application of nano-fluids can increase oil recovery by 10.4%. Polymer-coated silica nanoparticles enhance oil recovery by improving the microscopic scanning efficiency of rock-fluid interactions and fluid-fluid interactions. Polymer-coated silica nanoparticles can significantly reduce permeability and porosity, thus improving the sweep efficiency of water flooding.

3.3. Application of desulfurization technology in heavy oil

Hydrogen sulfide and organic sulfide (collectively referred to here as "sulfide") are typically removed from on-site natural gas before it is piped to market or off-site processing plants due to their corrosive and toxic properties. The current solution to removing H2S is desulfurization technology, but this technology is known to be very expensive and inefficient. S. I. Martinez [22]. developed a new desulfurizing adsorbent by taking advantage of the reactivity of metal oxides, the small size of sulfide and its dispersion in crude oil.

The desulfurization experiment results show that the removal rates of H2S are Ni (83%) <Fe (93%) <Cu (~100%). And using nanoparticles as H2S scavengers does not produce collateral byproducts, and because only very small amounts of the substance are needed, recycling them is unnecessary and does not pollute the environment.

3.4. Promote hydrothermal cracking reaction in cyclic steam huff and puff process

Steam huff and puff (CSS) is an effective stimulation technique, and hydrothermal cracking occurs at steam temperatures above 100°C. In the CSS process, metals can be used as catalysts for hydrothermal cracking reactions between heavy oil and water. Between 200°C and 325°C, these reactions become more intense. Siyuan Yi,Tayfun Babadagli[23]. compared the performance of nano-nickel and nano-iron in promoting hydrothermal cracking of CSS at temperatures up to 220°C. The results show that both nickel oxide and iron oxide nanoparticles can catalyze hydrothermal cracking. However, the catalytic effect of nickel is stronger than that of iron oxide, so the introduction of nickel nanoparticles can achieve higher oil recovery and lower oil viscosity. As the concentration of iron oxide nanoparticles increases, the viscosity of heavy oil decreases. The same charge on asphaltene and ferric oxide causes a repulsive force between them, and less asphaltene structure is attracted to the surface of the ferric oxide particle. Therefore, when the concentration of iron oxide particles increases, the exclusion phenomenon is enhanced, which makes it more difficult for iron oxide particles to catalyze asphaltene and reduce heavy oil recovery.

Yi [24] also conducted a detailed study on the optimal operating parameters. They conducted a series of experiments to study the role of nickel nanoparticles in promoting hydrothermal cracking in CSS, and reached the following conclusions :(1) Nickel nanoparticles can be used as a catalyst for hydrothermal cracking in the process of CSS, and can effectively break C-S bonds. However, with the passage of time, the catalytic effect of nickel tends to weaken and even disappear in the later stage. This may be related to the decrease of nickel content in the sand. (2) Improved recovery was accompanied by a substantial increase in water production after the introduction of Ni nanoparticles into the sand pack. (3) The contribution of nickel nanoparticles to EOR mainly comes from the distribution of nickel nanoparticles near the injection hole.

3.5. Improve foam stability

In a foam system, the gas phase is dispersed as a bubble in the continuous phase of the liquid. Emrani and Nasr-El-Din [25] proposed in 2015 that nanoparticle stabilized emulsions could be applied to improve the efficiency of CO2 foam EOR operations, especially under harsh reservoir conditions.

Ortiz [26] used the existing experiment of supercritical carbon dioxide (CO2) foam "stabilized by nanoparticles" to study the applicability of nanoparticles in the control of foam fluidity, so as to improve the swept efficiency. A 5-point well pattern was selected for simulation. The results show that the model can successfully reproduce the core displacement experimental data and form three different foam states (weak foam, strong foam and medium foam) and two stable strong foam states (high quality and low quality). When gas phase MRFs (model fit value 10) were applied to field simulations, the use of nanoparticles resulted in improved oil recovery compared to gas/water coinjection.

The study also shows that when the results of the mechanical foam model are compared with those of the locally balanced foam model, the gas-phase fluidity of the nanoparticle stabilized supercritical carbon dioxide foam is reduced by about 10 (MRF≈10). This value is much lower than that typical for surfactant foams in laboratory core displacement experiments (MRF-100 range).

