

Application and Progress of Nanotechnology in Oil and Gas Fields

Qi Hao

School of Mechanical Engineering, Xi'an Shiyou University, Xi'an, Shanxi 710065, China

Abstract: Nanotechnology, which emerged as a novel scientific and technological field in the 1990s, has gradually permeated the petroleum industry by virtue of its unique size and surface effects, as well as its excellent optical, electrical, thermal, and magnetic properties. It offers a new technical pathway to address development challenges in onshore oilfields, such as high water cut, strong heterogeneity, and low waterflooding recovery factor. This article reviews the origin and evolution of nanotechnology and summarizes relevant research findings and field application cases across six key areas: downhole nanosensors, drilling engineering, enhanced oil recovery, oil displacement operations, secondary development of mature oilfields, and reservoir nanorobots. The study indicates that nanomaterials and nanodevices exhibit distinct advantages in improving drilling fluid performance, reducing fluid loss, plugging high-permeability layers, altering reservoir wettability, lowering oil–water interfacial tension, and reducing injection pressure to enhance water injectivity. The research and field testing of reservoir nanorobots have achieved milestone-level progress, opening new possibilities for fine reservoir characterization and residual oil recovery. At the same time, this article identifies the technical challenges currently facing nanotechnology in petroleum industry applications and discusses future development directions, providing a reference for the large-scale deployment of nanotechnology in the petroleum sector.

Keywords: Nano- technology; Recovery rate; Oil- displacement agent; Nano- robot.

1. Introduction

Nanotechnology is the science of manufacturing substances using individual atoms and molecules. It involves the design, characterization, fabrication, and application of materials with structural dimensions ranging from 1 to 100 nanometers. Although its rapid development began in the 1990s, the conceptual origins date back earlier. Owing to its excellent optical, electrical, thermal, and magnetic properties, nanotechnology has now been widely applied in fields such as microelectronics, biology, fuel cells, and pharmaceuticals. As early as 1959, Richard P. Feynman predicted at the American Physical Society Annual Meeting that if materials could be prepared and controlled at a smaller scale, a brand-new world would be opened up. This prediction was regarded by the scientific community as the sign of the emergence of nanotechnology[1]. In 1974, Taniguchi coined the term “nanotechnology” to describe advancements in mechanical processing and material precision within the field of engineering[2]. In 1976, C.G. Granqvist and R.A. Buhrman of Cornell University used vapor condensation to prepare nanoparticles, marking the entry of nanotechnology into the stage of artificial synthesis of nanomaterials[3]. In 1989, Gleiter of Germany prepared nanoparticles using the inert gas condensation method, comprehensively studied the samples from both theoretical and performance perspectives, and proposed the concept of nanocrystalline materials[4]. This stage mainly involved exploratory laboratory research, using artificial synthesis to prepare nanomaterials and evaluate their various characteristics, thereby revealing the differences and unique properties between nanomaterials and traditional materials. In 1995, Choi[5] proposed the concept of nanofluids and discussed the changes in thermal conductivity caused by dispersing nanoparticles in the base fluid.

Today, nanotechnology has been applied in various fields[6][7], bringing revolutionary breakthroughs to

materials[8][9], biology[10][11], and electronics[12][13]. In recent years, this technology has gradually penetrated the petroleum industry, especially in response to the current development challenges in onshore oil fields, such as high water cut, strong heterogeneity, and low waterflood recovery factor[14]. Nanomaterials and nanodevices have shown unique potential in drilling fluids, cementing, fracturing, and improving recovery rates [15][16][17][18]. Major international oil companies, technical service companies, and oil research alliances are conducting research on nanotechnology, greatly promoting the development of technologies such as wellbore fluids, nanomaterial reactants, and downhole tools. Field applications have been realized using special additives to improve drilling fluid and cement performance, as well as to enhance drill bit wear resistance. Phased research results have been achieved in applications such as nanorobots, nanotracers, magnetic nanomaterials for improving recovery rates, and surface oil–water separation. China has conducted explorations in improving the performance of drilling fluids, cement slurries, and fracturing fluids.

