ADVANCES OF NANOTECHNOLOGY IN THE PETROLEUM INDUSTRY

Human's growing knowledge and ability to manipulate matter at the atomic and molecular levels has led to many previously unimagined possibilities for scientific discovery and technological breakthrough. Nanotechnology represents an emerging field of research and innovation with great potential to change the world [1]. Defined by the National Nanotechnology Initiative, nanotechnology is the manipulation of matter at the atomic, molecular or macromolecular levels, at a length scale of approximately 1 to 100 nanometers (a nanometer is one-billionth of a meter) [2]. The exceptionally small size of nanomaterials leads to the development of structures, devices and systems with novel properties. Products of nanotechnology are smaller, cheaper, and lighter while also being more functional and requiring less energy and fewer raw materials to manufacture [3]. These products are expected to increase the efficiency of energy consumption, help clean the environment, solve health problems, and increase manufacturing production at significantly reduced costs [3]. Characteristics such as color, strength, conductivity, and reactivity differ substantially between the nano-scaled materials and their macro-scaled counterparts, resulting in unique properties for the former [2]. Since nanotechnology plays such an important role in society, examining its applications and history of development is important.

In 1959, American physicist and Nobel prize winner, Richard Feynman initially introduced the concept of nanotechnology at the annual meeting of the American Physical Society at Caltech [4]. His work caught the attention of many scientists, and they eventually developed two possibilities for the synthesis of nanostructures: top-down and bottom-up, which differ in degrees of cost, speed and quality [4]. The top-down approach is the breakdown of a bulk material to obtain nano-sized particles. In the "bottom-up" approach, materials and devices are built from molecular components, which self-assemble themselves chemically by principles of molecular recognition [5].

Carbon nanotubes are a common nanomaterial applied into composite fibers in polymers and exploited for their high electrical conductivity and efficiency in conducting heat [4]. In 1991, Sumio Iijima discovered carbon nanotubes by Transmission Electron Microscopy (TEM) which formed another allotrope of carbon, following the discovery of fullerenes (Figure 1) [4]. The exceptional strength and flexibility along with the conductivity of these cylindrical carbon molecules render them useful in many nanotechnology applications, such as high-strength structures, capacitors, and solar cells [5].

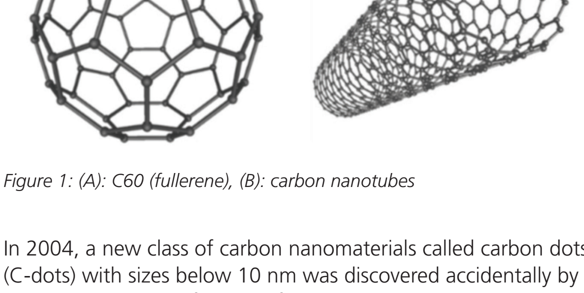

Figure 1: (A): C60 (fullerene), (B): carbon nanotubes

In 2004, a new class of carbon nanomaterials called carbon dots (C-dots) with sizes below 10 nm was discovered accidentally by Xu et al. during the purification of single-walled carbon nanotubes [6]. C-dots have gradually become a rising star as a new nanocarbon member due to their benign, abundant and inexpensive nature [6]. Properties such as low toxicity and good biocompatibility render C-dots favorable materials for applications in bioimaging, biosensing, and drug delivery [4]. Based on their excellent optical and electronic properties, C-dots also offer exciting opportunities for catalysis, energy conversion, photovoltaic devices, and nanoprobes for sensitive ion detection [6].

The beginning of the 21st century was a period when the fields of nanoscience and nanotechnology sparked the public's interest. Recently, several studies highlighted the significance of nanotechnology in biomedicine for the diagnosis and therapy of many diseases. The applications of nanotechnology in many biology related areas such as diagnosis, drug delivery, and molecular imaging are being intensively researched as studies have shown excellent results [4]. One of the most important applications of nanotechnology to molecular biology has been in investigating nucleic acids and the complexity of genes. Additionally, the field of nano-oncology has shown remarkable progress by improving the efficacy of traditional chemotherapy drugs for a plethora of aggressive human cancers [7]. These advances were achieved by targeting the tumor site with several functional molecules including nanoparticles, antibodies and cytotoxic agents [7]. In this context, many studies showed that nanomaterials can be employed to deliver therapeutic molecules or to modulate essential biological processes directly, like autophagy, metabolism or oxidative stress, exerting anticancer activity [4]. Nano-oncology is an attractive application of nanoscience and allows for the improvement of tumor response rates in addition to a significant reduction of the systemic toxicity associated with current chemotherapy treatments [4].

