*El-Abbas Moustafa. Int. Journal of Engineering Research and Application* *www.ijera.com*
*ISSN : 2248-9622, Vol. 7, Issue 9, ( Part -3) September 2017, pp.63-75*

RESEARCH ARTICLE OPEN ACCESS

# Studying the Effect of Nano-materials on Capillary Pressure Curves for Sandstone ReservoirUsing the Centrifuge Technique

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**ABSTRACT:**
In the past few years, the Effect of Capillary Pressure Curves on the Non-wetting and Wetting properties of fluid flow was the topic of several papers. This effect was usually examined by applying different EOR methods on the structure of pore space of cores made up of blocks of pore size distribution. In this paper, Capillary Pressure is created in the core by partial filling of the pore spaces with oil and injecting with Nano-particle solutions (NPS) which are used in EOR recovery to influence the pore size on core, and to create a core plug of heterogeneous wettability. The outcome of heterogeneous wettability on the capillary pressure is shown in a systematic way by the centrifuge technique with various concentrations of Nano-particle solutions relevant to the experimental data.The objective of this study is the use of centrifuge to measure capillary pressure. The measurements were performed on a selected core samples using formation crude oil and water. Centrifuge provided the opportunity to measure different capillary pressure curves. The experimental procedure consists of the following steps: (1) the core plug is fully saturated with Nano-particle solution and displaced by oil to reach the initial water saturation. Subsequently, a drainage experiment is performed in order to obtain the initial oil saturation, Soi, (2) the oil is displaced by Nano-particle solution to residual oil saturation, Sor; the experiment known as the imbibition experiment was achieved. This procedure was repeated several times on the same plugs with various rotation speeds, and finally (3) it has been observed that a change in the capillary pressure curve occurred when NPS is used with different concentrations.

**Keywords** Capillary Pressure; Centrifuge Technique; Saturation Redistribution; Nano-particle, Drainage Cycle, Imbibition Cycle

Date of Submission: 18-08-2017 Date of acceptance: 13-09-2017

## I. INTRODUCTION

It is proposed that the capillary pressure function is for interpreting rock-scale flow experiments. This function has been found suitable for a wide range of rock/fluid cycles with different pore geometry and wettability characteristics. In petrophysical evaluation, capillary pressure curve is an important parameter for calculating field-wide water-saturation versus height relationships from core and log information. Both imbibition and drainage capillary pressure curves may be required for field studies, depending on the history of saturation during the production. **Hassler and Brunner (1945) [1]** proposed a centrifuge method to determine the capillary pressure-saturation curves from small core plugs. Theyobtained an approximate solution to the equation relating capillary pressure and average saturation by neglecting the gravity effect. The length of the core was negligible compared to the radius of rotation ($r_1/r_2 \approx 1$). In a centrifuge capillary pressure experiment, a saturated core is rotated at different speeds.

Capillary pressure is essential for understanding and predicting the movement of multiple phases in petroleum reservoirs. Capillary pressure (Pc) is defined as the pressure difference across a curved interface between two immiscible fluids. For oil/water systems in porous rock, Pc is generally defined as the pressure difference between the oil phase ($P_o$) and water phase ($P_w$), i.e., $P_c = P_o - P_w$, and expressed as a function of water saturation ($S_w$). These properties are measured by a variety of laboratory methods, including a porous plate, mercury injection, centrifugal displacement, and displacements at normal gravitational acceleration **(Amyx 1960) [2].** Centrifuge methods are increasingly used for a number of reasons, including the short duration of the tests, and the potential for measurements proximate to the end-point saturations. Centrifugal measurements are generallylimited to fluids that have a high mobility contrast. Indeed, relative permeability can only be obtained for low-mobility fluids using standard tests **(Hagoort, 1980) [3].**

The centrifuge method imposes a centrifugal force on the sample which is saturated by one phase e.g. water and is immersed in another phase e.g., oil in a specially designed holder. At each particular rpm (revolutions per minute) the amount of water expelled from the core is measured and the average capillary pressure is calculated. The rate is then increased in steps and the capillary pressure is calculated at the corresponding water saturation and, therefore, a full drainage curve is produced. The main advantage of the centrifuge is obtaining capillary pressure data very quickly compared with the porous plate method. The main disadvantage of the centrifuge method is the limited maximum pressure which is around 1000 psi (6895 kPa)**O'Meara Jr., D.J., et al. [4], (Tiab, D., and Donaldson E.C. 2004) [5], (S. Karimi, and H. Kazemi, 2015) [6].**

In the centrifuge method, a brine or oil saturated core plug is placed in the holder surrounded by another type of fluid (oil or brine)or air.It is then spun with different rotational speeds. The centrifugal force applied on the core plug causes the fluid surrounding the core to displace the fluid inside the core. The produced fluid from the core plug is accumulated in the receiving cup. Fluid production from core, which changes the fluid interface location between oil and brine in the cup, is captured with a high resolution camera.

Using centrifuge, the known capillary pressures are applied on the core plug, and the fluid volume production from the core plug is measured. The produced fluid volume is converted into the average saturation change in the core plug, and the capillary pressure versus liquid saturation envelop can be plotted using the results **(Rajan 1986)[7]**. The limitation of this method is the maximum practical rotational speed of the apparatus**[8].**The procedure and discussion on measurement accuracy of multi-speed centrifuge experiments can be found elsewhere **(e.g., Kalaydjian, F.J-M. 1992; Ruth and Chen, 1995)[9, 10].**

**BinshanJu et al. [10]** analyzed the mechanism of enhanced oil recovery using Lipophobic and Hydrophilic Poly-silicon (LHP) nanoparticles for changing the wettability of porous media theoretically. In order to consider the migration and adsorption of LHP and wettability change in reservoir rock, a one-dimensional two-phase mathematical model was offered, and a simulator was developed to quantitatively predict the changes in relative and effective permeability of the oil and water phases as well as the oil recovery in sandstone after water driving. Numerical simulations were conducted to study the distribution of the particle concentration, the reduction in porosity and absolute permeability, the LHP volume retention on pore walls and in pore throats along a dimensionless distance, and oil production performance. Accordingly, the LHP concentration within 0.02-0.03%is recommendedto enhance oil recovery asthe increase in LHP concentration will lead to formation damage due to reduction of permeability. Additionally, it is concluded that oil recovery can obviously be improved by flooding with LHP.

