An Experimental Investigation of Polysilicon Nanoparticles' Recovery Efficiencies through Changes in Interfacial Tension and Wettability Alteration

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Presentation Outline

- ❑ Introduction.
- ❑ Nanoparticles (NPs).
- ❑ Nanofluids.
- ❑ Case study.

Introduction

- To meet the rising energy consumption in the world, there is a dire need to produce more crude oil.

- Oil recovery operations are subdivided into three stages:

    - Primary.
    - Secondary.
    - Tertiary.

Primary production

- Primary production results from the displacement energy naturally existing in a reservoir, such as:

    - Rock and fluid expansion drive.
    - Solution-gas drive.
    - Gas-cap drive.
    - Natural water drive.
    - Gravity drainage.

Secondary Recovery Processes

- Secondary recovery processes are:
  - Waterflooding.
  - Gas injection.
- In secondary recovery processes fluids are injected to supply the natural energy present in the reservoir to displace oil.

Tertiary Recovery Processes

- Tertiary recovery processes use miscible gases, chemicals and thermal energy to displace additional oil after the secondary recovery process.

- In tertiary processes, the injected fluids interact with the reservoir rock/oil system.

- These interactions might result in lower interfacial tensions (IFT), oil swelling, oil viscosity reduction, wettability modification, or favorable phase behavior.

- The term 'tertiary recovery' fell into disfavor in literature and the designation of "EOR" became more accepted.

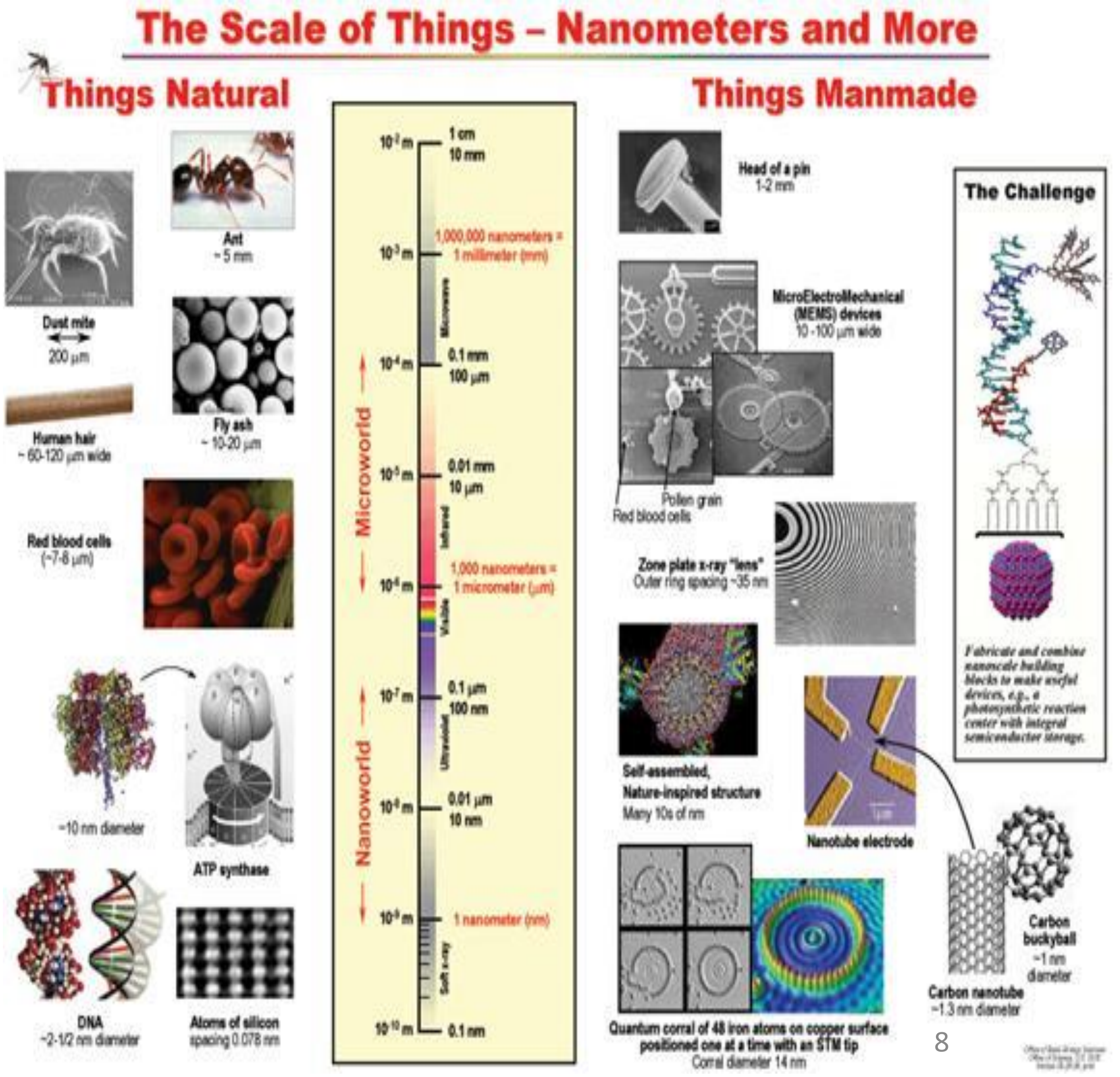
Tertiary Recovery Processes (cont.)

- These traditional EOR processes face some important challenges.
- For example:
- ❖ For gas methods, the injected gas often quickly penetrates through reservoirs from injection wells to producing wells, resulting in a large amount of residual oil remaining uncovered in reservoirs because of the high mobility ratio of injected gas and oil.
- ❖ Chemical processes are often limited by the high cost of chemicals, possible formation damages, and losses of chemicals.
- ✓ Therefore, less expensive, more efficient, and environmentally friendly EOR methods are greatly needed.
- ✓ Hence, attention is being paid to more efficient technology (i.e. Nanotechnology) for recovering more oil from the existing oilfields.

Nanoparticles (NPs)

- NPs are defined as particles with size ranges from 1 nm to 100 nm.
- NPs show some useful characteristics as EOR agents when compared to the available injection fluids used in the traditional EOR processes such as gas, water and chemicals.
- Nanoparticles' characteristics are:

  - **Ultra-small size.**
  - **Very high surface to volume ratio.**
  - **Low costs and environmental friendliness.**



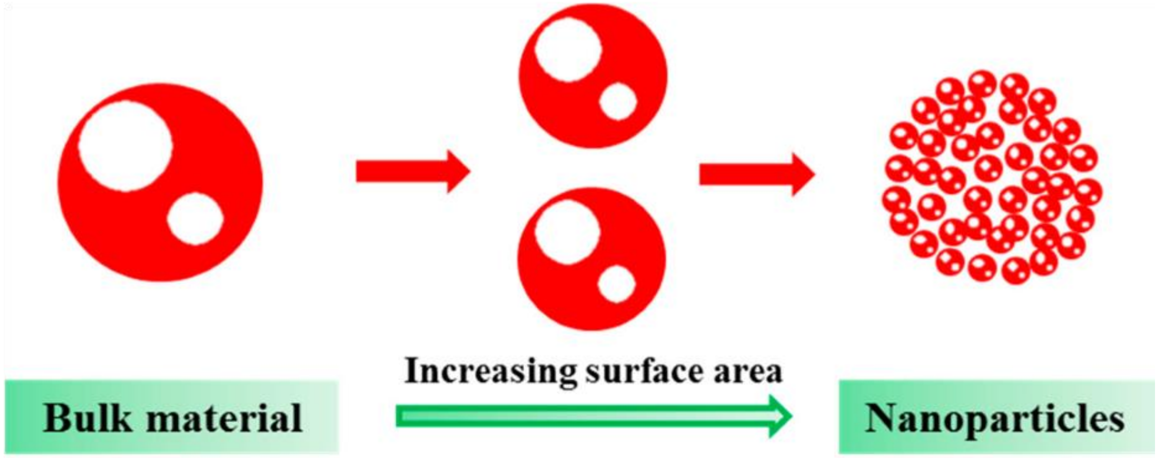
Ultra-Small Size

- ➢ Commonly used NPs are in the order of 1 nm–100 nm, which is smaller compared to pore and throat sizes.
- ✓ Thus, they can easily flow through porous media without severe permeability reduction and becoming trapped which increases the EOR effectivity of the injection fluids.

- ➢ NPs have the ability to penetrate some pores where traditional injection fluids are unable to.
- ✓ Thus, NPs can contact more swept zones, and increase the macroscopic sweep efficiency.

Very High Surface to Volume Ratio

- Due to their small particle size, NPs have a very high surface to volume ratio.
- The large surface area increases the proportion of atoms on the NP surface.



Low Costs and Environmental Friendliness

- One concern of using chemicals on the field scale is the injection cost.
- Because the price of NPs is usually cheaper than chemicals, NPs can be widely applied for EOR at oilfields.
- Moreover, most of the NPs used are environmentally friendly materials compared to chemical substances.
- For example:
- Most of the silica NPs are silicon dioxide, which is the main component of sandstone. In short, NPs are very cost effective and environmentally friendly.
- ✓ Due to the aforementioned characteristics of NPs, they provide many potential solutions to the existing challenges faced by traditional EOR methods.

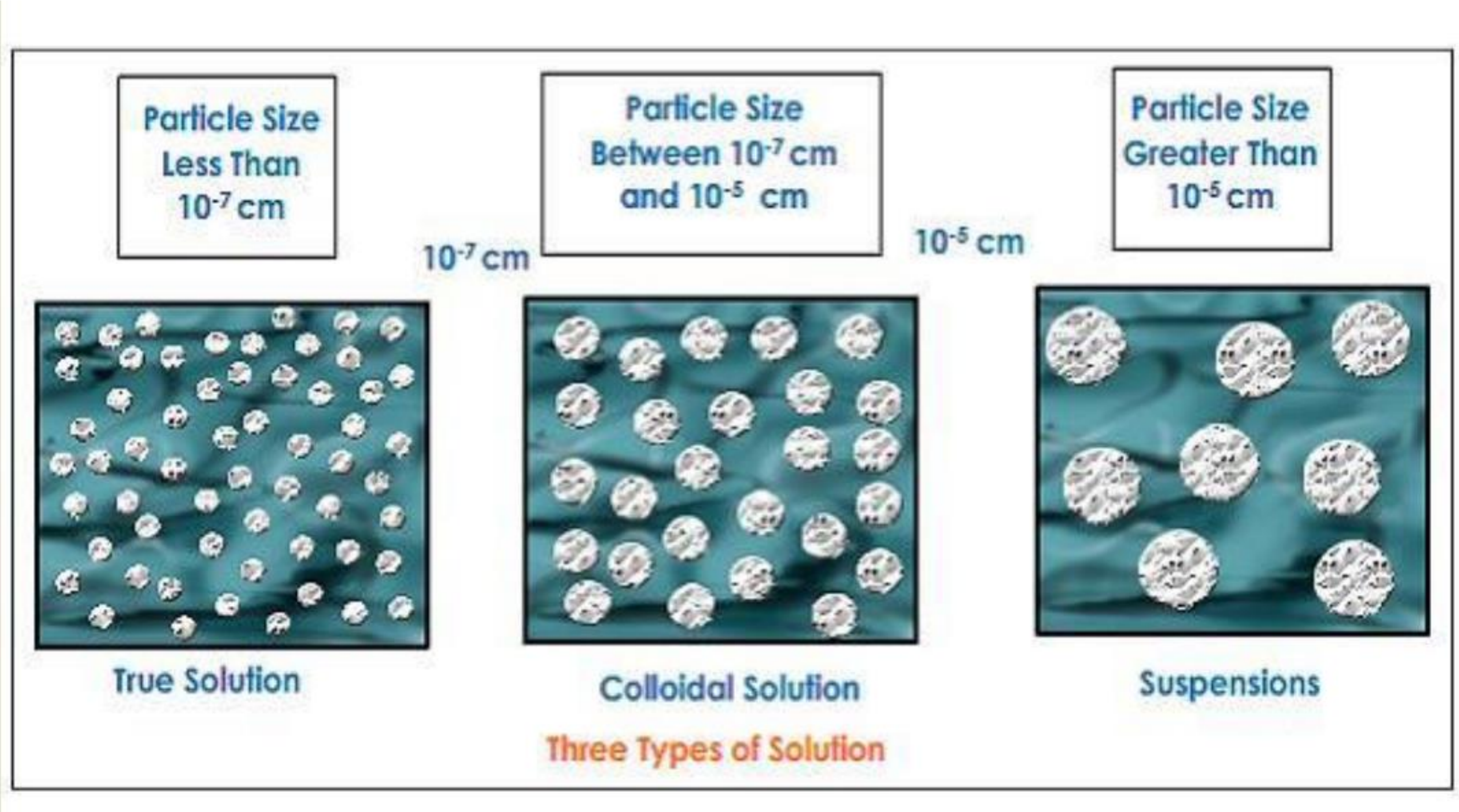
Nanofluids

- A nanofluid is simply defined as a base fluid with NPs that have an average size of less than 100 nm in colloidal suspension.
- The base fluid can be any liquid such as oil, water or gas [polar (water or alcohol) and non-polar (oil or toluene)].
- Nanofluids are colloidal solutions/suspensions.