In China’s current petroleum production sector, most waterflood development oilfields have entered the stage of high water cut and high recovery factor. The majority are onshore sedimentary oil fields, characterized by severe reservoir heterogeneity, high wax and aromatic hydrocarbon content in crude oil, and high viscosity. Consequently, the waterflood recovery factor is relatively low[19], averaging only about 35%. As a key focus of modern scientific research, nanotechnology has gradually evolved toward petroleum industry applications. China has developed nano-drilling fluid technology and nano-pressure reduction and injection technology, which have demonstrated good effectiveness in improving oil recovery rates.

To systematically review the fundamental principles, development history, and research and application progress of

nanotechnology in the oilfield sector, this article begins with the origin and evolution of nanotechnology, introduces relevant domestic and international achievements, and focuses on discussing its current application status and future development directions in petroleum production.

2. The Application of Nanotechnology in Downhole Nanosensors

Since 2000, nanotechnology has gradually expanded into the fields of oil exploration and logging[17]. Especially after 2010, it has been specifically applied to improving the performance of drilling fluids and characterizing logging parameters[18]. In July 1990, the first International Conference on Nanotechnology (NST) was held in Baltimore, USA. At that time, a few technologically advanced countries, such as Japan and the United Kingdom, formulated national plans for the development of nanotechnology, while the National Science Foundation of the United States designated nanotechnology as a project with limited support. These events marked the birth of nanotechnology, which has since become a global research hotspot[20]. As early as 2007, Saudi Aramco proposed the concept of reservoir nanosensors, and in 2010, feasibility tests under reservoir conditions were conducted[21].

Reservoir nanosensors are “functional molecular devices” capable of operating in nanoscale spaces—less than 1/1000 the diameter of a human hair. They are injected into the reservoir, where they analyze the properties of rocks and contained fluids during their underground travel, store the acquired information, and are subsequently recovered along with the crude oil from production wells. After data download, various reservoir and fluid parameters can be obtained[22], including pressure, temperature, relative permeability, pore size, pore throats and pore geometries, stress state, oil, gas, water, corrosive gases (CO₂, H₂S), oil and gas types, pH value, viscosity, oil–water saturation, and wettability, among others.

Alireza et al.[23] fabricated optical fiber sensors capable of detecting crude oil concentration variations by measuring both wavelength shift and intensity changes. A highly sensitive optical fiber probe was fabricated by partially removing the cladding and coating the sensing part with a zinc oxide/silver heterostructure layer, which was prepared in three configurations: nanoparticles, horizontally oriented nanorods, and vertically oriented nanorods.

3. The Application of Nanomaterials in Drilling

The application of nanomaterials in drilling has been increasing in recent years. As nanotechnology continues to penetrate the oil and gas industry, its excellent physical and chemical properties have enabled it to demonstrate broad application prospects in drilling and well construction, drilling fluid modification, and protection of low-permeability oil reservoirs. Sayyadnejad et al.[24] studied the spray pyrolysis method to synthesize nano-zinc oxide with a particle size of 14–25 nm and a specific surface area of 44–56 m²/g for the purpose of preventing corrosion of pipelines and equipment. The synthesized nanoparticles were used to remove hydrogen sulfide from water-based drilling fluids, and their efficiency in removing hydrogen sulfide from drilling mud was evaluated and compared with that of bulk zinc oxide. The results showed that, under the same operating conditions, the synthesized zinc oxide nanoparticles could

completely remove hydrogen sulfide from water-based drilling mud within 15 minutes, whereas bulk zinc oxide removed only 2.5% of hydrogen sulfide within 90 minutes, demonstrating the superior performance of nanomaterials in controlling mud properties. Shahwan et al.[25] studied the synthesis and characterization of iron nanoparticles in the presence of K10 bentonite. The introduction of K10 led to a partial reduction in nanoparticle aggregation, and the dispersed nanoparticles exhibited a typical core-shell structure, mainly distributed within the size range of 10–60 nm. The removal efficiency of the composite adsorbent for Co²⁺ ions in aqueous solutions was tested at different contact times, concentrations, pH values, and under repeated loading. The adsorption rate was evaluated using first-order and second-order adsorption rate equations and described by the Freundlich model. The adsorbent showed good removal efficiency after repeated use, and the adsorption capacity increased with increasing initial pH, thereby laying a theoretical foundation for the application of nanomaterials in mud performance control.