Another interesting application of nanoparticles is in the petrochemical industry, which includes increasing oil recovery, improving foam stability, cementing, filtration characteristics, and many more. Figure 2 shows the targeted areas for improvement by means of nanoparticles reported in 2020 [8]. The pie chart clearly demonstrates that nanoparticles have been investigated to a great extent to study their effects on increasing oil recovery, including enhanced oil recovery (EOR) applications. Two-thirds of the oil remains after the primary and secondary recovery; therefore, a number of studies have been conducted into the different EOR techniques with the addition of nanoparticles [8]. EOR involves different methods for the purpose of increasing the amount of crude oil that can be extracted from a hydrocarbon reservoir [9]. These methods include chemical injection, thermal recovery, and gas injection.

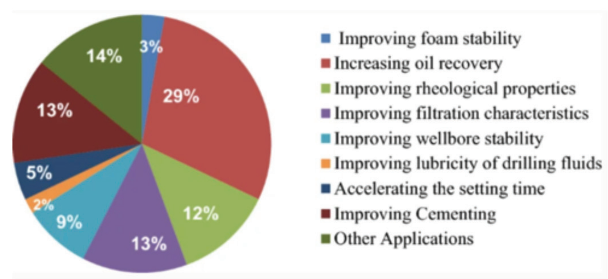

Figure 2: Targeted property of improvement by means of NP [8]

Since nanoparticles can pass through the pore throats in typical reservoirs, they can be retained by the rock. Therefore, information locating the position of the oil needs to be addressed firmly before applying nanoparticles in EOR [9]. Research in 2009 investigated injecting concentrated aqueous suspensions of surface-treated silica nanoparticles (up to approximately 20 wt. %) with diameters of 5 nm and 20 nm into sedimentary rocks of different lithologies and permeabilities [10]. The nanoparticles in an aqueous dispersion assemble themselves into structural arrays at a discontinuous phase, forming a wedge-like structure and forcing themselves between the discontinuous phase and the substrate (Figure 3) [10].

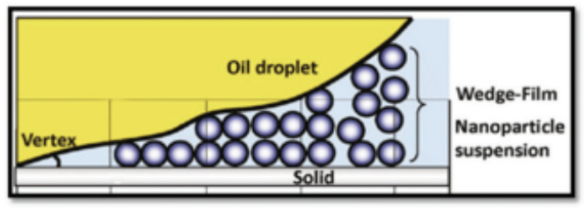

Figure 3: Nanoparticle structuring in the wedge-film [10]

Particles present in the bulk fluid exert pressure forcing the particles in the confined region forward. The energies that drive this mechanism are Brownian motion and electrostatic repulsion between the particles [10]. Even though the force imparted by a single particle is extremely weak, the force can reach up to 50,000 Pa when large amounts of small particles are present [10].

Table 1 lists a comprehensive review of the publications on investigated nanoparticles with their targeted and improved parameters, with the objective of enhancing EOR techniques [8]. The nanoparticles investigated were mostly oxides of aluminum, graphene, titanium, and silicon, as well as nanocellulose.

The extent to which the advances of nanotechnology have impacted multiple disciplines, including materials science, the biological field, and the petrochemical industry, has made it an interdisciplinary research area, with researchers from various fields such as physics, chemistry, materials science, computer science, and medicine coming together to find solutions for future challenges [4].