Colloidal Solution

- Colloidal solution is a solution in which a material is evenly suspended in a liquid. In other words, a colloid is a microscopically small substance that is equally dispersed throughout another material.
- A colloid is intermediate between a solution and a suspension.
- The size of the colloidal particles is in between the size of particles of true solutions and suspension.
- While a suspension will separate out, a colloid will not.

Colloidal Solution



Important Properties of Colloidal Solution

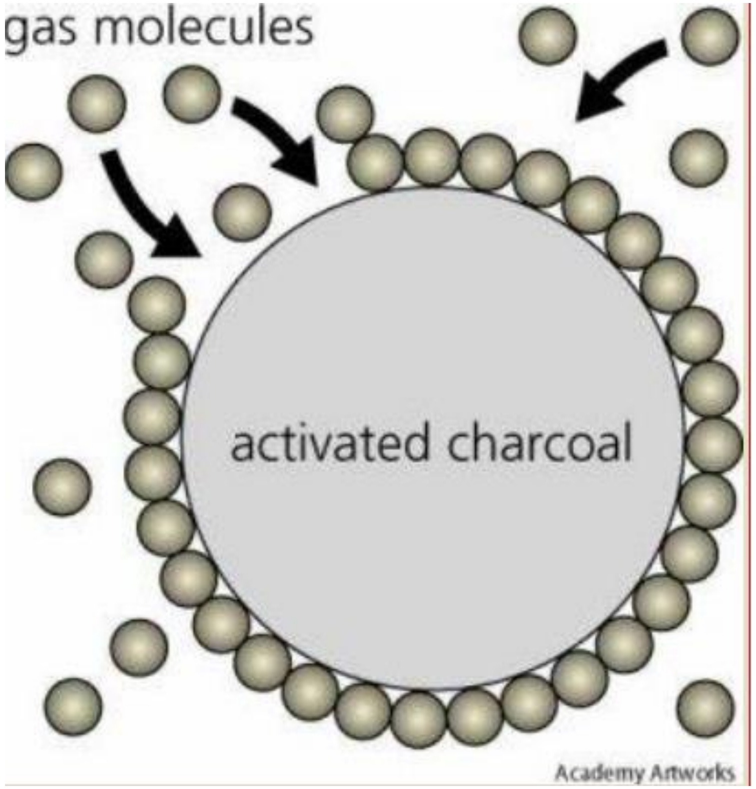
1. Filterability

- The colloidal particles are able/unable to pass through parchment membrane according to the diameter of the particles and that of the slots of the membrane.

Important Properties of Colloidal Solution (cont.)

2. Adsorption and Increased Surface Area:

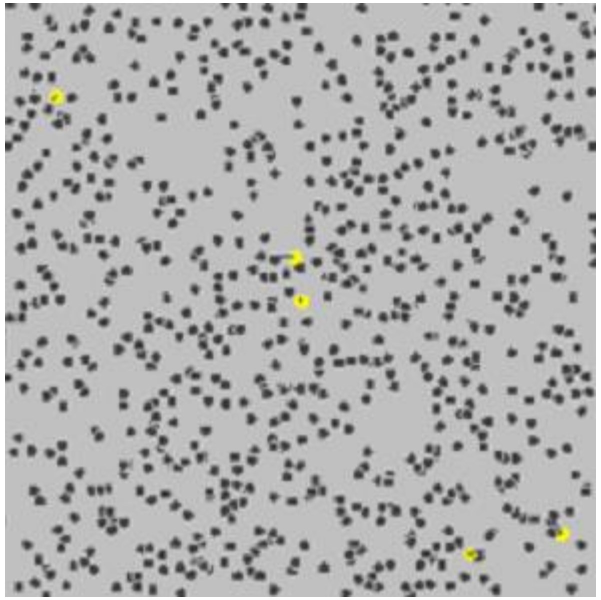
- The colloidal particles have a tendency to attract and retain at their surface other particles with which they come in contact. This is called as adsorption.
- The adsorption is increased if the surface area of the same mass of an adsorbent is also increased.
- In a colloidal solution the little mass of dispersed phase is present in the form of a large number of small particles, thus increasing its total surface area.
- The adsorption and the large surface area offered by the colloidal particles help to carry on many complex biochemical reaction in the protoplasm.



Important Properties of Colloidal Solution (cont.)

3. Brownian Movement

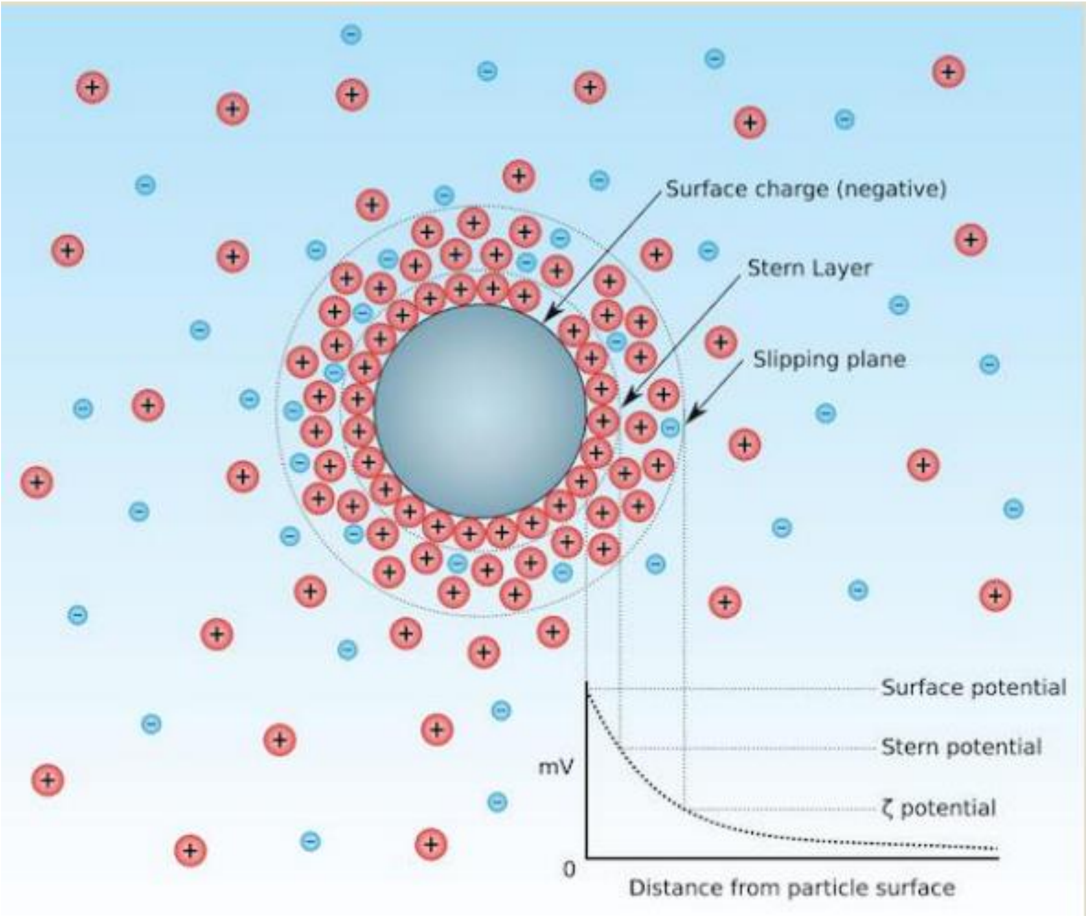
- Brownian movement may be used to distinguish between solutions and colloids.
- Brownian motion is the random movement of colloidal particles suspended in a liquid or gas, caused by interference with molecules of the surrounding medium.
- However colloid particles are large enough to be observed and are small enough to still be affect by the random molecular motion.



Important Properties of Colloidal Solution (cont.)

4. Electric Properties

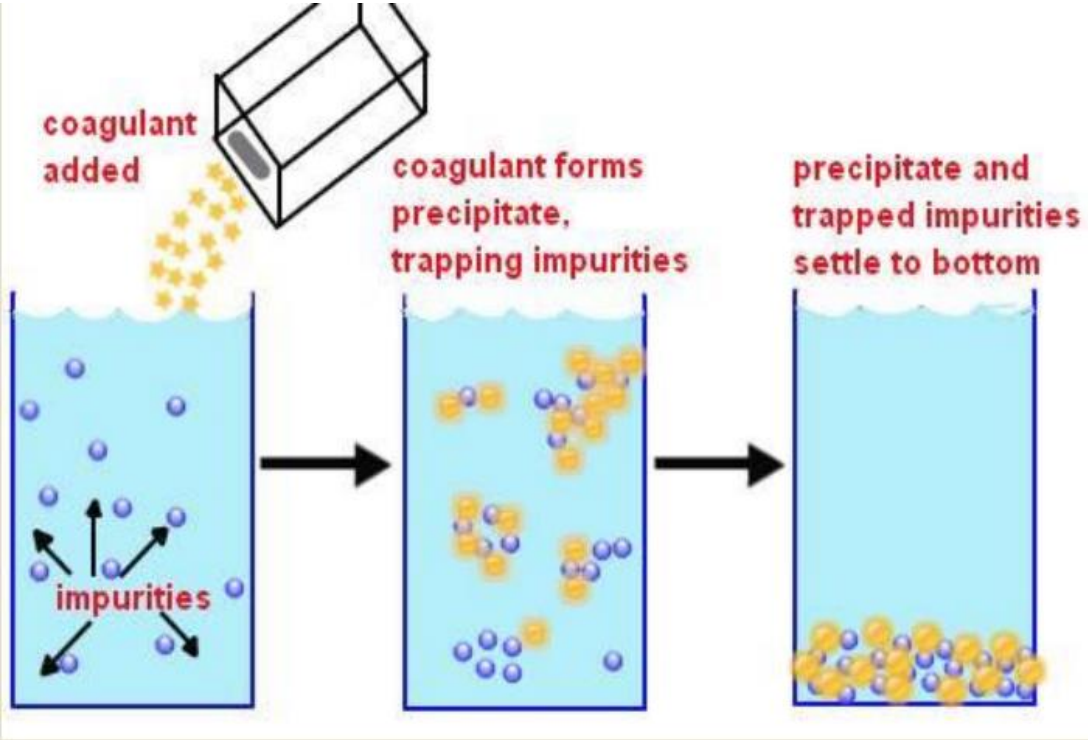
- The colloidal particles constituting the dispersal phase carry an electric charge probably due to the preferential adsorption of ions present in the dispersion medium.
- All these colloidal particles in a particular colloidal system carry electric charge of the same sign.
- As a result, they repel each other and remain dispersed in the dispersion medium, and if the colloidal solution is placed under an electric field, all these particles move towards the oppositely charged pole.
- However, a colloidal solution is electrically neutral as a whole because the particles of the dispersion medium have equal electric charge of opposite sign.



Important Properties of Colloidal Solution (cont.)

5. Coagulation or Flocculation

- The precipitation of the colloidal particles constituting the dispersed phase of the colloidal solution by the addition of an electrolyte is called as coagulation or flocculation.
- It is because the electric charge carried by the particles of dispersed phase is neutralized by the electrically charged ions resulting from the dissociation of the electrolyte in colloidal solution.
- Now these colloidal particles can no longer repel each other.
- They come close to each other due to Brownian movements and soon settle down to gravity.



Important Properties of Colloidal Solution (cont.)

