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Nanotechnology applied to the enhancement of oil and gas productivity and recovery of Colombian fields

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ABSTRACT

In Colombia, the estimated reserves of crude oil are approximately 2.0 thousand million barrels, decreasing by approximately 13% in the last year according to the National Hydrocarbons Agency (ANH). In addition, the exponential growth of the world population as well as increasing motorization and industrialization has led to higher demand for fossil fuels to supply energy requirements. Colombia is aware of this issue and has become a key player of incorporating advances in nanotechnology to address this challenge by increasing the productivity/reserves of crude oil. Nanotechnology progress in Colombia has been supported by academy – state – industry synergy, which has aimed to mitigate formation damage and enhance oil recovery to facilitate increases in oil productivity and reserves based on the development of nanoparticles/nanofluids. In this sense, Colombia has been a worldwide pioneer in the application of nanotechnology under field-scale conditions, which has led to significant increases in oil rate production. This document presents a review of the recent applications of nanotechnology in Colombia, from laboratory approaches to field conditions. This review addresses the development of nanoparticles/nanofluids for application to the inhibition/remediation of formation damage (asphaltenes, alteration of reservoir wettability from liquid-wet to gas-wet, and inorganic scales, among other applications), productivity improvement (hydraulic fracturing, drilling fluids, and improvement mobility of heavy and extra-heavy oils), enhanced oil recovery (EOR) and heavy oil transport. Finally, three cases of field trials employing nanofluids are discussed for inhibiting the formation damage of asphaltene in tight-condensate reservoirs and light oil crude, fines migration in tight-condensate reservoirs and mobility improvement of heavy and extra-heavy oils. It is expected that this document will aid in the alignment of the academic and industrial sectors to pursue and incentivize the opening of a wider range of applications under field conditions through the extrapolation of laboratory studies.

1. Introduction

The world has faced a crisis in oil prices since 2014 due to oversupply. Therefore, multiple nations, including Colombia, have elected to reduce their production and even to close fields for which production costs exceed profits. This decision has generated a reframing of the Colombian oil and gas industry based on investment in new strategies and/or technologies to improve the effectiveness of the production and transportation processes. In this sense, nanotechnology has recently emerged as an attractive topic of research in the oil and gas industry due to its exceptional characteristics that allow nanoparticles to travel smoothly through porous media without additional risks of pore blockage due to their small size (1–100 nm), which can be used to avoid formation damage. At the nano-scale, exceptional properties can be obtained, such as a high surface-area-to-volume ratio and dispersibility, in addition to high thermal, chemical stability and dispersibility. The reactivity of particles with nanometric dimensions is significantly enhanced because the functional groups on the material's surface are less hindered as the size of the particle decreases. In other words, atoms on the surface of the nanomaterials are not surrounded by other atoms of the material and can therefore interact with other compounds.

Further, it is of primary importance to clarify the nanotechnology concept and selected pioneer applications. Nanotechnology refers to the work of the professor Richard P. Feynman (1960) entitled "*There's plenty of room at the bottom*", in which he expressed his desire to open a wider landscape in which the problems associated with "*manipulating and*

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Nomenclature

ANH	Nation hydrocarbons agency (Colombia)
API	American Petroleum Institute
A:R ratio	Asphaltene-to-resin ratio
BSW	Base sediments and water
C_i	Asphaltene initial concentration
CHS	Chemical Stimulation
CMC	Carboxymethyl cellulose
CNS	Synthesized carbon nanospheres
DAO	De-asphalted oil
DAX	Diesel-alcohol-xylene (organic removal treatment)
DLS	Dynamic light scattering
DTPMP	Diethylenetriamine -pentamethylene
EDTA	Ethylenediaminetetraacetic acid
EHO	Extra heavy oil
EOR	Enhanced oil recovery
e-SDA	Enhanced solvent de-asphalting
G″	Viscoelastic modulus
HO	Heavy oil
HPAM	Partially hydrolyzed polyacrylamide
IEA	International energy agency
IOR	Improved oil recovery
IPR	Inflow performance relationship
K	Permeability
Kr	Relative permeability
Kro	Relative permeability of water
Krw	Relative permeability of oil
M	Solution volume to the dry mass of the nanoparticles ratio
MD	Measured depth
NEOR	Nanoparticles/nanofluids for enhanced oil recovery
NP	Nanoparticle
OBN	Oil-based nanofluid
PV	Pore volume
PVI	Pore volumes injected
Pwf	Bottomhole flowing pressure
Q	Injection rate
Qo	Oil rate production
SCMD	Simplex-centroid mixture design
SDA	Solvent de-asphalting
SHS	Supported hygroscopic salt
SimDis	Simulated distillation
Sor	Residual saturation of oil
SP	Softening point
Swr	Residual saturation of water
SY	Sylnil (Anionic surfactant)
TGA	Thermogravimetric analysis
VLP	Vertical-lift performance
W/O	Water-in-oil
W/O/W	Water-in-oil-in-water
XG	Xanthan gum

