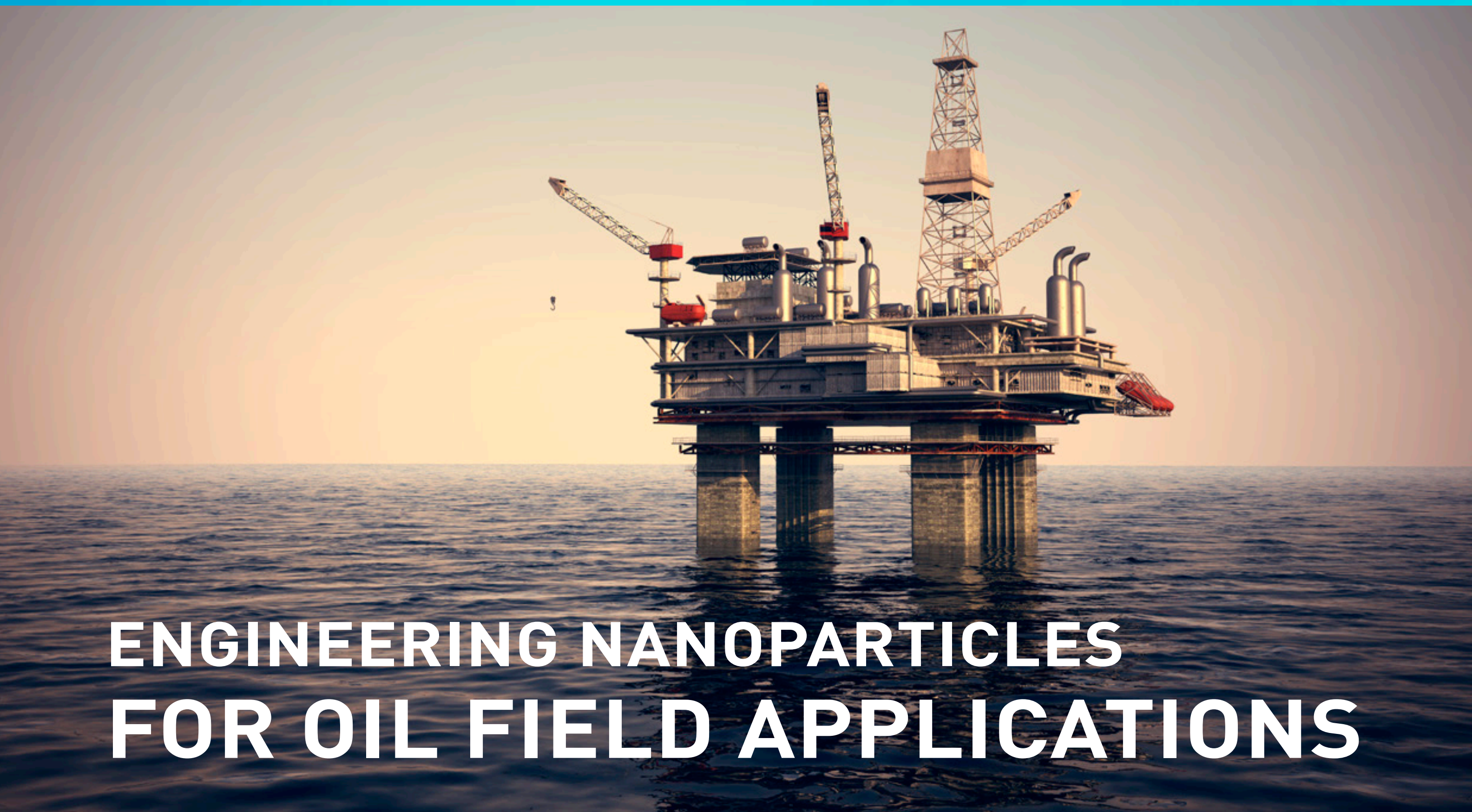

ENGINEERING NANOPARTICLES FOR OIL FIELD APPLICATIONS

Nanoparticles have already contributed to the technological advances in a variety of industries, such as medicine, electronics, biomaterials and renewable energy production, etc., over the last decade. Recently, a new interest springs up with the application of nanoparticle-based technology in the upstream petroleum industry. Large-scale molecular dynamics simulations could provide fundamental understanding of the role of smart nanoparticles on the upstream oil production, such as enhancing oil transport in micro/ nano-sized channel and the prevention of pressure-induced crack of cement sheath behind the casing.