Javad et al.[26] used a twin-roll mill to mix modified carbon nanotubes (ACNTs) bearing acidic surface groups with fluorosilicone elastomer (FE) to obtain an ACNTs/FE composite. By comparing the properties of the composite with those of the neat fluorosilicone elastomer, it was found that the ACNTs/FE composite exhibited more favorable mechanical properties at high temperatures, which could reduce the likelihood of cracking. It also possessed superior chemical resistance and thermal conductivity, thereby enhancing the resilience of conventional drilling fluids during drilling operations. When used as a sealing material, the ACNTs/FE composite enabled long-term drilling and allowed for greater drilling depths. Amanullah et al.[27] synthesized a commercially valuable nanoscale drilling fluid capable of significantly reducing formation damage and reducing fluid loss during drilling. Owing to the presence of highly wear-resistant bridging materials with a long-lasting particle size distribution (PSD), the wellbore fluid containing such materials requires only infrequent addition of supplementary bridging materials to maintain the ideal particle size distribution. This approach aims to reduce the potential damage of the drilling fluid to the formation during drilling and to increase the productivity of the oil well. The engineering significance lies in providing a guiding tool for selecting the most suitable size of bridging materials. The economic significance lies in increasing the ultimate recovery factor of oil and gas resources by optimizing the final mud management cost and increasing the return on investment. This approach also has commercial significance in reducing the impact of exploration operations on the formation.

4. The Application of Nanotechnology in Downhole Recovery Rate

In recent years, research and application of nanomaterials in the field of enhanced oil recovery have made significant progress. Nanoparticles are two orders of magnitude smaller than conventional colloidal particles and can pass through nanoporous structures. Moreover, nanoparticles possess active surfaces, high specific surface areas, and special chemical reaction properties. These unique characteristics give nanoparticles great development potential in enhanced oil recovery (EOR) and open new avenues for improving recovery techniques[28]. Zhu Hong et al.[29] prepared nano-

silica using the sol-gel method and conducted organic modification on it. They formulated composite systems consisting of nano-silica, modified nano-silica, and petroleum sulfonate—a surfactant widely used in oilfield displacement. The TX-500 interfacial tension meter was used to measure the ability of these composite systems to reduce oil–water interfacial tension. The results showed that at a total surfactant concentration of 1 wt%, both petroleum sulfonate alone and the nano-silica/petroleum sulfonate composite system could reduce the oil–water interfacial tension to approximately 0.01 mN/m, whereas the modified nano-silica/petroleum sulfonate composite system reduced the interfacial tension to about 3.37×10^{-3} mN/m, thereby increasing the oil recovery factor. Hou Jirui et al.[30] confirmed that nanotechnology is a highly promising technology for improving recovery rates. As a high-performance displacement agent, nanomaterials have attracted widespread attention for their influence on the viscoelasticity and temperature resistance of polymers, the reduction of interfacial tension by surfactants, and the reversal of wettability by surface-active agents. Ogolo[31] conducted two sets of experiments. In the first set, nanofluids were used to displace the injected oil. In the second set, sandstone samples were immersed in nanofluids for 60 days; then oil was injected into the system and displaced with low-salinity brine. The experimental results showed that when aluminum oxide nanoparticles were used as dispersants in distilled water and brine, they exhibited good oil recovery performance. Silane-treated silica achieved the highest recovery factor in ethanol, and hydrophobic silica also performed well under ethanol conditions. Aluminum oxide was found to reduce oil viscosity, while silica could alter rock wettability and, in the presence of ethanol, also reduce oil–water interfacial tension. When diesel was used as the dispersion liquid for nanoparticles, the actual crude oil recovery factor could not be determined, but the overall performance of aluminum, nickel, and iron oxides was better. Dispersed magnesium oxide and zinc oxide in distilled water and brine caused permeability problems. Ali Maghzi et al.[32] indicated that the wettability of porous media affects crude oil recovery. They conducted a series of injection experiments on a five-point glass micromodel after saturating it with heavy oil, using polyacrylamide (PAM) solution and silica nanoparticles dispersed in polyacrylamide (DSNP) solution as the injection fluids. They measured the crude oil recovery factor and the fluid distribution in pores and throats. The contact angle of the glass surface under different wetting conditions was measured using the solid-drop method. The results showed that silica nanoparticles increased the recovery factor by 10% during polymer flooding. The distribution of the DSNP solution in pores and throats during displacement experiments indicated that the medium exhibited strong wettability after displacement by this solution. The solid-drop experiment results also showed that coating with heavy oil could form an oil-wet surface.