6. Osmotic Pressure

- **The osmotic pressure of the colloidal solution is usually very small.**

Nanofluids Preparation and Stability

- As NPs are dispersed into the base fluid, the characteristic of the nanofluids will not be similar to its pure base fluid.
- Part of the challenges that faces commercialising nanofuids is their poor stability due to the interaction between the particles themselves and between the particles and the surrounding liquid. This kind of behaviour can be linked to two opposing forces:

1. The Van der Waals attractive forces.
2. The electrical double layer repulsive force.

DLVO Theory in Particles Stability

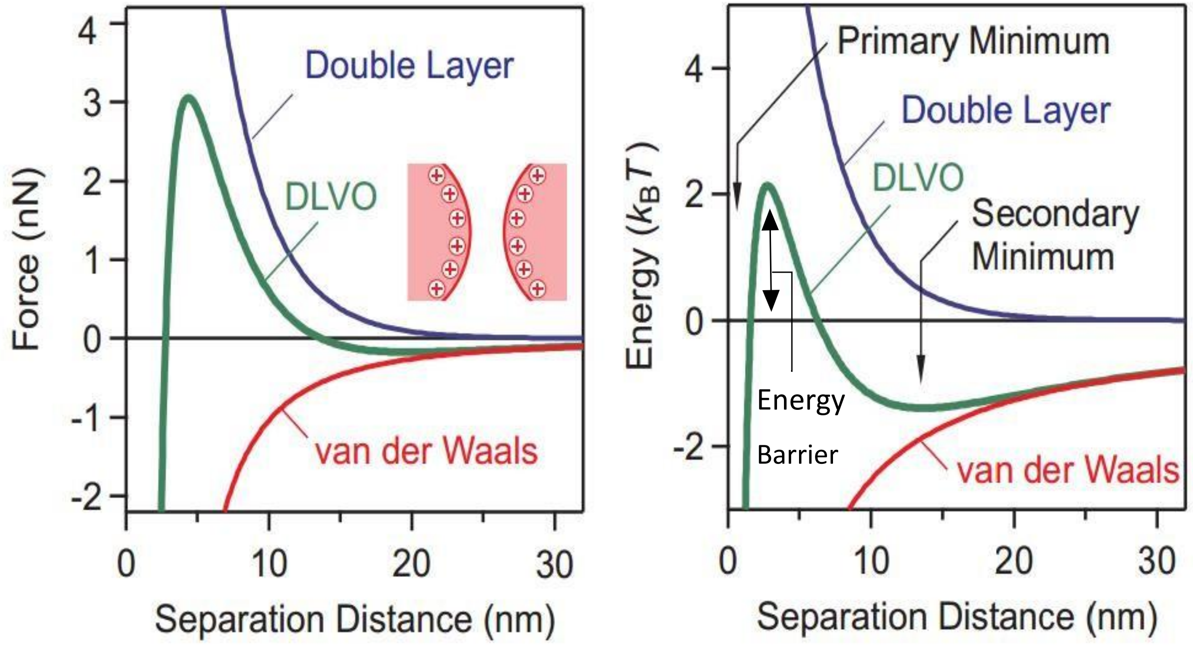
- Derjaguin, Landau, Vervey, and Overbeek (DLVO) developed the theory of colloidal suspension stability, or the so-called DLVO theory.
- It describes the relation between two forces that acts between particles, whilst the free energy per unit area is the sum of the van der Waals attraction and double layer repulsion energy.

$$W = WvdW + Wdl$$

- Van der Waals forces are the result of the dipoles rotation or fluctuation between molecules and atoms, which always present in every particle interaction.
- On the contrary, double layer repulsion (also called electrostatic repulsion) is the counter force of the vdW forces that becomes significant when double layers begin to interact with two approaching particles. The surface charge of the particles in the dispersion acts as double layer repulsion.

DLVO Theory in Particles Stability (cont.)

- Thus, the stability of the nanofluid is determined by the sum of vdW attraction and double layer repulsion.
- When the attractive force is higher than the repulsive force, it means the collision between particles will occur.
- Otherwise, if the repulsion is high enough, the dispersion will be stable.
- Therefore, in order to get stable dispersion, both particles need enough energy barrier which is commonly expressed as zeta potential.
- Higher zeta potential means more stable dispersion, while lower zeta potential will lead to the rapid coagulation of flocculation.



Interaction between two colloidal particles, DVLO theory

Nanofluids Preparation and Stability (cont.)

- Stability is a very important element in commercialising nanofuids as it extends the shelf-life of the product while conserving its thermophysical properties.
- To obtain a stable nanofuid the electrical double layer repulsive force should surpass the Van der Waals attractive forces.
- *Stability Enhancement Procedures:* Several literatures have reported diverse ways of improving the stability of nanofluids, which are:

1. **Addition of Surfactants.**
2. **Surface Modification Techniques.**
3. **Ultrasonic Agitation.**
4. **PH Control of Nanofluids.**

Nanofluids Preparation and Stability (cont.)

- The most common method to enhance the stability of nanofluid is by adding stabilizer, mostly in chemical solution form, to reduce agglomeration.
- The widely used stabilizers are surfactants and polymers.
- However, the application of surfactant as a stabilizer is limited since it will degrade under high-temperature condition.
- Polymers are used as the alternatives to stabilize nanofluids.
- By adding stabilizers, surface charges between particles went through an increase, leading higher energy barrier that could prevent agglomeration of smaller particles.

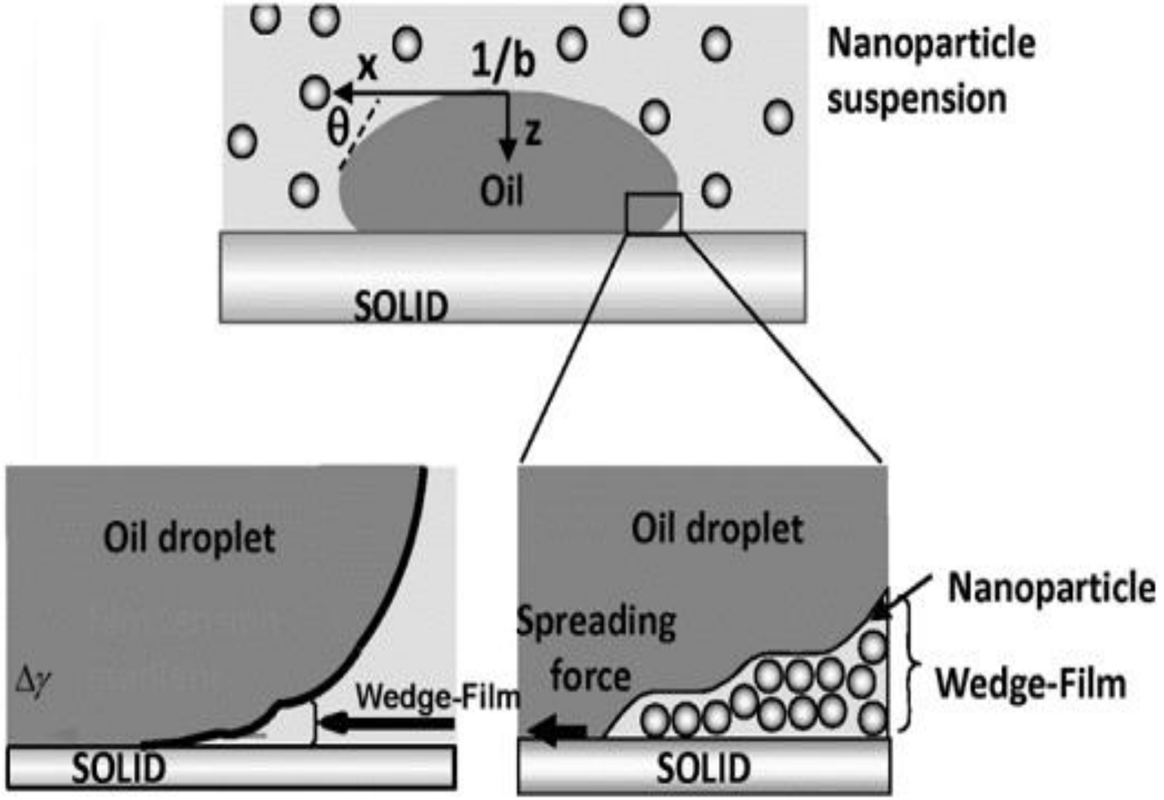
EOR Mechanisms of Nanofluids

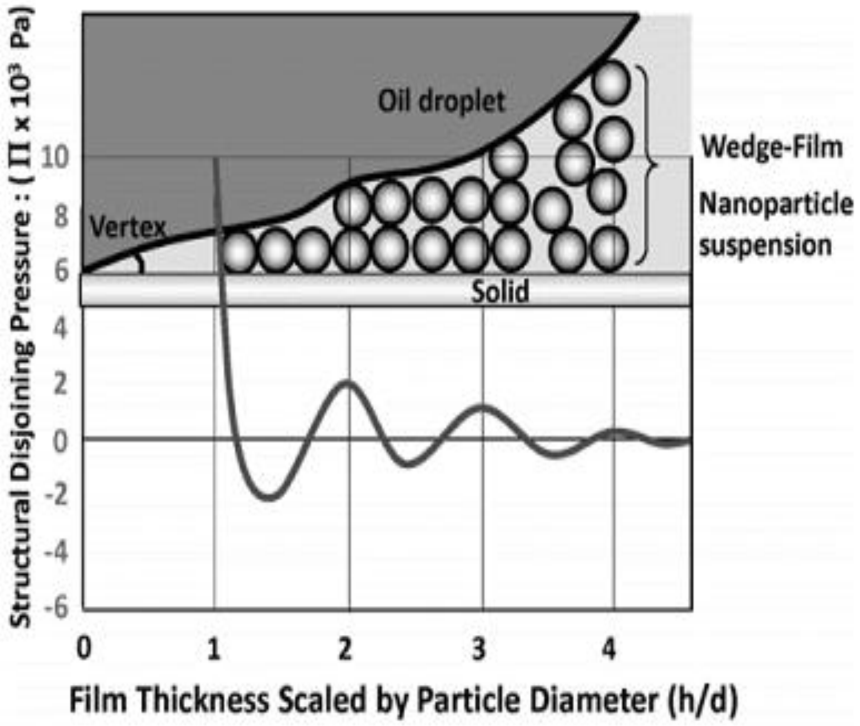
- The EOR mechanisms of nanofluids flooding include:
  - Disjoining pressure.
  - Viscosity increase of injection fluids (Mobility ratio reduction).
  - IFT reduction.
  - Wettability alteration.
  - Pore channels plugging.

Disjoining Pressure

- The Brownian motion and electrostatic repulsion between NPs are the energies that generate this disjoining pressure.
- In short, the disjoining force is responsible for the detachment of oil from the solid surface while allowing the nanofluid to spread further.
- The NPs in the nanofluids can form a self-assembled wedge-shaped film on contact with oil phase.
- The wedge film acts to separate the oil droplets from the rock surface, thereby recovering more oil than previously possible with conventional injection fluids.
- The wedge-shaped film is formed due to the existence of a pressure, called structural disjoining pressure.

Disjoining Pressure (cont.)





Disjoining Pressure (cont.)

- NP size, amount of the NPs, temperature, salinity of the base fluid, and the characteristics of the rock surface affect the magnitude of the disjoining pressure.
- Kondiparty et al. concluded that higher concentration and smaller size of nanoparticle would lead to the increasing disjoining pressure. Moreover, the force at wedge film will increase when smaller sizes of nanoparticle with higher charge density and electrostatic repulsion are used.

Mobility Ratio Reduction

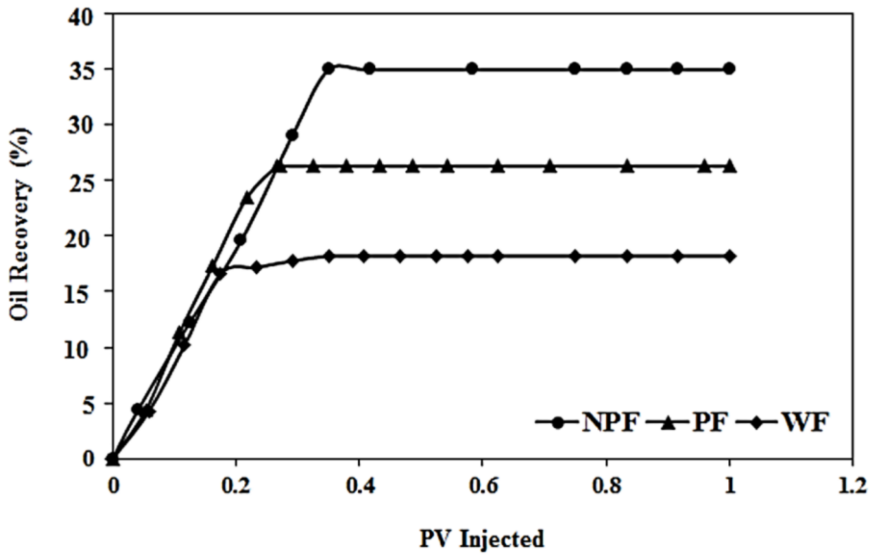
- The mobility ratio can be obtained by the following expression:

$$M = \frac{\lambda_i}{\lambda_o} = \frac{K_{ri}/\mu_i}{K_{ro}/\mu_o} = \frac{K_{ri}\ \mu_o}{K_{ro}\ \mu_i}$$

- where:
  - λ_i and λ_o are injected fluids and oil mobilities, respectively.
  - k_{ri} and k_{ro} are the relative permeabilities of the injected fluids and oil, respectively.
  - μ_i and μ_o are the effective viscosities of the injected fluids and oil, respectively.
- The high mobility ratio easily causes viscous fingering of injected fluids within oil, poor conformance, and poor sweep efficiency.