Poly-silicon nano-powder absorbs on the rock surface easily, due to the high-energy state of its surface and the extreme instability of its surface atoms, thus it changes the rock wettability **[11].** Since wettability of the reservoir rocks controls the location, flow, and distribution of fluids in the reservoir, relative permeability of fluids in porous media can be changed by modifying the wettability of porous walls.According to wettability of the surface of poly-silicon nanoparticles, such poly-silicon nanoparticles can be classified into three types: Lipophobic and Hydrophilic Poly-silicon (LHP), Hydrophobic and Lipophilic Poly-silicon (HLP), Natural Wet Poly-silicon (NWP) which can be used proportional to the reservoir wettability **[12].** Since the wettability of porous walls can be changed by adsorption of nanometer scaled poly-silicon with different wettability, each of the three types may be used in oil development for modifying the flow performance of oil water and gas in oil reservoirs.

## II. Experimental Procedure Technical and Setup

### Rock and Fluid Properties used in the Centrifuge Experiments

### Core Sample and Fluids preparation

### Restored Cores

Core sample plugs was selected from Gulf of Suez well in Egypt. Then they are cleaned and dried. A commercial laboratory measured the helium porosity, gas permeability, and liquid permeability as shown in **Table 1**. The core sample plugs was fully saturated with wetting phase (formation water) in a high pressure vessel (3000psi). This method was chosen because of the core samples were completely saturated with FW. Six core plug samples were cut with diameters of about 3.8 cm and lengths of 4.2-5.2 cm.

**.Table 1 Description of the Physical Properties for Core Samples.**

| Core Sample | Dry Weight of Core Sample | Core Sample diameter | Core Sample Length | Bulk Vol. | Grain Vol. | Pore Vol. | Grain density | Helium Core Sample Porosity | $K_{air}$ | $K_L$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **ID** | **(g)** | **(cm)** | **(cm)** | **(cc)** | **(cc)** | **(cc)** | **(g/cc)** | **$\Phi_{He}$ (%)** | **mD** | **mD** |
| **CRF 1-NP-I** | **87.995** | **3.81** | **3.91** | **43.98** | **33.59** | **10.39** | **2.62** | **23.62** | **7.68** | **2.84** |
| **CRF 2-NP-I** | **90.202** | **3.82** | **4.00** | **45.00** | **34.71** | **10.29** | **2.60** | **22.86** | **7.04** | **3.03** |
| **CRF 3-NP-I** | **97.266** | **3.82** | **3.81** | **43.18** | **36.65** | **6.53** | **2.65** | **15.12** | **1.22** | **0.70** |
| **CRF 4-NP-I** | **93.323** | **3.76** | **4.04** | **44.11** | **36.39** | **7.72** | **2.56** | **17.49** | **0.36** | **0.08** |
| **CRF 5-NP-II** | **95.415** | **3.74** | **3.88** | **42.18** | **36.60** | **5.58** | **2.61** | **13.23** | **2.76** | **1.53** |
| **CRF 6-NP-II** | **90.026** | **3.73** | **3.73** | **43.41** | **34.05** | **9.36** | **2.64** | **21.56** | **26.52** | **17.36** |

* Air permeability measurement, Ka

**Liquid permeability measurement after saturated 100% with formation water, $K_L$

The cores were divided into two groups. Group 1 consists of four core samples saturated with the first type of Nano-particle solutions and is used for drainage and imbibition cycles. Group 2 consists of two core samples saturated with the second type of NPS and is also used for drainage and imbibition measurements.**Table 2** illustrates the design of saturation for both of the two groups of the core plug samples.

**Table 2 Divided of core samples to two groups, first one is Core Samples are used with saturated of first type of nano-particle solutions and the second one were saturated with the second nano-particle solutions and measured their preparing for instill in Centrifuge device.**

| Core Sample | Dry Weight of Core Sample | Wetted Weight of Core Sample | Calculated Pore Volume | Saturation Percentage | Notes |
|---|---|---|---|---|---|
| **ID** | **(g)** | **(g)** | **(g)** | **%** | |
| **CRF 1-NP-I** | **87.995** | **98.956** | **10.45** | **100.60** | **NP-I: represent of first group saturated with the first type of nano-particle solutions** |
| **CRF 2-NP-I** | **90.202** | **100.990** | **10.29** | **99.98** | |
| **CRF 3-NP-I** | **97.266** | **104.110** | **6.53** | **99.96** | |
| **CRF 4-NP-I** | **93.323** | **101.578** | **7.84** | **100.31** | **NP-II: represent of first group saturated with the first type of nano-particle solutions** |
| **CRF 5-NP-II** | **95.415** | **101.398** | **5.70** | **100.27** | |
| **CRF 6-NP-II** | **90.026** | **100.101** | **9.61** | **100.51** | |

**Fluids**

Both formation water and crude oil obtained from Gulf of Suez, Egyptwere used. It was initially intended to use crude oil from the field in all experiments, but the centrifuge device to be used in capillary pressure experiments and ambient temperature work was available. Consequently, Nano-particle solutions with different NP concentrationswere prepared and used for Pc measurements. Density of crude oil or solutions has been experimentally measured by weighing the known volumes of liquid. **Table 3** contains the average results. The crude oil density is 0.8978 g/cc atambient temperature of 15.6°C and the dynamic viscosity is 17.868 cp at the temperature of 23.7°C.

**Table 3 Formation water and crude oil properties.**

| Fluids | Density | Viscosity |
|---|---|---|
| | **(g/cc)** | **(cp)** |
| Formation water | 1.117 | 1.100 |
| Crude Oil | 0.8978 | 17.868 |

**Table 4** displays the major Physical Properties of the different Nano-particle Solutions, such as density, pH Value, surface tension and interfacial tension between crude oil and certain high Phase. The fluid properties are measured at ambient conditions. The density of different NPS concentrations ranged **1.04804 to 1.05306** g/cc and pH values ranged **7.402 to 7.578**;the surface tension between air and different NPS concentrations at fluid temperature of 24.5°C ranged**60.13 to 72.44**mN/m; the measured value of crude oil/ NP solutions interfacial tension (IFT) ranged 34.25 **to 38.47**mN/m at the fluid temperature of 23.5°C.Moreover, the contact angle of different solutions was measured; it ranged 90 to 7.52 degrees. All above items were measured by Kruss Model K-100C Force Tensiometer device.