Ahmed Farid Ibrahim [27] used nanoparticles and visco-elastic surfactants (VES) to improve foam fluidity in 2018. They investigated the stability of CO2-foam using alpha-olefin sulfonates (AOS) as foaming agents, and the changes in the fluidity reduction factor (MRF) of different foam solutions with the addition of nanoparticles and VES.

They used 5% wt% NaCl brine as a base solution. AOS (α-olefin sulfonate) surfactant with 40% wt% active substance was used as foaming agent. Using nano silica (140nm) and VES stabilized foam. The results showed that AOS could not improve oil recovery at MRF of 1, and AOS foam could hardly recover oil. The addition of nanoparticles and VES to the foam system improved the MRF of the foam and produced more crude oil (12% with nanoparticles and 18% with VES). Therefore, the addition of nanoparticles is recommended for EOR applications, especially at high temperatures.

In conventional steam foam applications, chemical additives are injected through steam. However, the operation was seriously flawed due to the poor thermal stability of the additive and the large amount of additive loss due to adsorption on rock surfaces. To overcome these limitations, nanoparticles can be used as novel additives to improve foam formation and stability in steam foam applications. Maryam Khajehpour [28] investigated the synergistic action of silica nanoparticles (ranging in size from 5 to 50) with surfactants as steam additives. To capture the effect of nanoparticles on foaming and foam stabilization processes, experiments were conducted with and without nanoparticles. Synergies were demonstrated in systems containing 0.1wt% silica nanoparticles (optimal concentration) and 0.5wt% neutral Ph (~7) surfactant solutions. Using nanoparticles or surfactants alone produced much less foam than the combination of the two additives.

Carbon dioxide foam is often used as a fracturing fluid to develop unconventional resources, especially water sensitive reservoirs. Carbon dioxide foam not only reduces the amount of water entering the formation, thus reducing damage to the formation, but also reduces the amount of water needed for environmental protection. Arezoo S. Emrani [29] evaluated a new foam solution with nanoparticles to study the flow control performance when the foam was used as a hydraulic fracturing fluid. They studied the fluidity conversion coefficient (MRF) of CO2 foams produced in polymer-based solutions such as guar gum in the presence and absence of nanoparticles to assess the apparent fluid viscosity at high temperatures and salinity. The results showed that α-olefin sulfonates (AOS) increased MRF by 300% compared with NaCl solution. The addition of nanoparticles to AOS solution improves the stability of the foam, which greatly reduces the fluidity of the injected gas compared to the surfactant. With the increase of temperature, the half-life of foam decreases, the volume of foam increases and the bursting speed increases. At high temperatures, nanoparticles are added to AOS and AOS+ Guar solutions to improve foam stability because nanoparticles have adsorption on the bubble surface.

Adam Fehr [30] developed a nanofluid for steam co-injection. Nanofluids are formed using the synergistic action of silica nanoparticles and two surfactants (both readily available) to address thermal and foam stability in thermal enhanced oil recovery processes such as steam-assisted gravity flooding.

Static tests and high temperature core flooding tests show that there is a strong synergy between appropriate surfactant and nanoparticle combinations. The foaming properties of porous media can be increased by changing the length of nonpolar carbon chains on surfactant molecules. In addition to showing excellent performance in porous media containing gas and steam, the additive demonstrated excellent stability in foam generation in static tests at high temperature and pressure and at room temperature in the presence of oil. The synergy between nanoparticles and surfactants is demonstrable because they cannot foam in porous media alone, but when combined, the resulting synergy results in a strong reduction in mobility, and the synergy between nanoparticles and surfactants also ensures that they can be transported together as a mixture. This greatly reduces the potential for rock damage and can quickly create and spread foam, preventing it from destabilizing in the presence of oil. The results show that the selection of appropriate nanoparticles can greatly improve the effect of surfactants, and conversely, appropriate surfactants can make cheap nanoparticles an effective foam stabilizer. This provides a simpler, cheaper, and more effective stabilizer for high temperature foam applications.

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