Shah[33] developed a novel heavy oil viscosity reduction process that combines the advantages of three different techniques: thermal injection, chemical injection, and mixed-phase injection. Compared with conventional supercritical CO₂ (sc-CO₂) or viscosity reducer injection (VRI), metal nanoparticles can enhance the thermal conductivity of sc-CO₂ or VRI, rapidly reducing heavy oil viscosity. A soluble surfactant for sc-CO₂ is also added to the mixture to further enhance viscosity reduction. Thus, the

thermal properties of metal nanoparticles, the chemical properties of surfactants, and the mixed-phase properties of sc-CO₂ and VRI collectively reduce heavy oil viscosity. Chen Yuan et al.[34] found that nano-microspheres enter and seal high-permeability layers; as injection pressure increases, crude oil in low-permeability zones is mobilized, resulting in a higher recovery factor. Nano-polymer microspheres exhibit good compatibility with the formation, low viscosity, easy dispersion, and ease of injection. Online injection requires no station construction, and the construction process is safe and simple. Nano-microspheres can increase the swept volume of injected water, and their effect on improving the recovery factor is significant, making them an effective technology for the efficient exploitation of high-water-cut reservoirs.

Kumar et al.[35] reported that using an anionic surfactant (sodium dodecyl sulfate, SDS) as a co-stabilizer can not only control the influence of salt but also significantly improve the stability of nanofluids by controlling the agglomeration rate. It was found that SDS, as a stabilizer for SiO₂ nanofluids, improves nanofluid stability by controlling the agglomeration rate. Nanoparticles reduce the adsorption of surfactants onto porous media, and the combined effect of both achieves a higher recovery factor than that of surfactants or nanofluids acting alone, paving the way for future field applications. Hendraningrat et al.[36] conducted a systematic study on hydrophilic metal oxide nanoparticles (NPs) dispersed in brine using three coupled methods: direct visual observation, surface conductivity measurement, and particle size measurement. It was found that NPs improve the stability of metal oxide nanofluids, and that NPs alter the surface conductivity, pH value, and particle size distribution of the nanofluids. The researchers also performed two core flooding experiments, injecting stable nanofluids into water-wet and oil-wet core plugs. The combination of metal oxide nanofluids and dispersants was more effective in increasing crude oil recovery factor than using silicon-based nanofluids or dispersants alone. Wettability alteration plays a dominant role in the nano-EOR flooding mechanism. Magda et al.[37] studied the effect of commercial silica nanoparticles (SiNPs, approximately 20 nm in size) on recovery factor. They conducted three oil recovery experiments on a single core. The influence of nanofluid concentration on recovery factor was investigated; by calculating residual oil saturation to determine displacement efficiency, they studied silica nanofluids at concentrations of 0.01 wt%, 0.05 wt%, 0.1 wt%, and 0.5 wt%. The results showed that as silica nanofluid concentration increased, the recovery factor continuously improved, and the optimal silica nanoparticle concentration was 0.1 wt%, yielding the highest recovery factor. Compared with simple water flooding, the final recovery factor of crude oil increased by 13.28% after three-stage silica nanofluid flooding. Silica nanofluid flooding is a promising method for increasing recovery factor after water flooding.

Nanotechnology has been widely applied in oil extraction engineering. Oil-dispersing membranes prepared using nanotechnology exhibit better oil-dispersion effects than conventional ones. Compared with surfactants, nanofluidic membranes not only have better oil-dispersion performance but also possess many advantages. For instance, because nanofluidic membranes are composed of substances such as biological enzymes, macromolecules, and proteins, they have a strong electrostatic repulsion effect. Additionally, nanofluidic membranes can enhance the adhesion force between oil molecules, thereby better separating oil from

particulate impurities and water molecules in crude oil, thus improving oil extraction efficiency[38].