**Table 4 Summaries of Physical Properties for different nano-particle Solutions such as Density, pH Value, Surface Tension and Interfacial Tension between Crude Oil and Certain High Phase.**

| **Parameters Measurement,** <br> **Core ID and Concentration Solution** | **Nano Percent age** | Density[a], @ Ambient Temp. @24.5°C | **pH**[b] value, at Ts **@** 23.5°C | **Surface Tension**[c] **at$T_f$** **@** 24.5°C | **Standard Deviation** | **Inter-facial Tension**[c,d], **at $T_f$** @23.4 °C | **Standard Deviation** | **Contact Angle** |
|---|---|---|---|---|---|---|---|---|
| | **%** | **g/cc** | | **mN/m** | **mN/m** | **mN/m** | **mN/m** | **degree** |
| **CRF 1-NP-I**[e] **(0.5g/l)**[e] | ***0.50*** | **1.04804** | **7.402** | **72.44** | *0.0673* | **38.47** | *0.1422* | **90** |
| **CRF 2-NP-I**[e] **(2.0g/l)**[e] | ***2.00*** | **1.04868** | **7.515** | **60.13** | *0.0798* | **34.25** | *0.1437* | **11.27** |
| **CRF 3-NP-I**[e] **(3.0g/l)**[e] | ***3.00*** | **1.05242** | **7.545** | **65.87** | *0.0401* | **36.91** | *0.1144* | **7.59** |
| **CRF 4-NP-I**[e] **(5.0g/l)**[e] | ***5.00*** | **1.05306** | **7.578** | **68.89** | *0.0732* | **38.34** | *0.1986* | **7.53** |
| **CRF 5-NP-II**[f] **(3.0g/l)**[f] | ***3.00*** | **1.04930** | **7.518** | **62.43** | *0.0720* | **38.24** | *0.1685* | **0.0** |
| **CRF 6-NP-II**[f] **(5.0g/l)**[f] | ***5.00*** | **1.05050** | **7.546** | **61.59** | *0.0856* | **33.02** | *0.0954* | **0.0** |

a. Glass Pycnometer used to measure of density for different solutions,
b. JenWay pH Meter 3510 device used to measure of pH value for all fluids,
c. Kruss Model K-100C Force Tensiometer device used to measure Surface and Interfacial Tension, and Contact angle.
d. Interfacial Tension measurement between crude Oil and certain high phase (nano-particle solutions), Tare within Light phase (Crude Oil) is equal 0.1100 ( Density of Crude Oil is 0.8978 g/cc @ Ambient Temp. 15.6°Cand Dynamic Viscosity is 17.868 CP @temp. 23.7°C.
e. NP-I is the first type of nano-particle (Silicon oxide Nano-powder $SiO_2$, 95.9+Wt%, 20-30 nm, Amorphous),

f. NP-II is the second type of nano-particle (Silicon Oxide Nano-powder $SiO_2$, 99+Wt%, 20-30 nm, Amorphous).

**Group 1**

In Group 1, four core plug samples were selected and used saturatedwith the first type of Nano-particle solutions (NP-I is the first type of Nano-particle (Silicon oxide Nano-powder $SiO_2$, **95.9+ wt.%,** 20-30 nm, Amorphous). The different concentrations of NP-I solution were**0.5, 2.0, 3.0 and 5.0 wt. % of NP-I**carried out for drainage and imbibition cycles. **Table 2**is designed for the centrifuge experiments dividingthe core samples into two groups, the first is core samples used saturated with the first type of Nano-particle solutions and the second saturated with the second Nano-particle solutions and their preparedness for instill in the Centrifuge device are measured.

Helium porosities of the core samples ranged **15.12 to 23.26**%and absolute brine permeabilities ranged **0.08 – 3.03**mD.A crude oil was used as the oil phase. The crude oil density was**0.8978** g/cc and its viscosity was**17.868**cP at 25˚C. A synthetic NP-I solution with the density of **1.04804 to 1.05306**g/cc and viscosity of **1.101**cP was prepared. The solutions composition haddifferent concentrations. Themeasured interfacial tension between the solutions and the crude oil ranged **34.25 - 38.47**mN/m. The contact angle of those solutions was measured by Kruss Model K-100C Force Tensiometer device. The advancing contact angle ranged **90 -7.53** degree.

**Group 2**

In Group 2, two core plug samples (CRF-5NP-II and CRF-6NP-II) were selected and used saturatedwith thesecond type of Nano-particle solutions (NP-II is the second type of Nano-particle (Silicon Oxide Nano-powder $SiO_2$, **99+ wt.%,** 20-30 nm, Amorphous). The different concentrations of NP-I solution were**3.0 and 5.0 Wt. % of NP-II** carried out for drainage and imbibition cycles. The valuesof porosities of the core samples were **13.23 and 26.52**% and absolute brine permeabilities were **1.53 and 17.62mD**, respectively. A crude oil was used as the oil phase. The density of crude oil was**0.8978** g/cc and its viscosity was**17.86**cP at 25˚C. A synthetic NP-II solution with the density of **1.04930and 1.05050**g/cc, respectively and approximate measured viscosity of **1.101**cP was prepared. The solutions composition had different concentrations. Themeasured interfacial tension between the solutions and the crude oil ranged**38.24 and 33.02**mN/m for NPS-II at the concentration of **3.0 and 5.0 wt. %**. The advancing contact angle of those solutions measured **0.0 and 0.0** degrees, respectively.

The core plug sample was initially saturated with one fluid (e.g. water) and then another fluid (e.g. oil) was injected into the core to displace the first fluid, at certain low rate. Fluid injection continued until initial saturation of the displaced fluid is achieved.

## Centrifuge Capillary Pressure Measurement

## Laboratory methods of measuring capillary pressure

The centrifuge technique is a displacement technique depending on the force of centrifugal across the core plug sample. During the experiment, the core plug sample was saturatedin two phases,oil and irreducible water saturations. Then, it was centrifuged in a core holder filled with the other phase (e.g. NP solutions) to achieve the drainage cycles. The experiment continued to carry out the imbibition cycles. Subsequently, the production of the phase expelled from the core plug sample by force of centrifuge is measured as a function of time. Both drainage and imbibition experiments could be performed to determine capillary pressurecurves.Multi-speed experiments are achieved at a series of fixed centrifugal accelerations to reach the static equilibrium for capillary pressure measurements.The centrifuge measurements were conducted under ambient conditions.