Mobility Ratio Reduction (cont.)

- The mobility ratio can be decreased by viscosity reduction of oil phase or viscosity enhancement of injected fluids.
- Nanofluids can solve the above mentioned problem because adding NPs in traditional fluids can increase the effective viscosity of injected fluids causing an increase in the sweep efficiency. (Polymer solution is often degraded at harsh reservoir conditions P, T and salinity [The degradation will reduces its viscosity and sweep efficiency]).



- The viscosity of a nanofluid is influenced by several factors such as shear rate, temperature, NP concentration, NP type and brine salinities.

IFT Reduction

- IFT is one of the main parameters used to determine fluids' distribution and movement in porous media.
- ✓ Therefore, it is necessary to obtain the IFT between oil and injected fluids for evaluation of an EOR technique.
- The IFT between crude oil and nanofluids is usually measured using the pendant drop method.
- ❖ During the experimental process, an oil droplet is generated from the end of a capillary needle in a nanofluid at experimental pressure and temperature. The IFT value is calculated by analyzing the complete shape of the oil droplet by an accurate video system and analysis software.

IFT Reduction (cont.)

- Some types of NPs have been considered as potential agents to reduce IFT.
- The main reason for the IFT reduction is high adsorption of NPs that modifies oil and water surface.
- The IFT between crude oil and nanofluids is influenced by several factors, such as temperature, NP concentration, NP type and brine salinities.

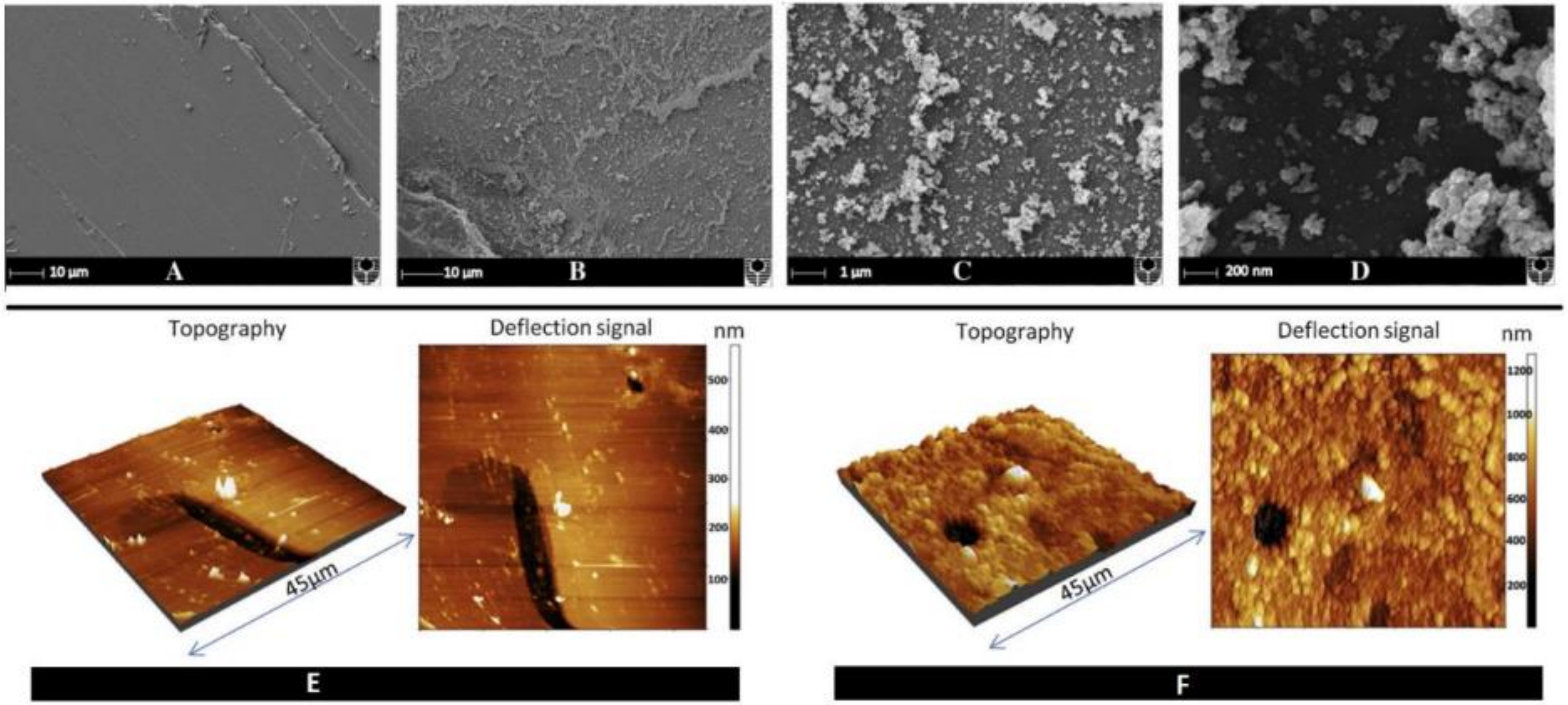
Wettability Alteration

- Rock wettability is the tendency of a fluid to adhere to the rock surface competing with another immiscible fluid.
- It is a key factor to govern oil recovery by affecting capillary pressure, fluids saturation, and relative permeability.
- Nanofluids have been considered as potential agents to alter wettability.

Wettability Alteration (cont.)

- Surfactant and nanoparticle have similarity in the mechanism of wettability alteration.
- Hammond and Unsal proposed two most possible mechanisms, the adsorption on the solid surface (coating mechanism) and removal of the absorbed molecule from the rock surface (cleaning mechanism).

- The adsorption process of NPs on the grain surface resulted in the formation of composite nanostructure-surface which improves the water-wetting behavior.
- The surface modification by nanoparticles also increases the roughness of the surface.

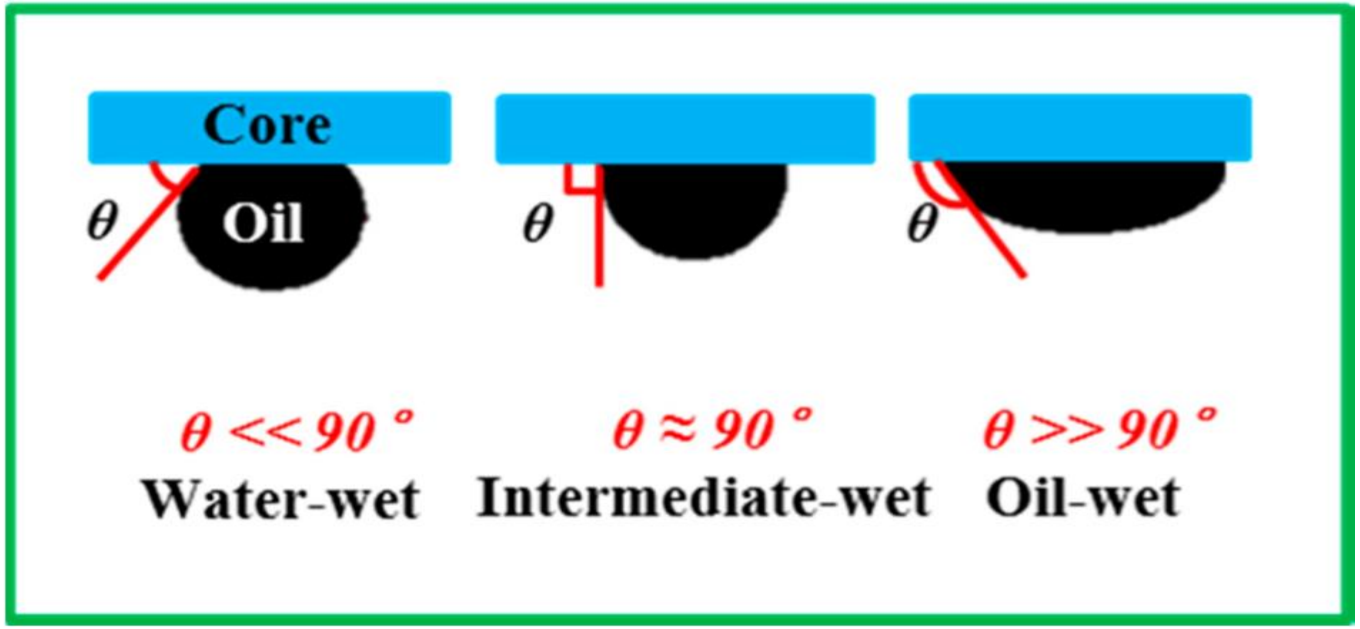


Wettability Alteration (cont.)

- Wettability alteration is influenced by several factors such as NP concentration, NP type, NP size, injection time, degree of water salinity and duration of NP interaction in the fluid-rock system.
- Currently, there are three main experimental methods that are commonly used by researchers for wettability measurement:
  - The contact angle method.
  - The Amott test.
  - The core displacement test.

The Contact Angle Method

- The contact angle method is the most universal used approach to determine wettability.
- The wettability can be easily obtained by the rules shown in the following figure:



The Amott Test

- The Amott test mainly uses the wettability index (I_w) to determine wettability that combines spontaneous and forced displacement at room condition. The definition of I_w is as follows:

$$I_w = \frac{V_{o1}}{V_{o1} + V_{o2}} - \frac{V_{w1}}{V_{w1} + V_{w2}}$$

- Where:

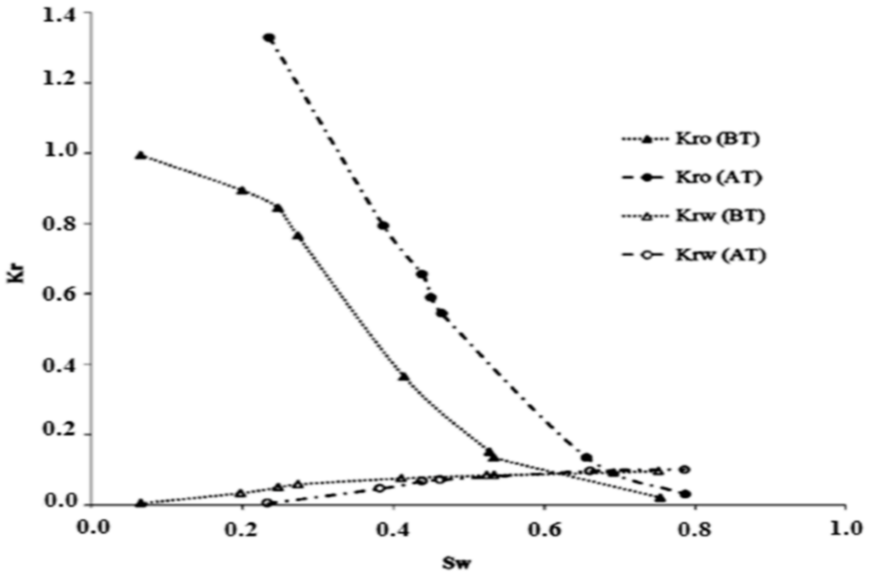
❖ V_o and V_w describe oil volume from imbibition process and water volume from drainage process, respectively.

❖ Subscript '1' means spontaneous displacement process and '2' means forced displacement process.

- I_w ranges from −1, as completely water-wet, to 1, as completely oil wet and 0 is considered as neutral wettability.