The main mechanism of pressure reduction and injection increase after injecting nanomaterials into the oil layer is to effectively expel the water film adsorbed on the inner surface of pores, expand the pore diameter, and significantly reduce the resistance of injected water flowing through pores, while avoiding hydration, thereby reducing injection pressure and balancing differences among injection wells. Lu Xianliang et al.[39] discovered in 2003 that nano-polysilicon materials have extremely strong hydrophobicity. This technology can be used to unclog, reduce pressure, and increase injection in water injection wells of low-permeability oil reservoirs, increasing the water absorption capacity of injection wells by 200% to 600%. It has significant advantages such as simple construction and no pollution, and yields remarkable economic benefits. When materials approach the nanometer scale, they exhibit three small-size effects: surface effects, quantum size effects, and macroscopic quantum tunneling effects.

Yang Lingxin et al.[40] used an additive activated by gamma-ray radioactivity for nanomodification and obtained good results with an aviation silicon polysilicon nanomaterial having discrete particle sizes ranging from 10 to 500 nm in the Wen Dong Oilfield. It is a granular white powder with a hydrophobicity rate exceeding 99%. The polysilicon nanomaterial, primarily composed of SiO₂, has extremely strong hydrophilic ability and strong adsorption capacity, effectively expanding the pore radius, significantly reducing the flow resistance of injected water in pores, and also separating the contact between formation rocks and water, thereby avoiding hydration and achieving the purpose of pressure reduction and injection increase in injection wells. Sun Zhiguo et al.[41] implemented polysilicon nanocomposite injection enhancement technology in 2005 in the Liangjialou Oilfield (Lixing Oilfield, Shengli Oilfield). This well had been acidized and treated for injection enhancement multiple times, with a general validity period of only one month and injection volumes generally below 200 m³/d. However, after the implementation of the injection enhancement technology, the construction effect was obvious, with daily injection reaching 400 m³, achieving the best injection effect since the well began injection. The results show that polysilicon nanocomposite injection enhancement technology can alter the wettability of the rock surface, increase permeability, and reduce injection pressure. This technology is suitable for enhancing injection in water wells with certain permeability and pressure relief capacity in medium- to low-permeability oilfields. After field implementation, the water flow resistance during injection decreased significantly, and the injection effect was good. Wang Yucheng[42] conducted experimental research in the Huicheng Oilfield (Shanshan County, Xinjiang Uygur Autonomous Region) in 2009. It was found that the injection mechanism of nano-polysilicon involves physical adsorption onto the rock surface to change rock wettability, peel off the water film, and prevent clay swelling and migration, thereby increasing water-phase permeability and reducing water flow resistance, thus achieving pressure reduction and injection increase. Field experiments in the Huicheng Oilfield demonstrated that nano-polysilicon injection enhancement technology can improve the water absorption capacity of the reservoir, reduce injection pressure, and play an important role in improving the injection development effect of this

oilfield. Li Hongmei[43] discovered that wax nanoemulsion has good compatibility with the polymer drilling fluid system commonly used in low-permeability oil reservoirs, improving the rheological properties of the system, reducing fluid loss, providing an obvious lubrication effect, and inhibiting the hydration swelling and dispersion of clay. It causes low damage to the core and provides good reservoir protection. Wax nanoemulsion was successfully tested in five wells in the Changjiang Oilfield. The results showed that after adding the wax nanoemulsion, there was no wellbore collapse, the drilling process was unobstructed, completion electrical logging and casing running operations were smooth, drilling efficiency was improved, oil and gas production was high, and the environmental protection effect was good.