A Core-Test URC-628 **[18]** rock centrifuge is performed to determine the capillary pressure curve and the connate water saturation. The maximum rotational speed of the centrifuge is 20,000 rpm. The geometric parameters of the centrifuge ensure a maximal **Pc=100 bar** reachable capillary pressure for the water-gas system. Three buckets can be placed into the rotor of the URC-628 centrifuge. In each bucket a sample with amaximum diameter of 1.5 inches and a length of 1.0-2.0 inches could be placed. After saturation of the samples with water and placing them in the buckets, the measurement started. The control program of the centrifuge keeps the rotational speed at a constant value forthepreset time interval, until the maximum rotational speedis acquired. The centrifuge device used for displacements in both drainage and imbibition, where the core holders are reversible for operating in either of the imbibition or the drainage cycles, includesa computer with control and data acquisition software. A High-resolution camera was used to give accurate measurements of the fluid interface changes.The samplesare collected in measuring tubes at different rotational speed values (capillary pressure values) so that the amount of the remaining fluid at a capillary pressure interval can be determined. Consequently, the saturated fluidof the sample can also be determined.

The centrifuge method for determining capillary pressure is a rapid approach for achieving a full drainage and imbibition cycles in a few days, from which oil-brine data can be obtained

**1-** Rotate at a fixed constant speed. The centrifugal force displaces certain liquid volume, which can be read at the window using a strobe light with a camera. Thus, the saturation can be obtained.

**2-** The outset centrifuge was performedat a rotation speed of 1000rpm; afterwards the speed was changed from 2000 to 8000 RPM, respectively. Then the resultant volume of the displaced fluid is collected (i.e. volume collected, $V_{disp}$ in measuring tubes) and recorded at each rotary speed. This was achieved at an interval of six minutes and thestrobe light frequency was turned off when the volume of collected fluid illustrates no further changes.

**3-** At each rotational speed it is converted into capillary pressure using appropriate equations **[5].**

**4-** Repeat for eight steps and plot capillary pressure versus saturation.

The following data sets are available from this experiment as programmed by the operator:

- Drainage Capillary Pressure
- Imbibition Capillary Pressure

**Drainage Cycle**

The measurement starts with the drainage capillary pressure cycle on the core sample. The centrifuge has a spatial drainage set up for conducting the drainage cycle. **Figure 1** shows a schematic of the centrifuge forced drainage set up. In drainage capillary pressure measurement, a completely nanoparticle solution (NPS) saturated core plug was used. The core was surrounded by oil.

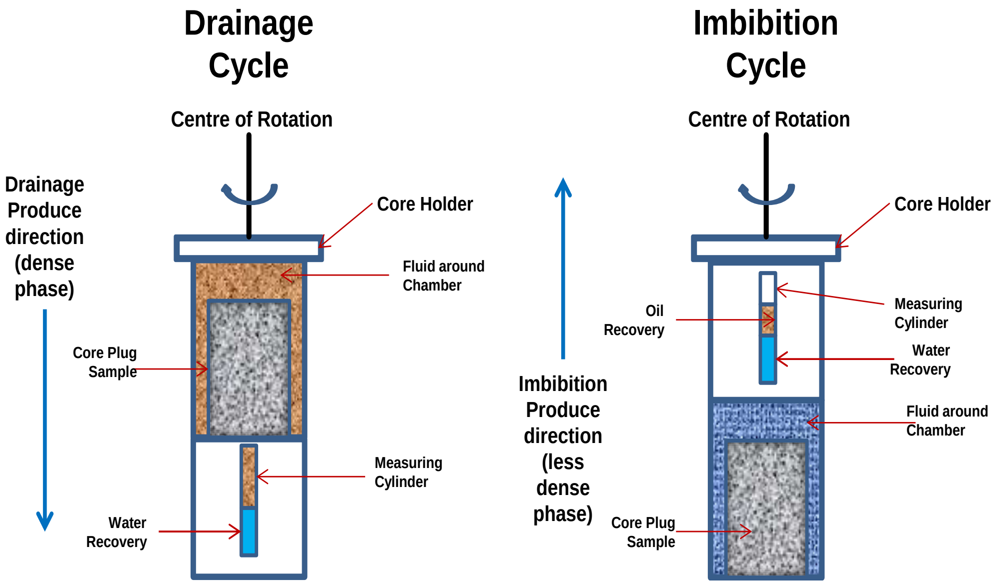

**Figure 1 A Schematic of Centrifuge Core Holder forced for setup of Drainage cycle (drainage Oil displacing NP solutions) and Imbibition Cycle (imbibition NPS displacing**

**Oil).**

When the centrifuge spins the core, centrifugal force causes the fluid with higher density (NPS in the pores) to move away from the center of rotation; therefore, oil enters from the inner face of the core, and displaces the NPS in the core plug. NPS is produced from outer-face of the core plug, and is collected in the receiving cup. A high resolution camera records the location of the interface between oil and brine. When NPS is produced from the core sample the interface changes. Based upon this result the amount of the produced fluid is calculated, as well as the average saturation of the core sample.In order to obtain the results of capillary pressure and water saturation, the drainage experiment must be conducted at different rotational speeds (rpm). Stabilization must be reached at each speed before going forward with a higher speed. It means, at each rpm, the test must be continued until the production from the core plug ceases **(O'Meara 1992) [4]**. Each rotational speed provides a single data point on the capillary pressure versus water saturation plot. At the end of the centrifuge drainage capillary pressure experiment, the core is at the residual water saturation corresponding to the highest capillary pressure applied.

**Imbibition Cycle**

Experiment Imbibition Centrifuge has a special set up for forced imbibition capillary pressure measurement. This imbibition cycle is to **force nanoparticle solution to displace oil in the core plug.Figure 1** shows a schematic of the centrifuge forced imbibition set up. In forced imbibition cycle, the core is placed in the centrifuge cup surrounded by NPS. At this stage, the core contains both residual water saturations and oil. Centrifugal force causes oil in the pores to be displaced by NPS. Oil moves towards the center of rotation, and the NPS enter the pores. Forced imbibition cycle was conducted at many different speeds, rpm, and each set provided a result point on the capillary pressure versus water saturation curve.

## III. RESULTS AND DISCUSSION

In this paper, the imbibition is defined by means of performance with water saturation and drainage with oil saturation irrespective of wettability. There are various laboratory techniques available for generating capillary pressure curves such as centrifuge technique.The centrifuge technique consists of rotating a core sample at different angular velocities. The core sample contains two liquids (Oil and nanoparticle solution) for which capillary pressure are to be determined. In the drainage cycle, the denser fluid (NPS) is forced out of the core sample by rotation speed. Phase production, or average phase saturation in the core sample is measured at hydrostatic equilibrium for every rotation speed.