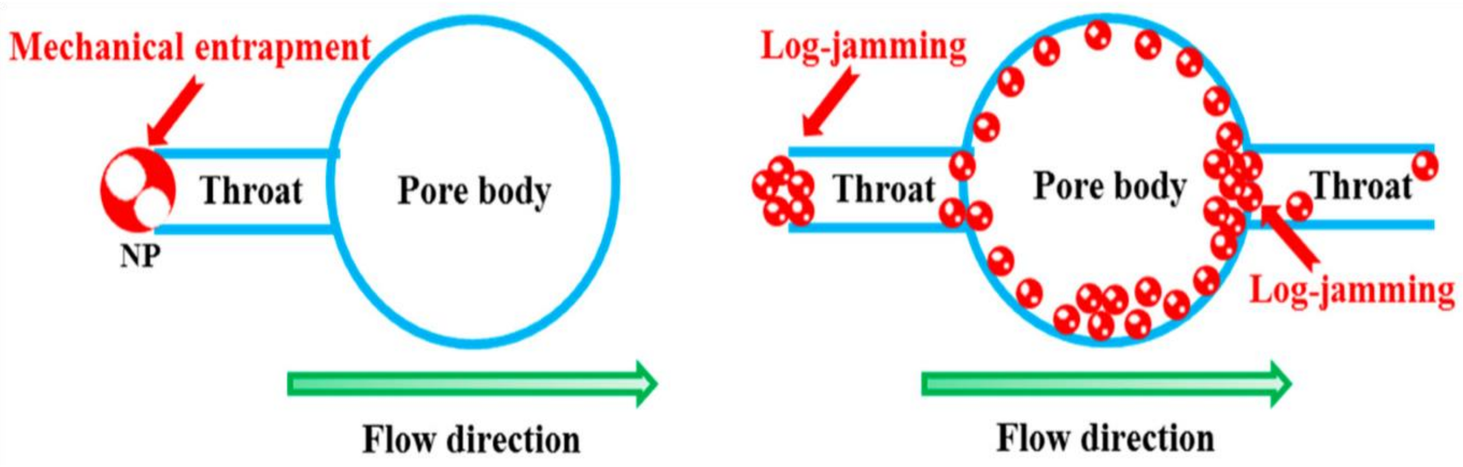
The Core Displacement Test

- The core displacement test can be used to determine wettability alterations by comparing the changes in residual water saturation (S_{wr}), oil relative permeability (k_{ro}) and the point where the water and oil relative permeabilities are equal (crossover point) before and after nanofluid treatment.
- Based on Craig's rules, if the S_{wr} increases, the k_{ro} and the crossover point move to the right after nanofluid treatment, the wettability is changed from an oil-wet to a water-wet condition as shown in the following figure.



Pore Channels Plugging

- Pore channel plugging can be caused by two mechanisms:
  - Mechanical entrapment.
  - Log-jamming.



Mechanical Entrapment

- Mechanical entrapment occurs because the diameter of injected components is larger than pore channels that they flow through.
- Generally, pore channels are in microscale, thousand times bigger than NPs.
- ✓ Therefore, NPs are able to penetrate pore channels without mechanical entrapment.

Log-Jamming

- Log-jamming is plugging of pore channels that are larger than each NP.
- When a nanofluid flows from pores to throats, the narrowing of flow area and the differential pressure will lead to a velocity increase of the nanofluid. The small H_2O molecules will flow faster than the NPs causing accumulation of NPs at the entrance of the pore throats.
- In some cases, plugging of pore throats due to log-jamming is beneficial to improve the performance of nanofluid flooding. In the very small pore throat, Log-jamming results in NPs accumulation and blockage of the pore throat. The pressure builds up in the adjacent pore throat, forcing out the oil trapped in the pore throat. Once the oil is freed, the surrounding pressure drops and the plugging gradually disappears and the NPs start to flow with the water. This can be considered as temporary log-jamming. This phenomenon is mainly governed by the concentration and size of NPs, flow rate and the diameters of pore throats.

The Effect of Nanofluid Parameters

- ❑ Nanoparticle size.
- ❑ Nanoparticle concentration.
- ❑ Salinity.
- ❑ Temperature.
- ❑ Wettability.

Nanoparticle Size

- Decreasing NPs' size improves macroscopic sweep efficiency, displacement efficiency and thus the ultimate oil recovery. As decreasing NPs' size will lead to:

✓Higher surface to volume ratio.
✓Higher NP charge density.
✓Stronger electrostatic repulsion.
✓Higher disjoining pressure.
✓Lower contact angle between fluid and rock surface.
✓Limiting Pore channel plugging.

Effect of NP Size on Disjoining Pressure

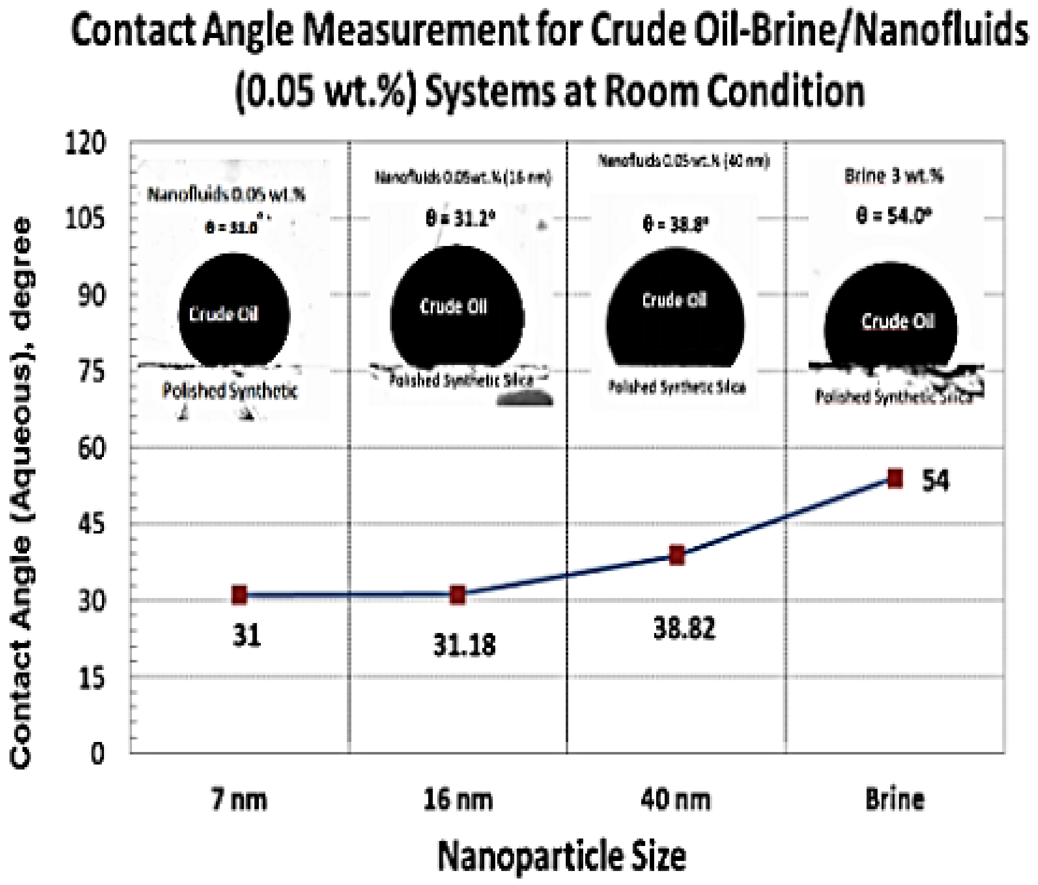
- A study proved that by decreased NPs' diameter from 30 nm to 18.5 nm, the structural disjoining pressure would increase for about 4.3 times.

✓ As decreasing NPs' size leads to higher particle charge density which improves the structural disjoining pressure significantly.

Effect of NP Size on Contact Angle

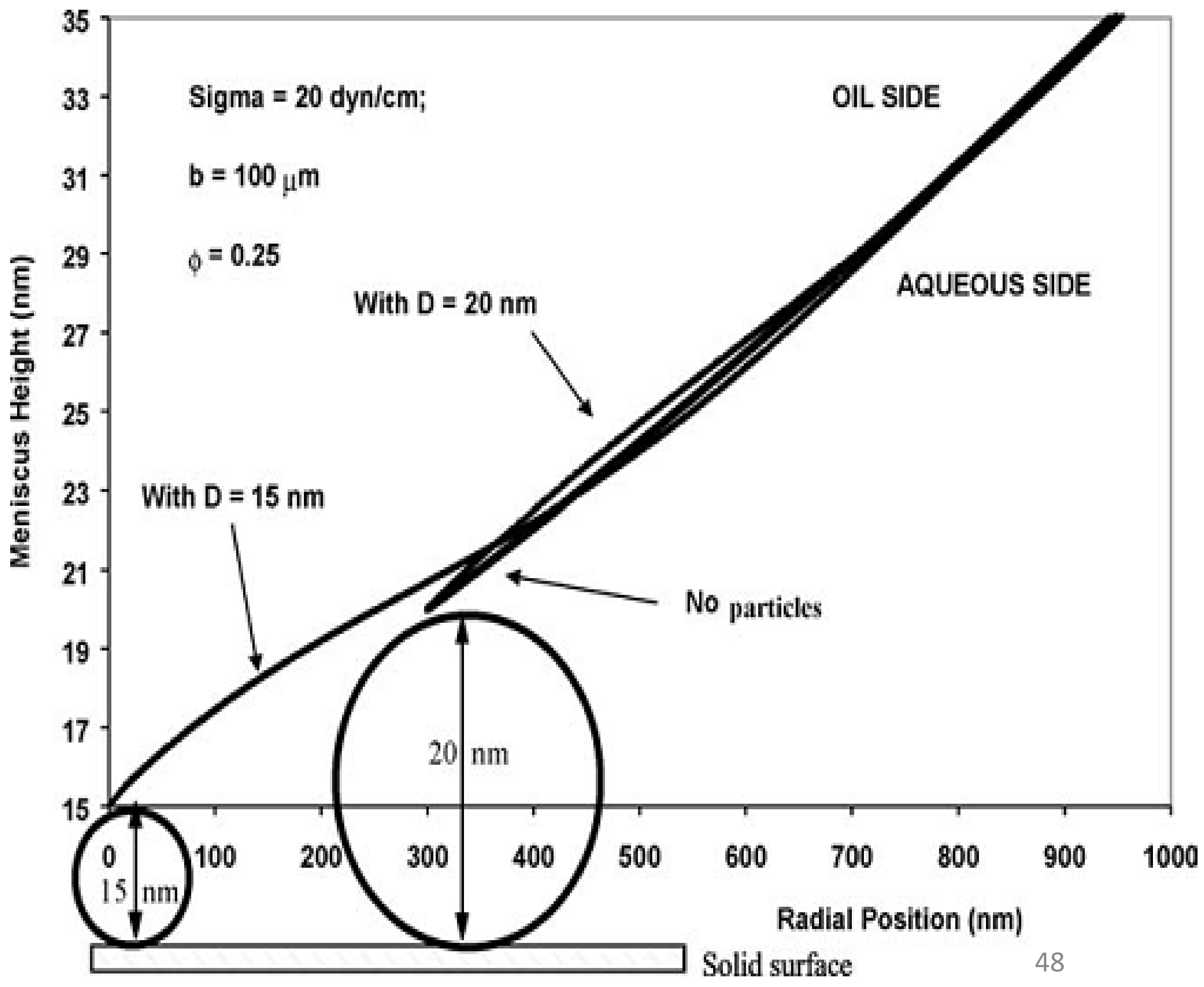
- For a similar mass, smaller NPs will give higher particle charge density and lower contact angle between fluid and rock surface.

✓ As higher particle charge density improves the structural disjoining pressure significantly.



Effect of NP Size on Contact Angle (cont.)

- Effect of NP size on meniscus profile.



Effect of NP Size on Pore channel plugging

- The size of the NPs should be small enough not to be mechanically trapped, but big enough to avoid extra log jamming.