AUTHORS
Jianyang Wu, PhD
Nanomechanical Lab
NTNU

Jianying He
Associate Professor,
Nanomechanical Lab
NTNU

INTRODUCTION

Energy is the number one in the humanity's top ten problems for the next 50 years. Currently, the main source of energy comes from the easily accessible energy such as oil, gas, and coal. And the oil and gas resource will still dominate the energy mix in near future, although renewable energy such as solar, wind power, bio-mass/-fuel, and geothermal energy, will experience fast growth. With the passing of the era of easy oil and the increasing difficulty of finding new economic resources, much attention of the traditional oil and gas industry has been directed to extract more resources from existing mature oilfields and from the fields exposed to extremely harsh environments by exploring new technologies and solutions.

Nanoparticles defined between 1 and 100 nanometers in size hold unexpected properties that differ remarkably from those observed in bulk materials primarily originating from the large surface-area-to-volume ratio. Structurally, the decreasing of particle size can directly result in changes in spacing between atoms. This effect is related to the compressive strains induced by the compression of surface atoms as a result of reduction of surface energy. Small nanoparticles therefore adopt a different crystal structure than their bulky counterpart. Once the compressive strain becomes critical, phase transformation spontaneously occurs. From the chemical point of view, size reduction changes the chemical reaction ability due to the increase in surface area to volume ratio. For example, the utilization of nanoscale particle catalysis can significantly enhance the rate, selectivity and efficiency of chemical reactions, and simultaneously result in reduction of waste and pollution. Moreover, a substance can dissolve easily at nanoscale although may not be soluble in water at micro scale. Mechanically, NTNU nanomechanical lab demonstrated by both experiment and molecular dynamics (MD) simulation that there exists a strong size effect in polymeric particles with diameters at nanometer length scale. The source for the increases in modulus is the increase in relative surface energy for decreasing particle sizes. Because of the unique properties of nanoparticles, it is believed that engineered nanoparticle can play a significant role in an upstream oil and gas industry, including exploration, drilling and completion, production and especially enhanced oil recovery. This paper presents some insights on the effect of nanoparticle on oil/water binary mixture transport through a nano-sized channel by MD simulation [1]. In addition, we also discuss the study of nanoparticle-based smart cement for oil and gas production by using large scale computational resource.

NANOPARTICLES FOR ENHANCED-OIL-RECOVERY

Up to now, oil recovery has experienced its primary and secondary stages, some bottlenecks are met in the conventional methods. One of the most promising potentials is to utilize the nanoparticles to increase the recovery efficiency of oil in the reservoirs. It mainly reflects in theses aspects: changing the properties of the fluid, wettability alternation of rocks, advanced drag reduction, strengthening sand consolidation, reducing the interfacial tension and increasing the mobility of the capillary-trapped oil. MD simulation is a powerful tool to understand the deformation and flow behavior of nanoparticles and its link to the atomistic structures. A fundamental understanding of the role of nanoparticles on the oil-water binary mixture in a confined nanochannel was studied by using MD simulations based on CLAY force-field. A set of computational experiments in which hydrophilic silica nanoparticles mixed with an oil-water system confined in kaolinite clay nanochannels were performed by MD simulations.

We first examine the effect of nanoparticle on a clay-oil-water system without a driving pressure. Figure 1 presents initial and equilibrium configuration snapshots of a clay-oil-water-nanoparticle multiphase system. Nanoparticles are placed in middle of both oil and water aqueous. After a simulation time of 4 nanoseconds, nanoparticles move towards and stick to the clay wall due to both van der Waals and coulombic force between nanoparticles and clay. This implies that the presence of nanoparticles changes the interface properties between aqueous and clay due to a new surface formation by nanoparticle. The same phenomenon is observed for the cases of nanoparticle placed only in oil or in water.