**Centrifuge Capillary Pressure Calculations**

Capillary pressure is the difference between the pressure of wetting phase and non-wetting phase or the pressure difference across the interface between two immiscible fluids at equilibrium conditions. Capillary pressure resulting from centrifuge data is calculated according to the following equation **(Tiab and Donaldson, 2004),[5]**:

$$(Pc)_i = 1.096 * 10^{-6} * (\rho_w - \rho_o) * N^2 * (R_2 - (L/2)) * L \qquad \text{(Eq. 1)}$$

Where

| | | |
|---|---|---|
| Pc | is | Capillary pressure,Kpa (*0.14507 in psi) |
| $\rho_w$ and $\rho_o$ | are | NP solution and oil density, g/cc |
| N | is | Number of rotations per minute (rpm), |
| R | is | The distance between the center of rotation to the outlet end of the core, cm, and |
| L | is | The length of the core sample, cm. |

The capillary pressure magnitude applied to core sample is maximum value at the end of core and reaches to zero at another end. Therefore, displacement process occurs from the end of core sample where the maximum CP is applied, and the saturation of displacing fluid (brine or oil) at this face is maximum (**Bentsen, 1977**) [14];**Torsaeter, 1994 [15];Forbes, 1997 [16]**and**PintérÁkos, TiborBódi (2012) [17].**

**Determination of connate water saturation with a rock centrifuge**

The average connate water saturation can be calculated by using the following equation:

$$S_{avg} = \left(1 - \frac{V_{disp}}{V_P}\right) * 100 \qquad \text{(Eq. 2)}$$

Where

$V_{disp.}$ is Volume produced from displacing with the another phase, cc
$V_P$ are Pore Volume, cc

By using these two equations, the points of the capillary pressure curve can be determined, thus, the capillary pressure curve can be plotted.The summary of this experimental work is to measure the capillary pressure in a core sample and subsequently, plot the capillary pressure versus water saturation curve. In this experiment, four core samples of very close porosity and permeability were used. The samples were tagged sample CRF 1-NP-I, CRF 2-NP-I, CRF 3-NP-I and CRF 4-NP-I for the first type of nano-particle solution at different concentration. In additionthe samples were tagged core plug CRF 5-NP-II and CRF 6-NP-II for the second type of NPS at two different concentrationsis shown in **Table 2**.

### Effect of different concentration of nanoparticle solution

**Figure 2** Effect of different concentration of Nano-particle solution (Type of NP-I) as a function of the capillary pressure curves for drainage and imbibition tests and water saturation, % pore space. In case of the first group including the four core samples and used the first type of nano-particle (Silicon oxide Nano-powder $SiO_2$, **95.9+ wt.%,** 20-30 nm, Amorphous). This Figure shows the produced saturation profiles result from the drainage and imbibition cycles compared to with different concentration of NPS and different rotation speeds.

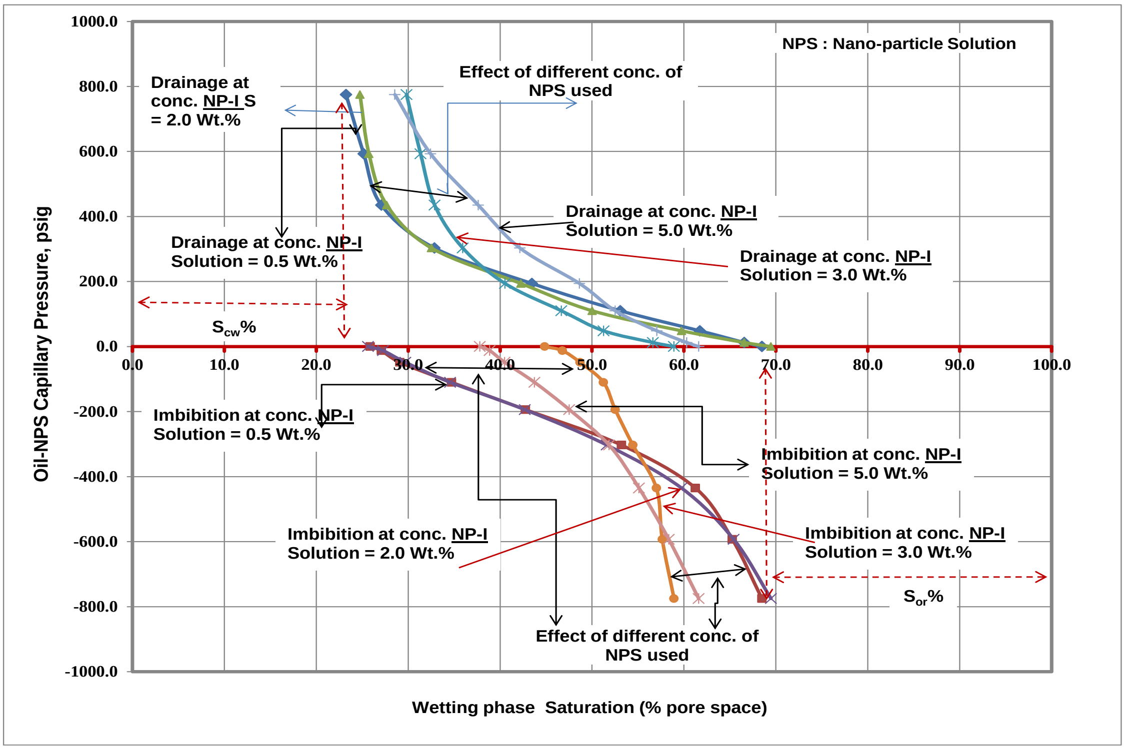

**Figure 2 Effect of different concentration of Nano-particle solution (Type of NP-I) as a function of the capillary pressure curves for drainage and imbibition tests and water saturation, % pore space.**
**NP-I: is the first type of nano-particle (Silicon oxide Nano-powder $SiO_2$, 95.9+Wt%, 20-30 nm, Amorphous),**

From the capillary pressure curves of the Oil-NPS system, the wetting phase (NPS) with group 1 included that the concentration of NPS are 0.5, 2.0, **3.0** and 5.0 Wt. %, the irreducible or connate water saturation were 54.76, 56.27, **70.14** and 65.25%PV, respectively and in case of drainage cycle; while that of the NPS- Oil system (oil), the residual oil saturation were range of 48.99, 47.52, **83.15** and 71.50 %PV, respectively and in case of imbibition cycle.Thehighest value of irreducible or connect water saturation of the wetting phase (*Sw*c) at the concentration of **3.0 wt. %** ($S_{wc}$=70.14 %PV).In case of the residual oil saturation, the highest value of $S_{or}$ is 83.15%PV at the same concentration of NPS 3.0 wt. %. **Tables 5** and **6** illustrated that the determination of the effect of different nanoparticle solution for the connate water saturation and residual oil saturation. It can be seen from **Tables 5 and 6, and** graphically **in Figure 2** that for effectof the nanoparticle on the flowing fluid in the pore space and this means that the further increase of affectit on the structure of size of pore. These are shown from the values of connect of water saturation and residual of oil saturation.