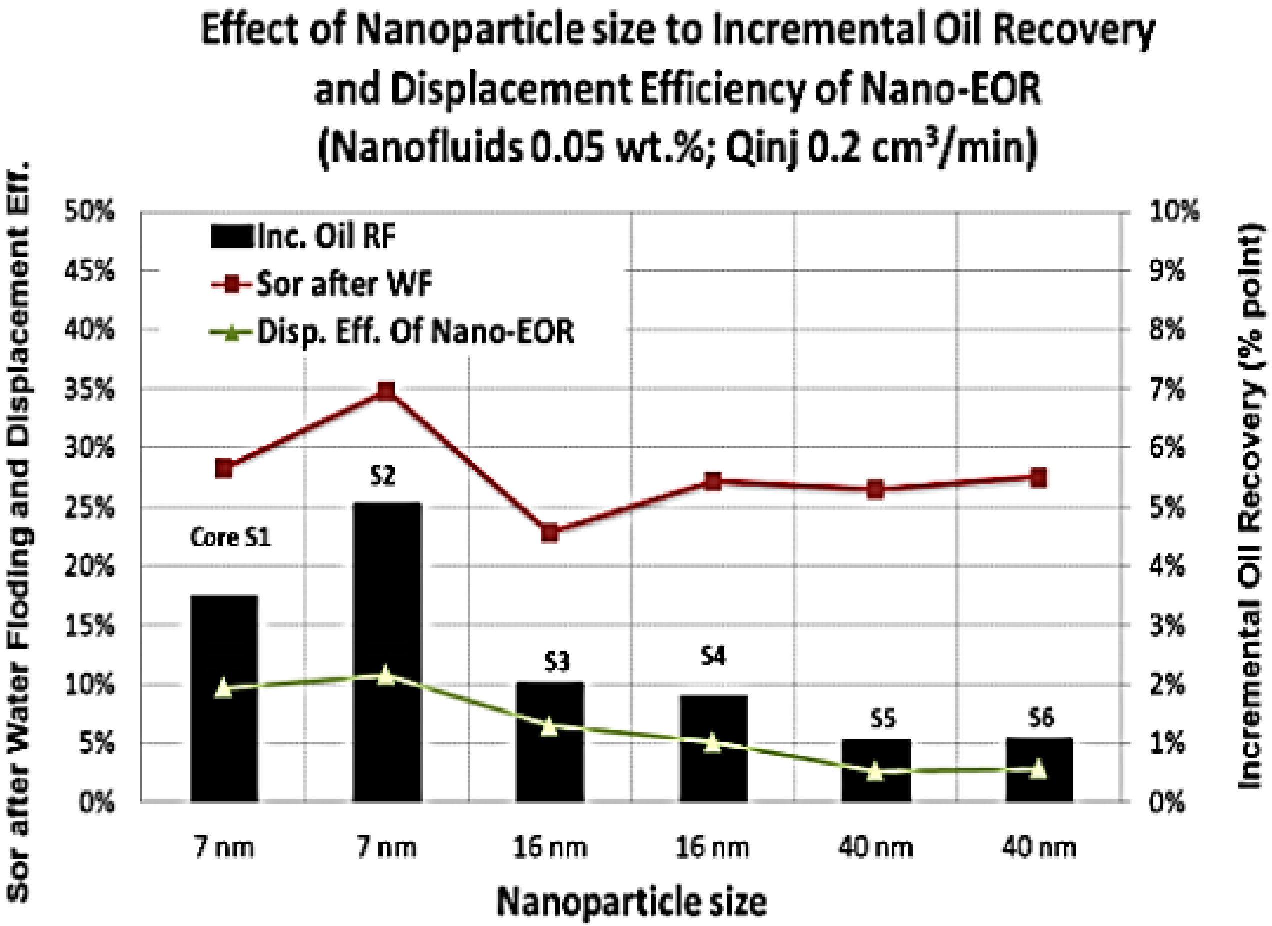
✓ NPs can easily flow through porous media without severe permeability reduction which increases the EOR effectivity of the injection fluids.

✓ NPs have the ability to penetrate some pores where traditional injection fluids are unable to. Thus, NPs can contact more swept zones, and increase the macroscopic sweep efficiency.

❖ Therefore, smaller particles are favorable for the higher oil recovery.

Effect of NP Size on Oil Recovery

- Smaller NPs are proven to increase the incremental oil recovery and displacement efficiency Nano-EOR.



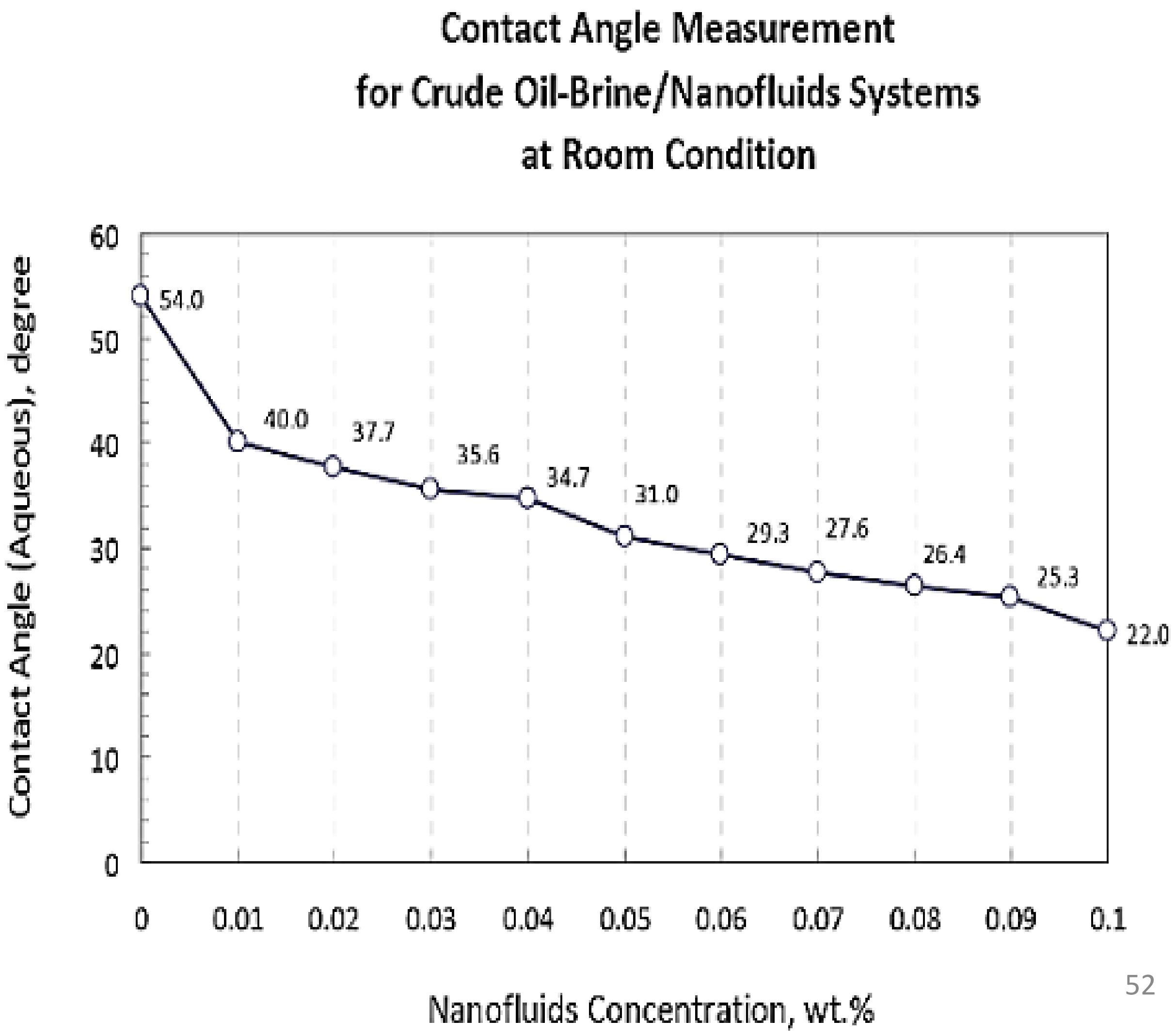
Nanoparticle Concentration

- ❖ Increasing NPs' concentration improves macroscopic sweep efficiency, displacement efficiency and thus the ultimate oil recovery. As increasing NPs' concentration will:

  - ✓ Increase Brownian motion.
  - ✓ Increase the repulsion forces.
  - ✓ Increase disjoining pressure.
  - ✓ Enhance the nanofluid viscosity (Reduce mobility ratio).
  - ✓ Enhance the spreading of NPs on the grain surface.
  - ✓ Reduce the contact angle (Higher wettability alteration).
  - ✓ Reduce IFT between reservoir fluids.

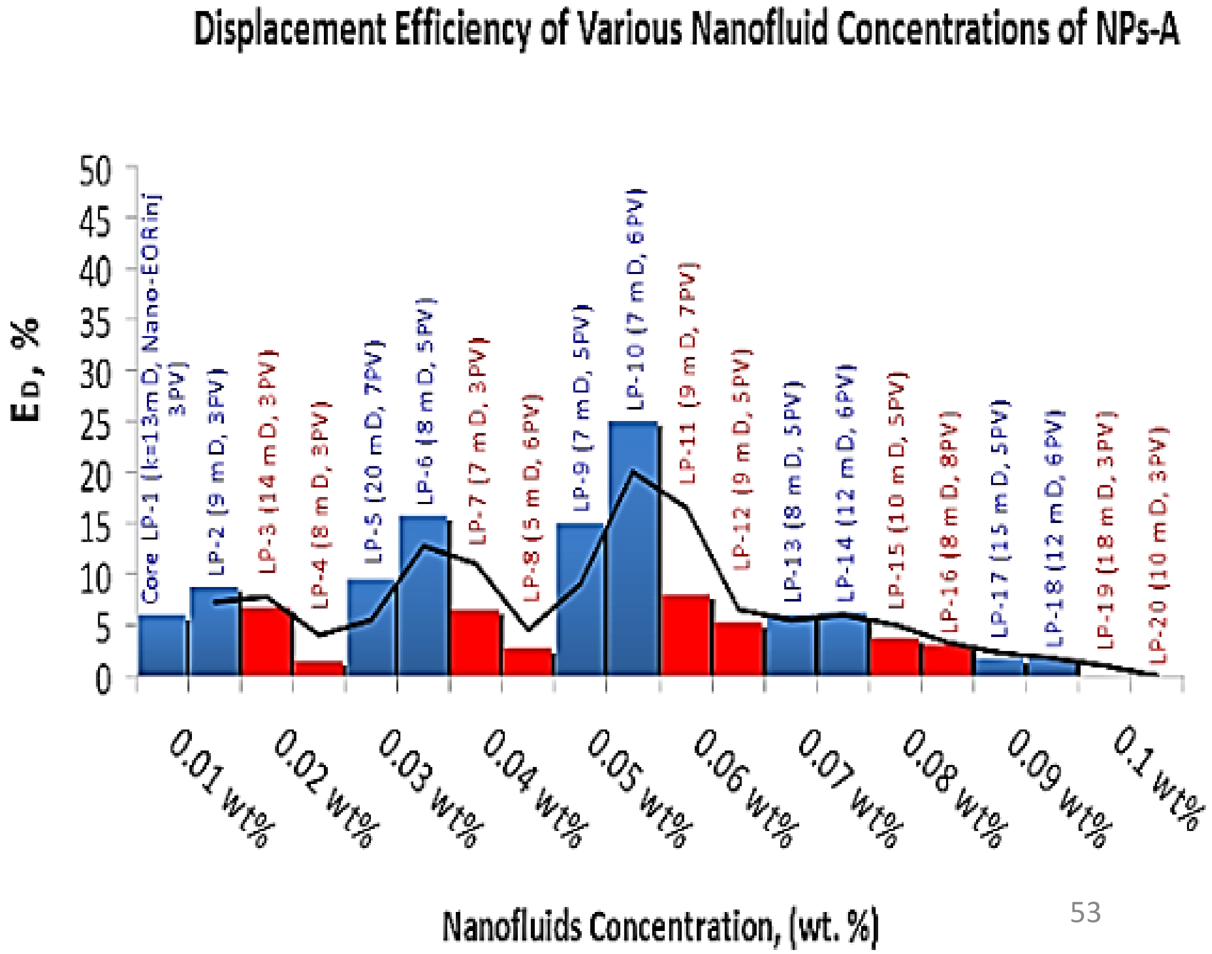
Effect of NP Concentration on Contact Angle

- Increasing concentration will decrease the contact angle.



Effect of NP Concentration on Displacement Efficiency

- Increasing concentration will improve the displacement efficiency.



Optimum NP Concentration

- A higher NPs’ concentration will improve the displacement efficiency, the wettability alteration and the IFT reduction. However, when the concentration is too high, the aggregated NPs were found to accumulate around the inlet, block the pore throat, reduce the displacement efficiency and the ultimate oil recovery.
- Therefore, an optimum injected NPs’ concentration is necessary to get maximum oil recovery. It is varied based on the type of nanoparticle, porous medium and the environmental condition.

Salinity

- Salinity of Reservoir fluids and nanofluids have a significant effect on:

  ✓ The stability of the dispersion.
  ✓ Wettability alteration.
  ✓ Ultimate oil recovery.

Effect of Salinity on Nanofluid Stability

- The salinity of the reservoir fluid and the nanofluids have a significant effect on the stability of the dispersion.
- Increasing salinity is proven to reduce the zeta potential of each particle which leads to easy agglomeration.
- High ionic strength in the fluid due to the presence of salt will lead to the lower electrical repulsion between particles and allows the vdW attraction forces to dominate.

✓Thus, in high salinity environment modification on nanoparticle is necessary to maintain the stability which can be achieved by surface modification, ionic control via surfactant, or the combination of both.