To reveal the effect of nanoparticles on the oil-water flow through the nanochannel, three cases of one, two and four nanoparticles placed in water phase of left reservoir were investigated, respectively. Figure 2 displays a typically perspective snapshot of oil/water fluid with four nanoparticles in a clay nanochannel. It is observed that the flow pressure of oil-water mixture with nanoparticle through the confined nanochannel is found to be strongly channel size dependent. The presence of nanoparticles not only alters the dynamical and structural properties of oil-water-clay systems, but also enhances the oil-water flow through the nanochannel at a small nanoparticle concentration, which implies that nanoparticles can be potentially utilized for enhanced oil recovery. While the nanoparticle-free oil-water flow behaves in a laminar flow manner, with the increase concentration of nanoparticle the flow tends to change from a laminar to turbulent type. The nanoparticle first slides along the clay wall in a local low velocity with the process of breaking and forming hydrogen bonds, whereas it rotates forwards in a local high velocity aqueous environment, and escapes from the attractive clay wall ultimately to enter into the nanochannel.

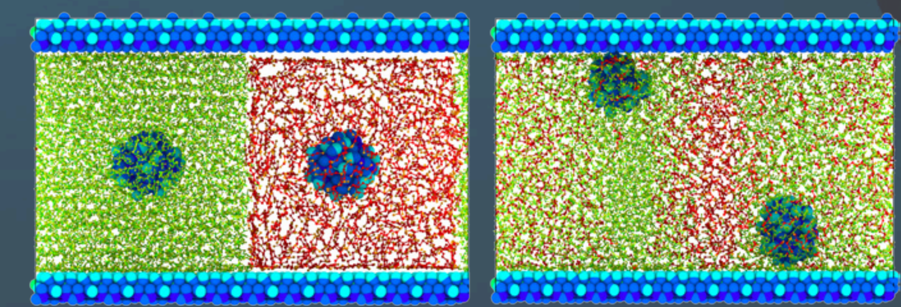

Figure 1 Representative side-views of a clay-oil-water-nanoparticle multiphase system simulation box. (a) Initial configuration, one nanoparticle in oil and one in water. (b) Equilibrium configuration, two nanoparticles stick to the clay wall and stand in a water-surrounded environment. Green: water; red: oil; and blue: clay and silica nanoparticle