**Table 5** Initial water saturation determines through displacing with crude oil and calculated of water–out drainage.

| Core Sample Code | Helium Porosity | Air Permeability | Bulk volume | Pore Volume | Cum. Water Out Drainage | Initial Water Saturation, $S_{wi}$ |
|---|---|---|---|---|---|---|
| | **%** | **mD** | **cc** | **cc** | **cc** | **%PV** |
| **CRF 1-NP-I** | 23.6 | 7.68 | 43.98 | 10.39 | 4.70 | **54.76** |
| **CRF 2-NP-I** | 22.9 | 7.04 | 45.00 | 10.29 | 4.50 | **56.27** |
| **CRF 3-NP-I** | 15.1 | 1.22 | 43.18 | 6.53 | 1.95 | **70.14** |
| **CRF 4-NP-I** | 17.5 | 0.36 | 44.11 | 7.72 | 2.65 | **65.67** |
| **CRF 5-NP-II** | 13.2 | 2.76 | 42.18 | 5.58 | 1.90 | **65.95** |
| **CRF 6-NP-II** | 21.6 | 26.52 | 43.41 | 9.36 | 4.30 | **54.06** |

**Table 6** Residual oil saturation determines through displacing with Nanoparticle solution and calculated of oil–out imbibition.

| Core Sample Code | Helium Porosity | Air Perme-ability | Bulk volume | Pore Volume | Cum. Oil Out Imbibition | Residual Oil Saturation $S_{or}$ |
|---|---|---|---|---|---|---|
| | **%** | **mD** | **cc** | **cc** | **cc** | **%PV** |
| **CRF 1-NP-I** | 23.6 | 7.68 | 43.98 | 10.39 | 5.30 | **48.99** |
| **CRF 2-NP-I** | 22.9 | 7.04 | 45.00 | 10.29 | 5.40 | **47.52** |
| **CRF 3-NP-I** | 15.1 | 1.22 | 43.18 | 6.53 | 1.10 | **83.15** |
| **CRF 4-NP-I** | 17.5 | 0.36 | 44.11 | 7.72 | 2.20 | **71.50** |
| **CRF 5-NP-II** | 13.2 | 2.76 | 42.18 | 5.58 | 1.40 | **74.91** |
| **CRF 6-NP-II** | 21.6 | 26.52 | 43.41 | 9.36 | 4.15 | **55.66** |

### Effect of different two types of Nanoparticle used

**Figure 3** Effect of different concentration of Nano-particle solution (Type of NP-II) as a function of the capillary pressure curve drainage and Imbibition and water saturation, % pore space. In case of the first group including the four core samples and used the second type of nano-particle (Silicon oxide Nano-powder $SiO_2$, **99+ wt.%,** 20-30 nm, Amorphous). This Figure shows the produced saturation profiles result from the drainage and imbibition cycles compared to with two different concentrations of NPS-II and different rotation speeds.

From the capillary pressure curves of the Oil-NPS system, the wetting phase (NPS-II) with group 2 included that the concentration of NPS-II are **3.0** and 5.0 wt. %, the irreducible or connate water saturation were **65.95** and 54.06 %PV, respectively. In case of drainage cycle; while that of the NPS-II Oil system (oil), the residual oil saturation were range of **74.91** and 55.99 %PV, respectively and in case of imbibition cycle.

The highest value of irreducible or connect water saturation of the wetting phase (*Sw*c) at the concentration of **3.0 wt. %** (**$S_{wc}$=65.95 %PV**). In case of the residual oil saturation, the highest value of $S_{or}$ is **74.91%PV** at the same concentration of NPS

**3.0 wt. %.Tables 5** and **6** illustrated that the determination of the effect of different nanoparticle solution for the connate water saturation and residual oil saturation. **Figure 3** shown that the crossing saturation point (Red dash Line) a high difference can be noticed which leads to a change in capillary entry pressure for the non-wetting phase. In addition it can be seen from **Tables 5 and 6, and** graphically **in Figure 3** that for effect of the nanoparticle on the flowing fluid in the pore space and affect it on the structure of size of pore.