Effect of Salinity on Ultimate oil Recovery

- The result of a laboratory study had shown that the oil recovery increases at high salinity environment.
- At high salinity, the adsorption of NPs is improved due to the increasing physicochemical interaction.

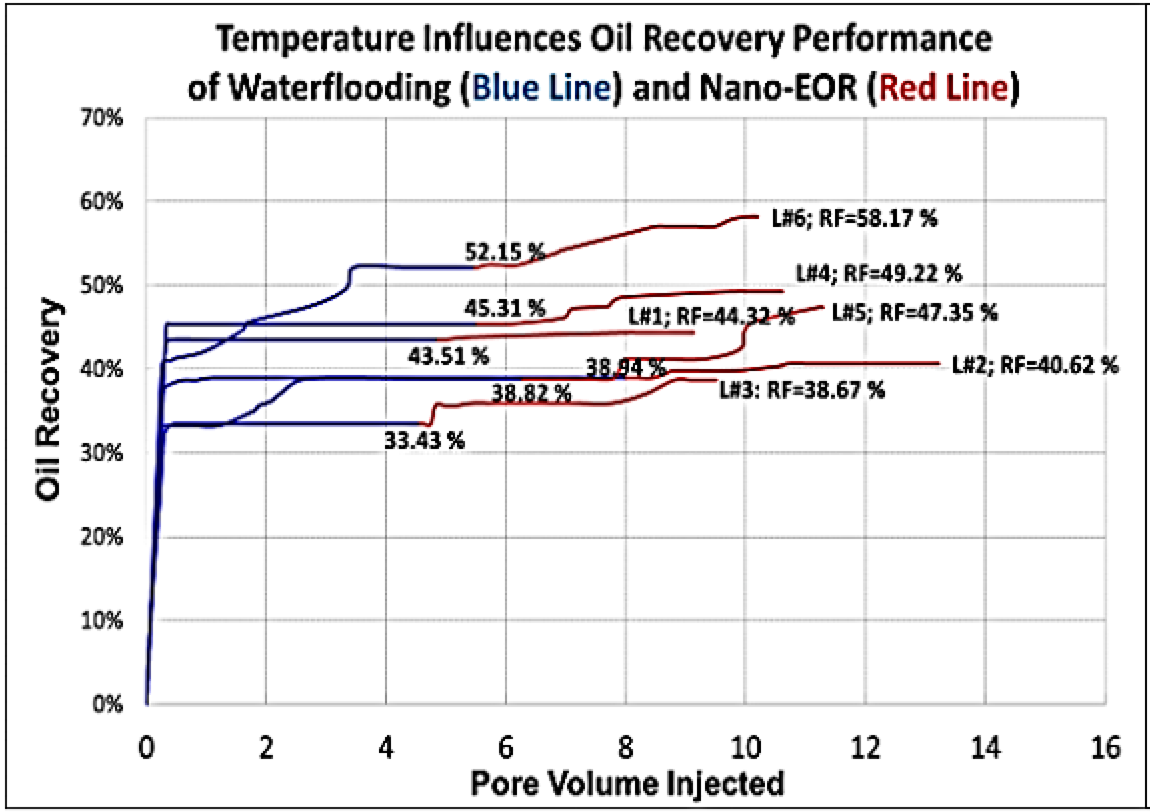
Effect of Salinity

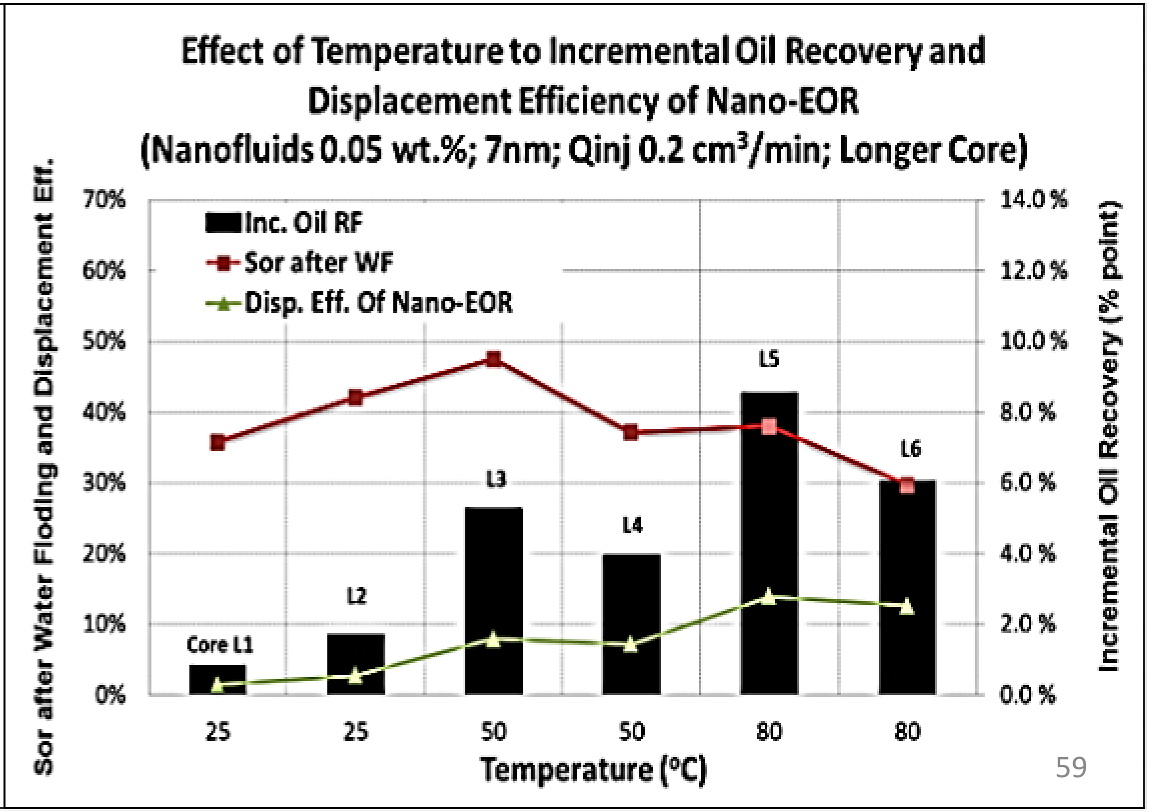
- The correct salinity level and surface coating are important aspects to be considered to prevent agglomeration of NPs.

- By using high stability silica NPs, Hendraningrat et al. proved that high salinity nanofluid injection could improve the wettability alteration to be more water-wet and thus improve the ultimate oil recovery.

Temperature

- A set of experiments by Hendraningrat et al. showed that temperature significantly influences the oil recovery.
- The higher temperature is favored for higher oil recovery than lower temperature.
- The higher temperature condition could possibly alter the reservoir fluids at the molecular level, which reduces the contact angle between the fluids.





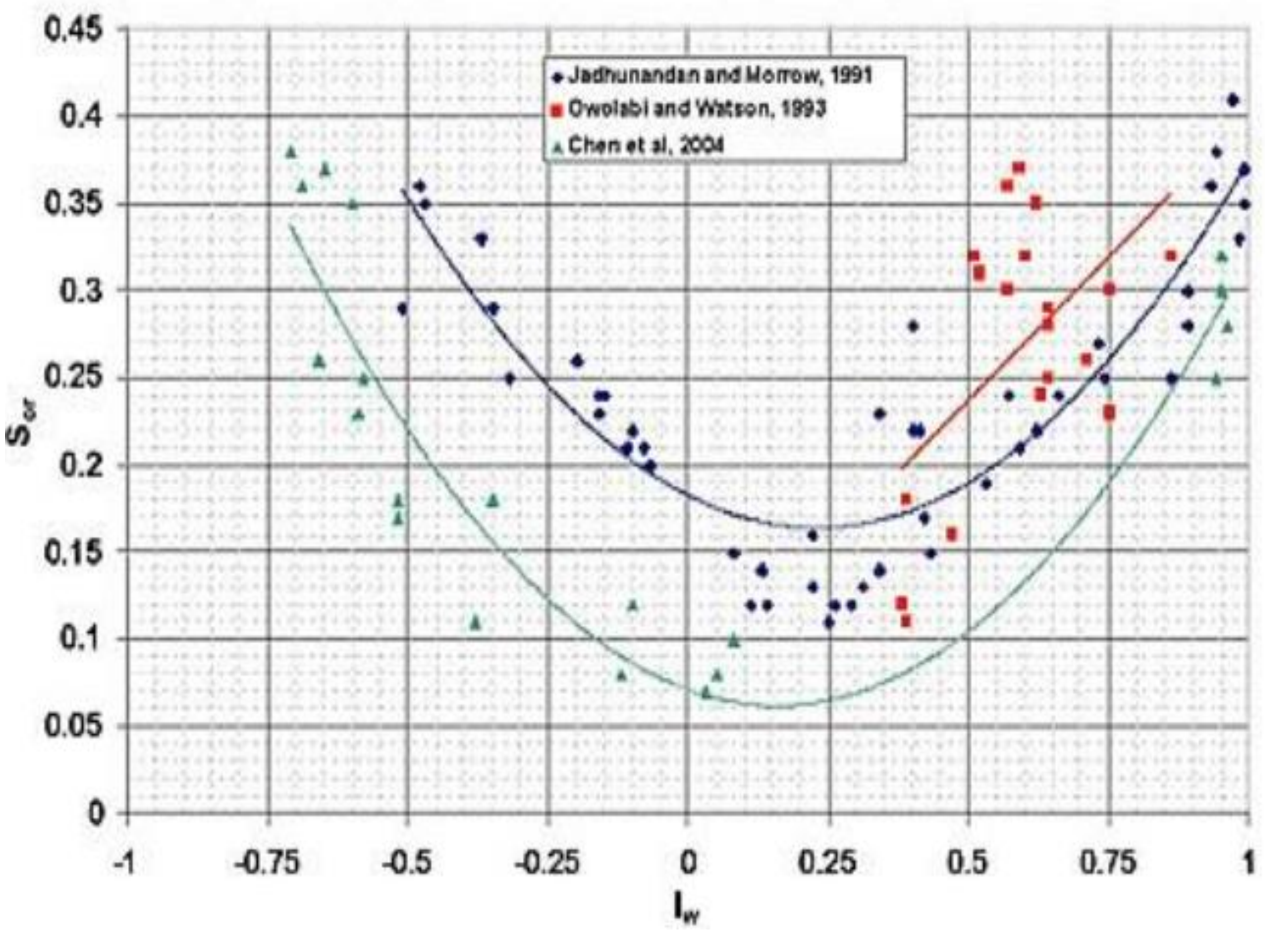
Temperature (cont.)

- The increment on recovery could probably be ascribed to decreasing IFT at high temperature since it weakens molecular interaction or to the increasing Brownian motion and a reduction in viscosity.
- However, increasing the temperature tends to decrease the zeta potential of the particles. This means decreasing the stability of the nanofluid and will likely reduce the oil recovery.

✓ Since changing temperature will affect both nanofluids and the reservoir system, the effect of temperature on the recovery cannot be generalized.

Wettability

- Wettability is playing an important role in the hydrocarbon mobility.
- It affects distribution and displacement process of hydrocarbon and other reservoir fluids within the matrix.
- According to Morrow, strong water wetness and associated high capillary imbibition are favorable for more efficient oil displacement. However, at special cases, it had been reported that oil-wet reservoir and neutral wettability were proven to give higher oil recovery.



Wettability (cont.)

- During nano-EOR, initial wettability will determine the magnitude of the wettability alteration.
- According to Li, wettability affects the adsorption quantity of NPs. Water-wet and neutral-wet have higher adsorption than oil-wet media.
- An experimental study using silica NPs showed that the highest incremental oil recovery was yielded from intermediate-wet core.

Case Study

- On an average, only about a third of the original oil in place can be recovered by the primary and secondary recovery processes.
- The rest of oil is trapped in reservoir pores due to surface and interfacial forces.
- This trapped oil can be recovered by reducing the capillary forces that prevent oil from flowing within the pores of reservoir rock and into the wellbore.
- Capillary pressure which is the force necessary to squeeze a hydrocarbon droplet through a pore throat reduces by reduction of oil-water interfacial tension and wettability alteration.

Case Study (cont.)

- Polysilicon Nanoparticles have a great potential for increasing pore scale displacement efficiency through reduction of interfacial tension and wettability alteration.
- There are three types of Polysilicon Nanoparticles which can be used according the reservoir wettability conditions.
- In this study, hydrophobic and lipophilic polysilicon (HLP) and neutrally-wet polysilicon (NWP) are investigated as EOR agents in water-wet sandstone rocks.
- These two Nanoparticles recover additional oil through major mechanisms of interfacial tension reduction and wettability alteration.