meta

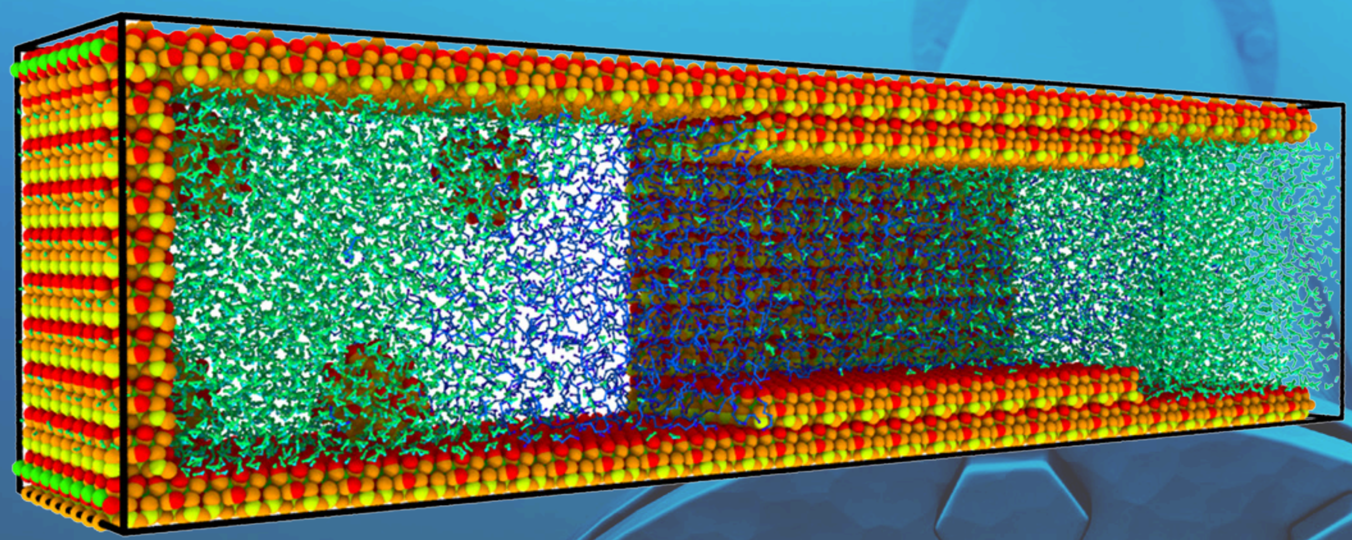

Figure 2 Perspective view of nanoparticle-based oil/water fluid in a confined clay nanochannel.

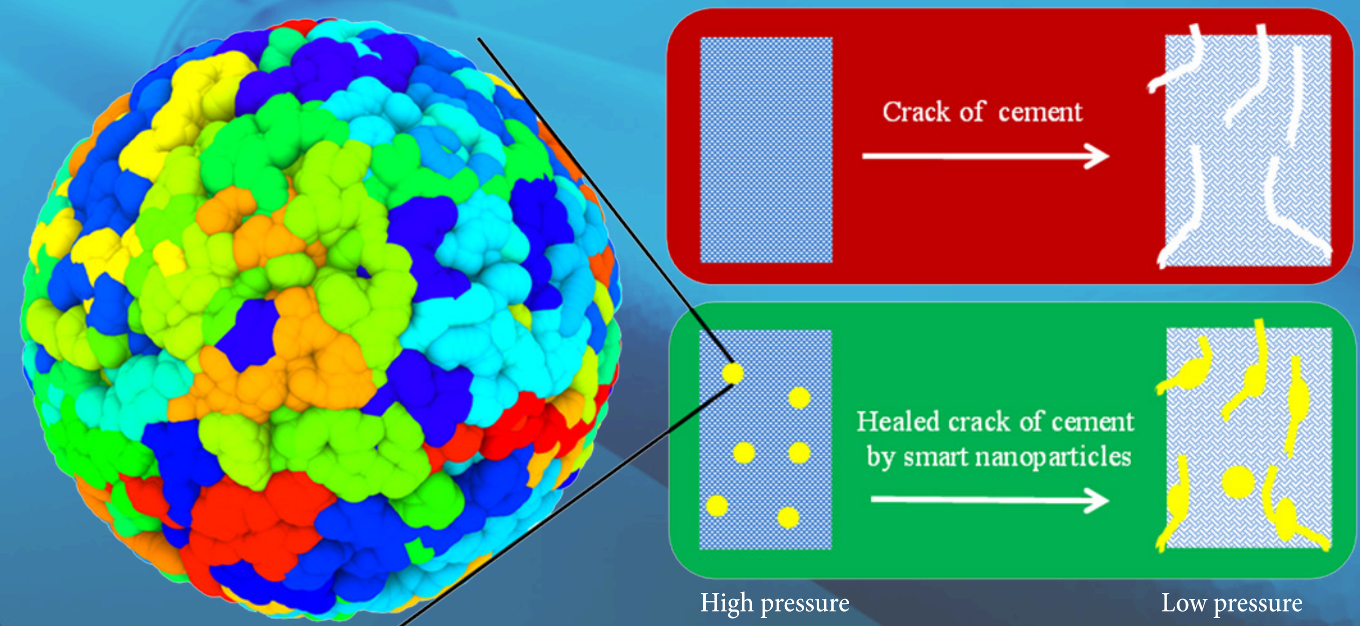

Figure 3 Schematic of nanoparticle-based technology for the pressure-induced crack of cement in the oil well. (Left) Zoomed-in polymeric nanoscale particle and (Right) Cracking of cement occurs when the pressure decreases in the oil well.