Table 2 illustrates the timeline for the development of nanotechnology during the time period between 2000 and 2020. Nanotechnology has evolved in four generations of products and production processes, in terms of industrial prototyping and nanotechnology commercialization [1]. Passive nanostructures are the first generation of nanotechnology products. These materials are relatively simple with passive or merely reactive behavior and have steady or quasi-steady structures and functions during their use [1]. Aerosols, colloids, polymers and ceramics fall into this category and are readily available in the market today. The second generation, established in 2005, is active nanostructures, which change their state during operation [1]. Examples are bio-active and physico-chemical devices including biodevices and actuators respectively. The third generation consists of integrated nanosystems. These systems are generated using various synthesis and assembling techniques and can be applied to the fields of nanomedicine or nanoelectronics [1]. The most recent and fourth generation of nanoproducts is heterogeneous molecular nanosystems. In this generation, each molecule in the nanosystem has a specific structure and plays a different role [1]. Molecules are used as devices in nanotechnology, and new functions will fundamentally emerge from their engineered structures and architectures [1].

As the development of nanotechnology remains an exigent area of research, there are many concerns regarding its benefits and risks. There are high expectations that nanotechnology can solve a bunch of social problems, such as global warming, and cure illnesses like cancer. On the other hand, research studies have shown that nano-sized particles accumulate in the nasal cavity, lungs, and brain, and the obscurity of the form of future nanotechnology has bred some end-of-the-world scenarios [3]. In conclusion, more research still needs to be conducted to understand nanotechnology to its fullest extent and account for possible toxic effects that some nanomaterials can have on humans, animals and the environment.

Table 1: A comprehensive review of the nanoparticles and their targeted parameters for EOR

Investigated NP	Improved parameters
Aluminum oxide Titanium dioxide	Reducing oil viscosity Improving the stability of the injected water for EOR application
Aluminum oxide Silicon dioxide	Improving oil recovery using low salinity hot water (LSHW) injection with addition of nanoparticles
Aluminum oxide Silicon dioxide Titanium dioxide	Improving the rheological properties of the injected water for EOR application Improving oil recovery
Cellulose nanocrystals (CNCs)	Conformance control Stability of oil in water emulsions
Graphene oxide	Reducing oil viscosity
Graphene oxide	Reduction in oil viscosity Increasing oil recovery
Graphene-based zirconium oxide nanocomposite	Reducing excess water production Used it as a cross-linker for water shutoff
Magnesium oxide Aluminum oxide Zinc oxide Zirconium oxide Tin oxide Iron oxide Nickel oxide Hydrophobic Silicon dioxide	Altering wettability Reducing interfacial tension Reducing oil viscosity Reducing mobility ratio Altering permeability
Nickel oxide/silicon dioxide Janus nanoparticles	Enhancing oil recovery at low concentration Reducing formation damage Reducing interfacial tension, hence increasing oil recovery
Polymer-coated nanoparticle	Improving mobility control, altering surface wettability
Silicon dioxide	Increasing sweep efficiency Improving foam stability for alpha-olefin sulfonate (AOS) solution Increasing oil recovery
Silicon dioxide	Improving foam stability Improving mobility reduction factor (MRF)
Silicon dioxide	Improving foam stability
Silicon dioxide	Reducing surfactant adsorption on the porous media of an oil reservoir
Silicon dioxide	Improving emulsion with lower surfactant concentration Improving oil recovery
Silicon dioxide	Reducing oil viscosity
Silicon dioxide	Improving surfactant properties Reducing surfactant adsorption on the porous media of an oil reservoir
Surface-functionalized nanocellulose	Improving oil recovery using "green" chemical EOR through water flooding

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Table 2: Timeline of nanotechnology development from 2000 to 2020 [1]

Period	Generation	Category	Examples
~2000	***1st Passive nanostructures (1st generation products)***		
		a. Dispersed and contact nanostructures	e.g. aerosols, colloids
		b. Products incorporating nanostructures	e.g. coatings; nanoparticle reinforced composites; nanostructured metals, polymers, ceramics
~2005	***2nd Active nanostructures***		
		a. Bio-active, health effects	e.g. targeted drugs, biodevices
		b. Physico-chemical active	e.g. 3D transistors, amplifiers, actuators, adaptive structures
~2010	***3rd Systems of nanosystems***		
			e.g. guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary biosystems
~2015–2020	***4th Molecular nanosystems***		
			e.g. molecular devices 'by design', atomic design, emerging functions

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https://www.petro-online.com/news/fuel-for-thought/13/koehler-instrument-company/dr-raj-shah-director-at-koehler-instrument-company-conferred-with-multifarious-accolades/53404

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