controlling things on a small scale" could be solved. A nanometer is a billion times smaller than a meter (1×10^{-9} m), approximately equivalent to the diameter of a DNA chain (2.5 nm), one thousand times smaller than the mean size of a bacterium, and a billion times smaller than a tiny droplet of water (National Nanotechnology Initiative). By definition, a nanomaterial is one with dimensions between 1 and 100 nm; such as material can be classified as a nanoparticle, nanofiber, nanosphere or nanofilm depending on its morphology and its physicochemical characteristics. Specifically, a nanoparticle is a solid particle with defined geometry in the nanosize range and a nanofluid is a stable suspension of nanoparticles in determined carrier fluid (Sheikholeslami and Ganji, 2016d). Nanotechnology has been applied in areas of knowledge such as energy storage, production, and conversion (Elmouwahidi et al., 2017; Leschkies et al., 2007; Liu et al., 1999; Randviir and Banks, 2017; Rowell et al., 2006), agricultural productivity enhancement and food processing (Avella et al., 2005; Cerqueira et al., 2017; Duncan and Singh, 2017; Grillo et al., 2012; Pérez-de-Luque and Rubiales, 2009; Ramesh et al., 2010; Sorrentino et al., 2007), water treatment and remediation (Anbia and Amirmahmoodi, 2011; Dasgupta et al., 2017; Franco et al., 2014a; Nassar, 2012), medicine (Bayford et al., 2017; du Toit et al., 2010; Gupta and Jain, 2010; Jahangirian et al., 2017; Moghimi et al., 2005; Nie et al., 2007; Sumer and Gao, 2008; Wagner et al., 2006), air pollution and remediation (Cheng et al., 2006; Nakajima et al., 2000; Nel et al., 2006; Yu et al., 2017), heat transfer enhancement (Dogonchi et al., 2017; Sheikholeslami and Ganji, 2016c, 2017a,c), construction (De Matteis et al., 2017; Makar and Beaudoin, 2004; Sierra-Fernandez et al., 2017; Zhu et al., 2004), and pest detection and control (Bhattacharyya et al., 2010; Yang et al., 2009; Zhang et al., 2017), among others. Nanotechnology is currently the focus of attention in the scientific community, including the most recent Nobel Prize in Chemistry (2016), which was awarded jointly to Jean-Pierre Sauvage, Sir J. Fraser Stoddart and Bernard L. Feringa *"for the design and synthesis of molecular machines"* (Class for Chemistry of the Royal Swedish Academy of Sciences, 2016).

For the oil and gas industry in particular, different applications of nanoparticles and nanofluids have been proposed, including drilling operations, production improvement, inhibition of formation damage, enhanced oil recovery, heat transfer improvement, wastewater treatment, and improvement of mobility of heavy and extra-heavy oils under both surface and reservoir conditions, among others. In Colombia, where the drilling and exploration operations have been reduced considerably due to the sector's crisis, a need exists to develop new and cost-effective technologies that allow the optimization of the available resources for preventing a national energy crisis in a short-term period. Thus, the academic sector, as aligned with the industry and the respective state entities, has focused its efforts in the development of nanotechnology-based solutions. One of the primary applications of nanoparticles/nanofluids is the inhibition of various mechanisms associated with formation damage for improving the productivity of oil and gas wells. On this basis, the first field trial of nanotechnology application was performed in the Cupiagua Field in Colombia and aimed at inhibiting the formation damage caused by the precipitation and deposition of asphaltenic compounds. Other research areas associated with formation damage that have been studied are fines migration, condensate banking, damage in hydraulic fracturing and drilling operations, inorganic scale deposition, alteration of reservoir wettability from liquid-wet to gas-wet, and improvement of heavy and extra-heavy oil mobility, among other areas. Furthermore, the success of the nanotechnology applied to formation damage inhibition has led to expansion in other applications. Indeed, due to the significance of heavy and extra-heavy oils in Colombia, different solutions based on nanoparticles/nanofluids have been proposed and include the reduction of oil viscosity and the improvement of oil mobility under both reservoir and surface conditions. In addition, nanotechnology has shown potential for enhancing the heat transfer efficiency, improved oil recovery (IOR) and enhanced oil recovery (EOR) processes and up to the diluent reduction used for heavy oil (HO) and extra-heavy oil (EHO) transport. Nevertheless, despite significant advances in nanoparticle and nanofluid technology in Colombia, the industrial sector still lacks initiative for the implementation of most of the proposed solutions in field trials. In the specialized literature, different authors have focused their efforts on the review of recent advances in nanotechnology to overcome different problems in the oil and gas industry with emphasis on nanomaterial design (Khalil et al., 2017), application of silica nanoparticles (Fakoya