The field application of nanomaterials in enhanced oil recovery (EOR) for oil and gas shows great potential and prospects, and has become a new technological direction for increasing efficiency in oil and gas development. Numerous studies have shown that nanoparticles such as silica and metal oxides can be combined with oil-soluble sulfonates, polyacrylamide, and other oil-displacing agents to form composite systems, effectively reducing oil-water interfacial tension, altering the wettability of reservoir rocks, and reducing crude oil viscosity. Through the synergistic effect of nanofluids and surfactants, the oil recovery factor can be significantly improved. At the same time, nano-microspheres can achieve sealing of high-permeability layers in the reservoir, mobilize low-permeability remaining oil, and further expand the swept volume of water flooding. Polysilicon nanomaterials can alter rock surface wettability, peel off the pore water film, and inhibit clay hydration swelling, thereby reducing pressure and increasing injection in water injection wells of low-permeability oil reservoirs, while improving water absorption capacity. Wax nanoemulsion has good compatibility with drilling fluids and also provides functions such as lubrication, wellbore stability, reservoir protection, and improved drilling efficiency. In summary, nanomaterials have opened up a new technical path for improving oil and gas recovery factors and for the efficient development of oilfields.

5. The Application of Nanotechnology in Oil Displacement

The small size advantage of nanometer microspheres enables a single large-sized microsphere to expand and seal pore throats during migration, while multiple small-sized microspheres can aggregate and accumulate to achieve sealing[44]. Under applied pressure, numerous microspheres continuously undergo hydration expansion, sealing, deformation, and resealing within pore throats. At the same time, they can also alter oil-water interfacial tension and reservoir wettability through their hydrophobic and hydrophilic groups, thereby improving oil displacement efficiency[45]. Bai Jiang et al.[46] independently prepared polymer-based nanometer microsphere oil displacement agents in the laboratory, characterized and evaluated their microstructure, morphology, and performance, and analyzed their in-depth profile control and displacement mechanism. Through laboratory core flooding experiments, the injection parameters for the polymer nanometer microsphere system were selected and applied in field-scale tests. Using inverse microemulsion polymerization, polymer nanometer microspheres with a particle size of approximately 60 nm

were prepared. The effective mass fraction of separable solids exceeds 20%, and the microspheres exhibit good salt resistance and swelling properties, which favor enzymatic hydrolysis and fermentation conversion. Under high dry-matter content conditions, longer enzymatic hydrolysis time leads to lower cumulative concentration of soluble polysaccharides and more complete substrate degradation, which is beneficial for improving substrate utilization and ethanol fermentation yield.

Li Chen et al. [47] utilized the far-well sealing property of polymer nanometer microspheres and the near-well displacement property of modified nano-SiO₂ to develop a nanometer microsphere-based oil displacement system. Based on inverse microemulsion theory, they prepared polymer nanometer microspheres and silane coupling agent-modified nano-SiO₂ with good performance, and analyzed the chemical mechanisms. Combined with core flooding experiments and field well-group tests, the displacement effects of the two materials in low-permeability oilfields were evaluated. The results showed that sequential injection of polymer nanometer microspheres followed by modified nano-SiO₂ produced a positive synergistic effect, achieving effective sealing of high-permeability formations while also improving oil-washing efficiency in low-permeability zones, ultimately increasing the crude oil recovery factor. Li Zhenwu et al. [48] reviewed the action mechanisms of nanomaterials for oil displacement, including: reducing surface/interfacial tension to increase the number of capillary tubes and reduce oil displacement resistance; the structural disjoining pressure effect, which enhances the dynamic spreading behavior of nanofluids at the microscopic level, detaching oil droplets from the rock surface and improving oil mobility; wettability alteration—because oil displacement efficiency during water flooding is higher in strongly water-wet layers than in strongly oil-wet layers, nanoparticles can change rock wettability from oil-wet to water-wet, thereby strengthening water imbibition; microemulsions (a highly dispersed low-tension system composed of water, oil, surfactant, co-surfactant, and salt in certain proportions) constitute an effective chemical technology for reducing residual oil saturation by lowering interfacial tension or improving the viscosity ratio, enabling dispersed oil droplets or films to flow and coalesce, enhancing system stability; improving the displacement ratio to increase volumetric sweep efficiency; inhibiting asphaltene deposition and catalyzing asphaltene decomposition to prevent pore blockage and reduce formation damage; and inhibiting particle migration to reduce formation damage.