Case Study (cont.)

- The impact of these two Nanoparticle types on water-oil interfacial tension and the contact angle developed between oil and the rock surface in presence of water phase are investigated.
- Then, several coreflood experiments are conducted to study their impacts directly on recoveries.
- Furthermore, optimum pore-volume injection of each Nanofluid is determined according the pressure drop across the core samples.

Case Study (cont.)

- These investigations are performed for different modes of:
  - NPs type.
  - NPs size.
  - NPs concentration.
  - Base fluid salinity.
  - Permeability (pore throat diameter).
  - Injection rate.
  - Injection time.
  - Temperature.

Contact Angle and Interfacial Tension Measurement

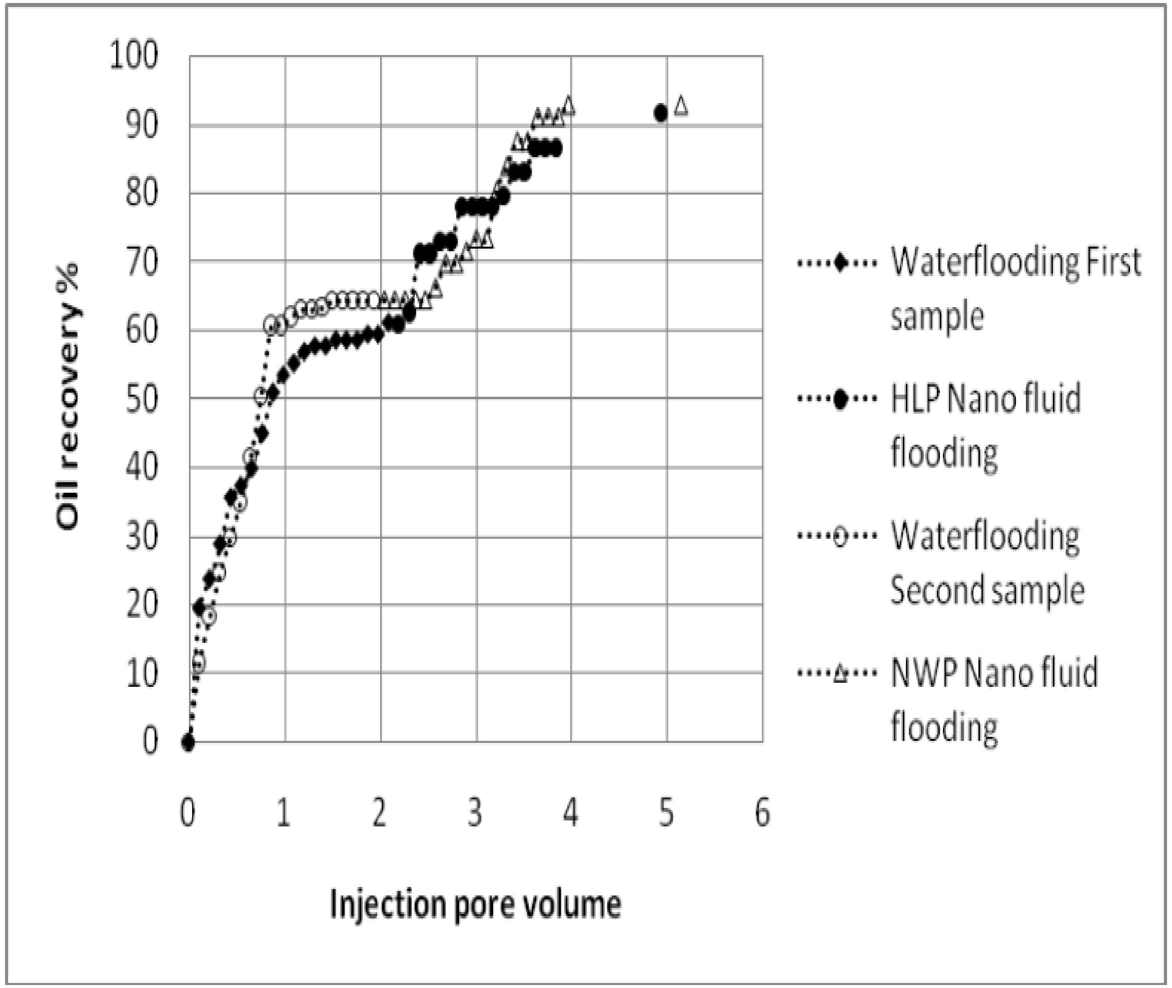
- An alteration observed in rock wettability after surface treatment with both NWP and HLP Nanoparticles. The oil/water contact angle of cleaned sandstone plates were about 135.5° and 130° respectively before application of Nano fluids which demonstrate water-wet characteristic of the rock surfaces (Anderson, 1986). In these cases, oil droplet has no tendency to spread on the surface of the rock. After treatment of surface with Nanoparticles, contact angle between oil droplet and rock surface decreases to 81.88° in the case of NWP Nanoparticles while, it dips to 95.44° in that of the HLP Nanoparticles.
- This reduction of contact angle is the result of Nanoparticles adsorption on the rock surfaces. Measurement of contact angle after application of both HLP and NWP Nano fluid shows that rock wettability alters from water-wet to neutral-wet condition (Anderson, 1986).
- However, a comparison between contact angle measurement results of different types of Nano fluids reveals that NWP Nanoparticles have stronger impact on wettability and its alteration.

Contact Angle and Interfacial Tension Measurement (cont.)

- Oil-water interfacial tension experiences a reduction in presence of both HLP and NWP Nanoparticles. Interfacial tension between oil and water get the value of 26.3 mN/m before application of Nano fluids. However, in presence of Nano NWP and HLP fluids, it reduces to 2.55 mN/m and 1.75 mN/m respectively.
- This amount of reduction in interfacial tension shows the efficiency of Nanoparticles in oil mobilization.
- Reduction of oil-water interfacial tension leads to easy flow of trapped oil, because it reduces the work of deformation needed for oil droplets to move through pore throat. (Donaldson et al., 1989)
- A comparison between the amount of interfacial tension reduction in the cases of NWP and HLP Nanoparticles shows that there exists little difference between the impacts of these Nanoparticles on oil-water interfacial tension so that HLP Nanoparticles have greater influence.

Oil Recovery

- Total oil recovery increases after application of Nano fluids in both first and second core samples. As can be clear seen, waterflooding recovery of first core plug is 59.33% and that of the second one is 64.28%. HLP Nano fluid injected into first core sample and NWP Nano fluid were used for second sample.
- Oil recovery increases by 32.20% and 28.57% respectively in first and second core samples after injection of Nano fluids.
- Therefore, total oil recovery hits to more than 90% in both samples.

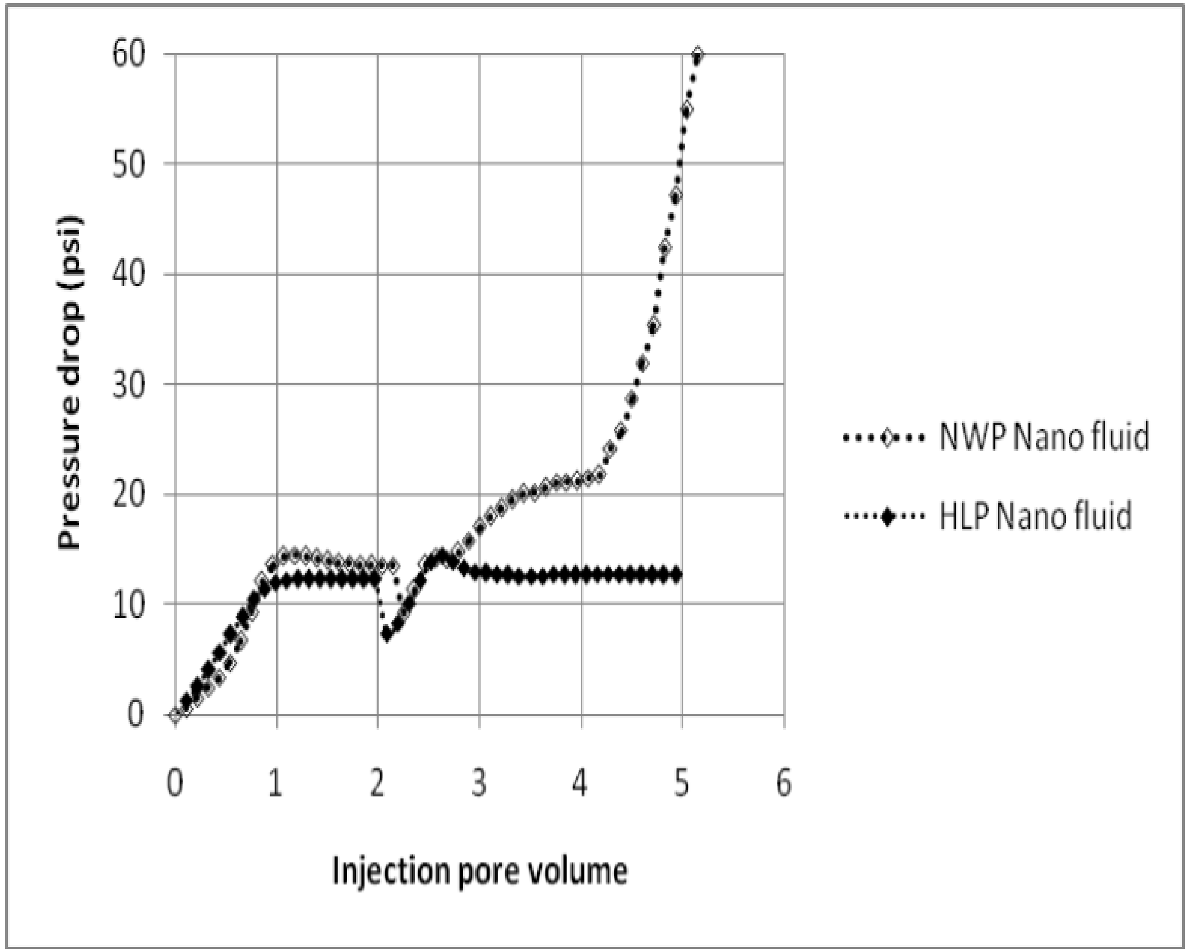


Oil Recovery (cont.)

- A comparison between recovery results after injection of Nano fluids reveals that both NWP and HLP Nanoparticles can produce significant amount of oil after primary and secondary recovery process. However, HLP Nanoparticles can recover higher amount of residual oil.
- According to Results of interfacial tension and contact angle measurement, when Nanoparticles introduce to the porous media, some of them may adsorb on the rock surface and others react with immobile oil droplets and mobilize them to flow.
- In both samples, reduction of interfacial tension between oil and water and alteration of wettability are different.
- HLP Nanoparticles have higher influence on oil-water interfacial tension while, NWP Nanoparticles have greater impact on wettability alteration.
- However, as reduction of interfacial tension plays an essential role in mobilization of immobile oil and reduction of capillary force, higher amount of recovery would be seen in the case of HLP Nanoparticles

Optimum pore volume for injection

- When Nano fluid injection begins, at the first place, a pressure shock observed due to switching of displacing fluid.
- However, pressure drop curve shows different behavior for injection of different Nano fluids.



NWP Nano fluid

- During injection of NWP Nano fluid, two mechanisms affect pressure drop curve. A reduction due to oil production and an intensification due to surface adsorption and pore throat plugging.
- The intensification of pressure backs to pore size distribution in the core.
- Therefore, Nanoparticles deposition which is the result of instability of Nano fluid under dynamic condition, partially reduces rock permeability induces a minor damage to the core due to plugging of small pore throats.
- After injection of two pore volumes of nano-fluid pressure drop climbed dramatically, which shows system is dealing with significant damage.
- According to recovery and pressure drop data, injection of two PV of nano-fluid improves oil recovery without inducing any significant formation damage.

HLP Nano fluid

- On the other side, during injection of HLP Nano fluid no damage observed in the pressure drop curve.
- This type of polysilicon Nanoparticles have higher stability under dynamic condition. Therefore, Nanoparticles deposition occurs later and no damage induces to the rock up to injection of three pore volumes of Nano fluid.

Optimum pore volume for injection (cont.)

- Nanoparticles type determines the amount of dynamic stability of Nano suspension.
- Because NWP Nano fluid possess both hydrophilic and hydophobic Nanoparticles it has low stability and needs more sonication time and energy.

Thank You