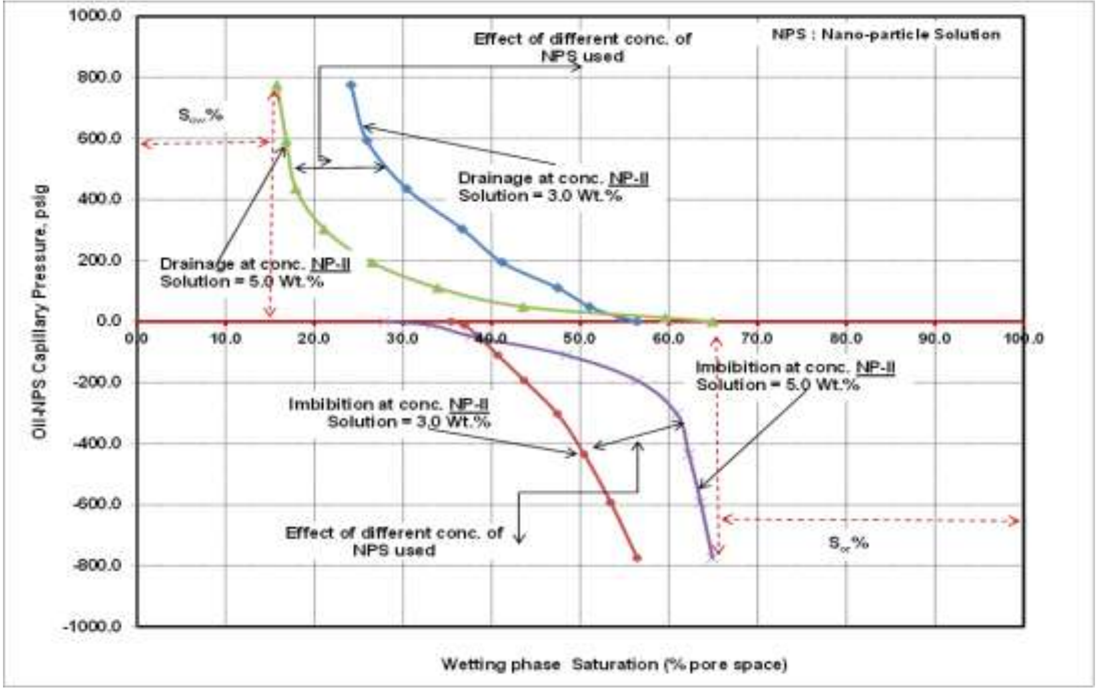

**Figure 3 Effect of different concentration of Nano-particle solution (Type of NP-II) as a function of the capillary pressure curve drainage and Imbibition and water saturation, % pore space. NP-II is the second type of nano-particle (Silicon Oxide Nano-powder $SiO_2$, 99+Wt%, 20-30 nm, Amorphous).**

## Comparison between type of nanoparticle and different concentration

**Figure 4**is shown that the comparison between drainage and imbibition with used to two different type of NP-I and NP-II at the same concentration 3.0 wt. % and effect their on capillary pressure curves. In addition **Figure 5** is illustrated the comparison between drainage and imbibition with used to two different type of NP-I and NP-II at the same concentration 5.0 wt. % and effect their on capillary pressure curves. The main difference between **Figure 4 and Figure 5** is that the effect of different concentration of nanoparticle solution such as **3.0 wt. %** and **5.0 wt. %** in the drainage and imbibition processes were achieved.

From the capillary pressure curves of the Oil-NPS system, the wetting phase (NPS-I) with group 1 that the concentration of NPS-I are **3.0 wt.**, the irreducible or connate water saturation were **70.14** %PV, in case of drainage cycle; while the wetting phase (NPS-II) with group 2 that the same concentration of NPS-II are **3.0 wt.**, the irreducible or connate water saturation were **65.95** %PV, in case of same cycle.

In addition the NPS-IOil system (oil), the residual oil saturation were range of **83.15** %PV with group 1 that the concentration of *NPS-I* are **3.0 wt.**, and in case of imbibition cycle. while the non-wetting phase ($S_{or}$) with group 2 that the same concentration of NPS-II are **3.0 wt.**, the residual oil saturation were **74.91** %PV, in case of same cycle.

It is similar for included **5.0 wt. %**concentrations of two different Nanoparticle solutions, **Figure 5** shown that compares capillary pressure curve of the core samples from Group one and two. They were changed by meaning paint on some surface faces of the cores**.** For the irreducible or connate water saturation in Oil-NPS system, the wetting phase (NPS-I) with group **1** that the concentration of NPS-I are **5.0 wt.**, that the $S_{wc}$ were **65.67** %PV.In case of drainage cycle; while the wetting phase (NPS-II) with group **2** that the same concentration of NPS-II are **5.0 wt.**, the irreducible or connate water saturation were **54.06** %PV, in case of same cycle.

In addition the NPS-I Oil system (oil), the residual oil saturation were range of **71.50** %PV with group **1** that the concentration of *NPS-I* are **5.0 wt.**, and in case of imbibition cycle. while the non-wetting phase ($S_{or}$) with group **2** that the same concentration of NPS-II are **5.0 wt.**, the residual oil saturation were **55.66** %PV, in case of same cycle.

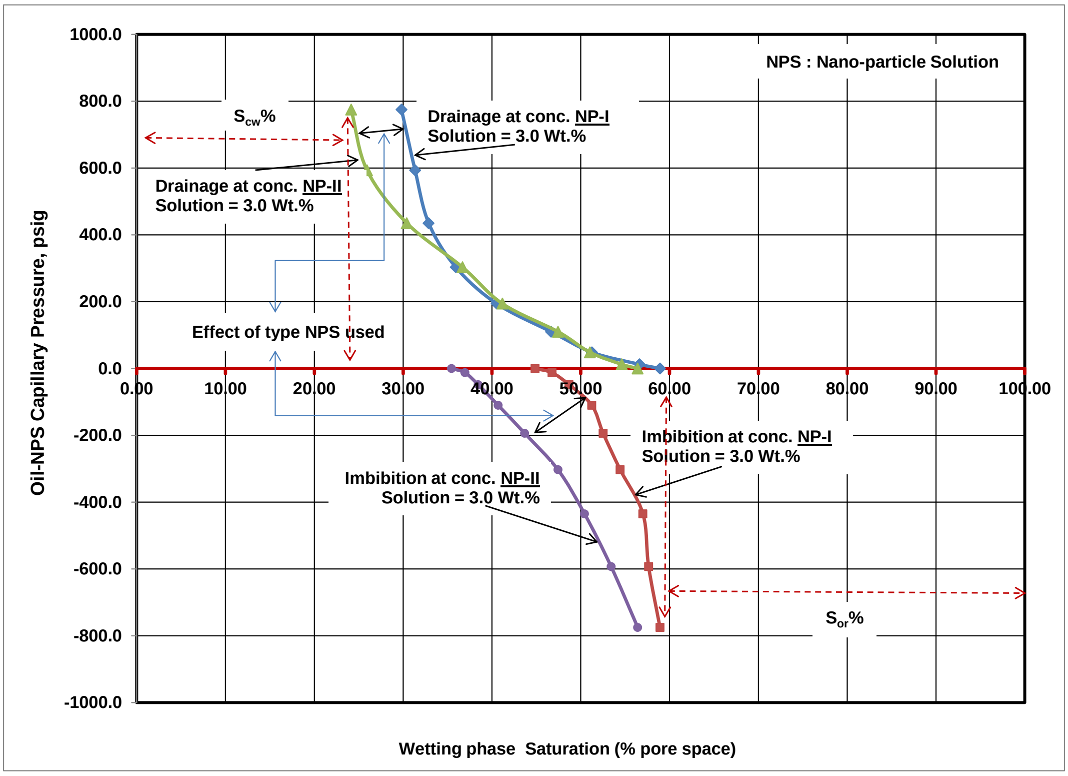

**Figure 4 Comparison between drainage and imbibition with used to two different type of NP-I and NP-II at the same concentration3.0 Wt. % and effect their on capillary pressure curves.**