Zhang Zhichao et al. [49] addressed the problem that in low-permeability and ultra-low-permeability unconventional reservoirs under waterflood development, water injection often cannot enter the reservoir, making production difficult. They systematically discussed the oil recovery mechanisms of microemulsion flooding for pressure reduction, formation profile control, water shutoff, and reservoir protection to improve recovery efficiency. The viscosity of microemulsion in the injected reservoir is higher than that of water. Compared with water flooding, microemulsion flooding can improve the oil-to-water mobility ratio and reduce the viscosity of the displacing fluid. Moreover, when the microemulsion contacts oil, it generates extremely low interfacial tension, reduces capillary resistance, alters rock wettability, and expands the macroscopic sweep volume of the reservoir. In addition, as the microemulsion flows through

reservoir pore channels, it can enhance oil-washing efficiency through crude oil solubilization, elastic drag, and other synergistic effects. Typically, the injection pressure of water injection wells in low-permeability reservoirs can be reduced by more than 35% using this method, and oil production performance is also improved. Yin Junrong et al. [50] believed that nanoemulsions adsorb at the oil–water interface, causing the related molecules to become closely arranged, resulting in a significant decrease in surface tension, an increase in contact angle, and a reduction in capillary resistance. This enables better removal of residual fracturing fluid. They also provided formulas for calculating adhesion work, capillary number, and mobility ratio, indicating that the lower the interfacial tension, the less adhesion work is required, and the easier it is for oil droplets to detach from the rock surface; the larger the cosine of the contact angle, the greater the capillary force, and the easier oil droplets detach. Consequently, the capillary number increases, the oil–water interface advances uniformly through pores of different diameters, residual oil saturation decreases, and oil recovery efficiency improves. When the mobility ratio is less than 1, crude oil mobility is greater and the swept area is larger. Maintaining the mobility ratio at ≤ 1 can better improve the recovery factor of unconventional reservoirs. Xu Ning et al. [51] conducted a series of experiments including multiphase media imbibition, sequential injection, and cyclic displacement to clarify the efficiency variation characteristics of nanoagent imbibition and displacement, as well as secondary oil recovery development methods and the potential for improving oil recovery efficiency through sequential development. The imbibition experiment showed that nanoagent displacement efficiency exhibited four stages: blank period, high-speed period, rapid period, and low-speed imbibition and displacement period. This finding helps determine a reasonable well shut-in time based on the imbibition mechanism. The sequential displacement experiment showed that the displacement efficiency of the nanoagent during the sequential displacement stage was close to that during the imbibition stage, and the combined displacement efficiency reached 74.67%, with residual oil saturation reduced by 7.43% compared with water flooding. Cyclic displacement can better leverage the nanoagent's ability to imbibe and displace remaining oil in micro- and nano-pores and throats, thereby improving microscopic sweep efficiency. Oil recovery efficiency was 14.1 percentage points higher than that of continuous displacement (with an injection of 0.478 PV). Therefore, timely switching to nanoagent cyclic displacement after horizontal well stimulated reservoir volume fracturing is an important direction for secondary oil recovery to significantly improve the recovery factor of unconventional reservoirs.

6. The Application of Nanotechnology in The Secondary Development of Old Oil Fields

In well completion technology, a salt-resistant, low-filtration-loss agent containing lignin nanoparticles was used. Before aging, the filtration loss volume decreased from 194 mL to 4 mL, and after aging, it decreased from 212.0 mL to 13.8 mL [52]. In the technology for improving the injection–production relationship, a certain heavy oilfield with river-type sandstone reservoirs operated by the China National Offshore Oil Corporation (CNOOC) had an overall

water cut exceeding 94%, and 80% of the well groups exhibited inefficient or ineffective water injection circulation. From 2009 to 2019, multiple rounds of nanosphere deep stimulation were carried out. A deep stimulation effect evaluation model was established using injection pressure and pressure drop as variables, and the deep stimulation performance was assessed. After the treatments, a cumulative oil increase of 11.4×10^4 t (114,000 t) was achieved. Modified nanomaterials compounded with polymers, surfactants, and other agents for deep stimulation are of great significance for improving the recovery factor[53].

Oil reservoir nanorobots can precisely delineate the reservoir, control the scale of investigation, accurately identify and determine the distribution of faults, fractures, and high-permeability channels, and precisely identify and track the distribution of remaining oil and gas in the reservoir. In the secondary development of mature oilfields, they can optimize well placement design and establish precise reservoir geological models, thereby increasing the proven reserves and recoverable reserves of the oilfield and extending its development lifecycle.