NANOPARTICLE ENABLED CEMENT FOR OIL AND GAS PRODUCTION

As one of important constitutions of oil well, oil well cement locates in the annular space between the well wall and the casing to form a cement sheath. The cement sheath in the oil well plays an important role in the oil production process. There are three principal functions of cement in the well [2]: a) to restrict fluid movement between formations, b) to bond the casing to the formation, and c) to provide support for the casing. Poor quality of oil well, especially the failure of cement sheath, would lead to severe accidents. For example, annular gas migration is considered as one of the major problems in the petroleum industry. Most cases of gas migration are highly relative to the integrity of cement sheath. A recent survey of 406 North Sea production and injections wells showed that 18 % of the wells had integrity problems and 7 % of all wells had to be shut in [3].

Why the integrity problem of cement sheath occurs so often? The answer should trace back to the cement hydration process. The reaction between the water and cement is associated with a loss in volume because the reaction product (solid matter) occupies a less volume than the reactants (cement + water). This volume loss favors pores in the binder phase and can be considered an integral part of the gel and capillary pore structure of solid product [4]. On the further hydration, the pore water is consumed and the pore structure is gradually emptied, resulting in the pressure reduction. This pore structure in the cement sheath could grow with the time, the volume shrinkage on the cement interface, which leads to a potential pathway for the gas migration.
Nanoparticle-based technology can help the cement to avoid the abovementioned problem. Smart nanoparticles have been developed which can respond to the environmental stimulus. The variation of temperature and pressure in the cement hydration process can be utilized to drive the expansion of smart nanoparticles in the cement slurry for counteracting the shrinkage of cement in the hydration. The potential pore structure also can be avoided by the replacement of volume increment of nanoparticles. This nanoparticle-enabled cement has its advantage to solve the integrity problem of cement sheath which can enhance the safety and efficiency of oil or gas production and thus shows a great promise in petroleum engineering. Figure 3 presents the possible nanoparticle-based solution for pressure-induce crack of cement in the oil well.

It is widely accepted that the property of nanoparticles can be optimized by tuning their atomic structure, architecture, size and surface function groups. Extensive MD simulations will be therefore performed to design a qualified candidate of nanoparticles from the molecular structure with the aid of NOTUR resources. Next, MD simulations under the NOTUR platforms will be conducted to study the behaviour of nanoparticles in cement in the hydration process, to predict the physical and chemical interaction between smart nanoparticles and cement, as well as to better understand the mechanism of cement shrinkage counteraction caused by nanoparticle. Lastly, in order to link the relationship between the cement mechanical strength and introduced nanoparticles, mechanical loading tests of MD simulations are carried out to investigate the mechanical sheath strength at molecular scale. The laboratory work consisting of nanoparticle selection, property control and the effect of nanoparticles in cement is ultimately guided by the outcome from MD calculations.

Acknowledgement
This work is funded by the Research Council of Norway via NANO2021/PETROMAKS2 project WINPA (project no. 234626/O70) and PETROMAKS2 project SustainCEM (project no. 228599/E30). The computational resources are provided by NOTUR- the Norwegian metacenter for computational science. The authors would like to thank Professor Zhiliang Zhang, PhD candidates Mao Wang and Yi Gong for contributing part of the text and proof-reading the manuscript.

Reference

[1] Wu, J. Y.; He, J. Y.; Torsæter, O. and Zhang, Z. L., Effect of Nanoparticles on Oil-Water Flow in a Confined Nanochannel: a Molecular Dynamics Study. Paper SPE 156995 presented at the SPE International Oilfield Nanotechnology Conference and Exhibition held in Noordwijk, The Netherlands, 12-14 June 2012

[2] Well Cementing (1983) ISBN 0-88698-112-3.

[3] Vignes, B. and Aadnøy, B. S., Well-integrity issues offshore Norway. SPED & C, May 2010, 145-150

[4] Concrete Technology 1, 2009. ISBN 82-7482-098-3.