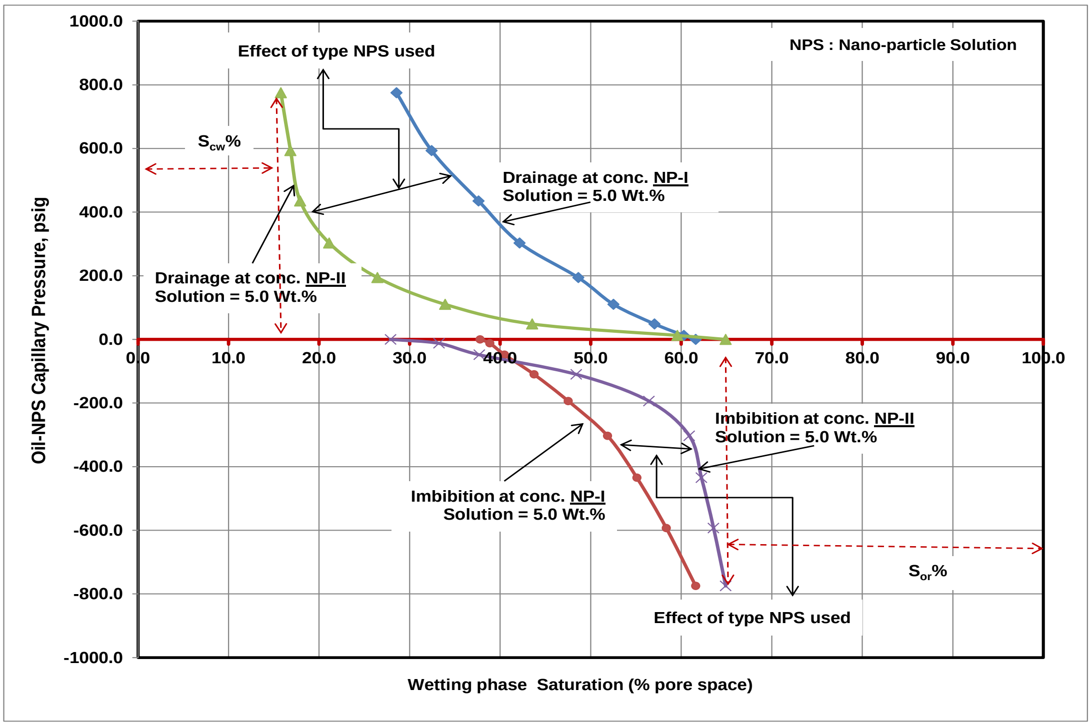

**Figure 5 Comparison between drainage and imbibition with used to two different type of NP-I and NP-II at the same concentration 5.0 wt. % and effect their on capillary pressure curves.**

For previous notes, it is estimates the experiment results compared to the highest $S_{wc}$ and $S_{or}$values at **3.0 wt. %** concentrations of nanoparticle solution either NPS-I or NP-II for different types than the another one.Capillary pressure for these points of the saturation profile is then estimated from the force exerted on the retained fluid above and below the pore space level for producing either capillary drainage curve or imbibition curve for the core plug, which includes $S_{wc}$ and $S_{or}$, which highest changing of an appropriate saturation state at **3.0 wt. %** concentration of NPS.

## IIII. CONCLUSIONS

Results of the present study support the following conclusions:

1- This study has shown how effects of nanoparticle on the pore space of rock with used of different concentration of NPS and affect it on capillary pressure curve and irreducible saturation.

2- In case of forced Drainage Cycles This yielded an irreducible wetting phase saturation of **83.15** %PV at **3.0%** concentration of NPS-I are the highest value and **65.95** %PV at the same concentration but with different type of NPS-II.

3- In case of forced Imbibition Cycles, the highest value the residual oil saturation (nonwetting phase) **83.15** %PV with group 1 that the concentration of **NPS-I** at the same concentration (**3.0 wt**.) and while the non-wetting phase ($S_{or}$) with group 2 at the same concentration of NPS-II are **3.0 wt.**, the residual oil saturation were **74.91** %PV, in case of same cycle.

**4-** It can be concluded that there are a wide range of methods and technologies to determine the connate water saturation and residual oil saturation for the rock samples of both concentration of nanomaterials used and different type of there, and application on EOR Techniques.

**Nomenclature**

Pc = Capillary pressure, psi
Po = Pressure oil phase, psi
Pw = Pressure water phase, psi
k = Permeability, mD
L = length or characteristic length of core samples, cm
D = Diameter of core sample, cm
P = Pressure, psi
S = Saturation, % pore space
T = Temperature, $^{o}$C
Vp = Pore Volume, cc
Vdisp = Volume of displaced phase or fluid
NPS = Nanoparticle Solution
NPS-I = Nanoparticle Solution for Type I
NPS-II = Nanoparticle Solution for type II
LHP = Lipophobic and Hydrophilic Poly-silicon,
HLP = Hydrophobic and Lipophilic Poly-silicon
NWP = Natural Wet Poly-silicon

**Greek**

$\Delta$ = difference
$\theta$ = contact angle, degree
$\mu$ = Viscosity, cp
$\sigma$ = interfacial tension, IFT, mN/m
$\varphi$ = Porosity, %

**Subscripts**

c = capillary or characteristic
i = initial
or = residual oil
S = solution
N = rotational speed of the centrifuge, rpm
Pc = capillary pressure, kPa or psi
r = radial distance from the center of the centrifuge, cm
$r_1$ = radial distance to inlet end of core, cm
$r_2$ = radial distance to exit end of core, cm
R = $r_1/r_2$, fraction
rpm = Rotation per minute
S = average saturation, fraction
Sw = water saturation, fraction or percentage
$S_{wc}$ = irreducible or connate water saturation, fraction
$S_{oi}$ = initial oil saturation, fraction
$S_{or}$ = residual Oil Saturation, fraction

## ACKNOWLEDGMENTS

The author is grateful to staff of the Energy and Petroleum Department, School of Science and Engineering, the American University in Cairo for using the facilities experimental setup in this study. The author wish to thank Dr.Shedid A. Shedid for support of the nanomaterial to complete this study. In addition, the author wish to acknowledge Eng. ShadiAzer, Mr. Marwan Mourse and Mr. SamerMakramfor their help during Experimental work.

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