7. Applications and Progress of Oil Reservoir Nanorobots

Nanorobots are “functional molecular devices” designed and manufactured based on molecular-level biology and capable of operating in nanoscale spaces. They are smaller than 1/1000 the diameter of a human hair and have been widely applied in medical and military fields. After proposing the concept of reservoir nanorobots in 2007, Saudi Aramco completed a feasibility study on injecting and recovering nanorobots into reservoirs in 2008, and successfully conducted field tests of reservoir nanorobots in 2010. In June 2010, Saudi Aramco injected 250 barrels of diluted nanorobots into the Arab-D formation[54]. Fluorescence spectroscopy was used to analyze the produced samples, confirming that the nanorobots had a very high recovery rate [55], and the fluid carrying the nanorobots exhibited good stability and fluidity. This marks a milestone achievement in nanorobot research.

In the context of oil production engineering, nanorobots have transcended traditional constraints. As integrated systems combining chemical molecular systems and mechanical systems, they can understand the matrix, fractures, and fluid properties between wells, as well as the “functional molecular devices” related to oil and gas production changes. They have broken through the limitations of existing logging and geophysical exploration technologies in terms of detection range or resolution. They can measure and report the reservoir environment, interact with it, and even monitor and alter reservoir properties. Reservoir nanorobots have multiple applications in oil exploration and production: assisting in delineating reservoir boundaries, drawing fracture and fault maps, identifying and determining high-permeability channels, identifying overlooked oil and gas in the reservoir, optimizing well design and establishing more effective geological models. In the future, they may also be used to deliver chemicals into the deep reservoir for oil displacement[56][57]. Nanorobots used in oilfield logging can be placed in drilling mud to obtain useful information. Nanorobots are equipped with sensors, vehicle-mounted drive mechanisms and microcomputer interface mechanisms, and they can send instructions to microcomputer computers[58].

The research and development of reservoir nanorobots has made significant progress, but many technical problems remain to be solved and challenges to be faced. Fu Yarong et al.[59] raised several questions: how to deploy nanorobots in reservoirs; what methods should be adopted to effectively send nanorobots into reservoirs; how nanorobots move in reservoirs, either actively or passively; how to conduct telemetry and positioning of nanorobots in reservoirs; how to provide communication and collect data from millions of nanorobots entering reservoirs in real time; how nanorobots can detect oil and gas resources outside the injection (percolation) channels; and what is the appropriate detection depth for nanorobots. These are all problems that need to be solved. Currently, the primary issue to be addressed is the detection capability of nanorobots. Nevertheless, the prospects in the field of oil production engineering are very broad, with nearly unlimited possibilities, which can help extend the production life of oil wells and slow the natural decline of oilfields.

8. Conclusion

This article reviews the development history of nanotechnology and its current application status in the petroleum field. By synthesizing relevant research and field case studies, it summarizes the achievements and provides an outlook for the future. Nanotechnology has become deeply integrated into the entire process of petroleum exploration and development and demonstrates great potential: downhole nanosensors can accurately obtain key reservoir parameters; in drilling, nano-zinc oxide, lignin nanoparticles, and other materials effectively resolve issues such as filtration loss and corrosion of drilling fluids, while wax nanoemulsions offer multiple benefits. Improving the recovery factor and oil displacement efficiency are its core application directions. The combination of nanomaterials with displacement agents, nano-microsphere sealing, and nanofluid synergy can significantly enhance the recovery factor. In the secondary development of mature oilfields, nanotechnology has achieved remarkable results in reducing filtration loss and increasing oil production. Field testing of reservoir nanorobots has achieved breakthroughs, and their application potential is enormous; however, technical challenges such as deployment and telemetry remain to be resolved. In addition, the task of reducing costs while increasing efficiency with nanomaterials remains highly challenging. The high cost of existing nanomaterials directly results in most novel materials staying at the laboratory research stage. How to effectively reduce the cost of nanomaterial preparation and modification processes, and how to make improvements in property evaluation and product development, still needs to be addressed.

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