WETTABILITY ALTERATION OF OIL-WET DOLOMITE USING NANOSOLUTION IN CATIONIC SURFACTANT FOR ENHANCED OIL RECOVERY

MOHD SHAHRIZAN BIN MOSLAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Faculty of Chemical and Energy Engineering
Universiti Teknologi Malaysia

NOVEMBER 2017

Specially dedicated to *Mak* and my late *Abah*

I love you *Mak* and I really miss you *Abah*

Also to *abang, akak, ude, ateh and adik*

This is for all of you

ACKNOWLEDGEMENT

In the name of Allah, the most beneficent and the merciful

First and foremost, I thank Allah (SWT) and Alhamdulillah for His blessings to complete this project. I would like to take this opportunity to extend my most sincere appreciation to my supervisor, Dr Wan Rosli Wan Sulaiman for his guidance, constant supervision and support in completing this project. I am highly indebted for all his advices and instructions given throughout the project period. Furthermore, I would also like to acknowledge my colleagues, reservoir engineering lab staffs and to the people who had involved directly or indirectly in this project. Thank you for your assistance and invaluable information. Finally, I would like to express my profound gratitude to my beloved parent and family for their continuous love, support, motivation and encouragement. They are indeed a source of inspiration to me.

ABSTRACT

Reservoir wettability is depending firmly on the existence of polar components (acids or bases) which are soluble in crude oil and their interaction on the solid surfaces. Wettability alteration by chemical agents such as surfactant and nanoparticles is seen to be one of the realistic methods to modify the wettability of carbonate rock from oil-wet to water-wet conditions. An experimental study of wettability changes upon exposure to cetyltrimethyl ammonium bromide (CTAB) surfactant and nanoparticles dispersed in CTAB has been conducted. Besides that, the stability of the nanoparticles colloidal was also determined by sedimentation and transport test. In addition to that, interfacial tension (IFT) before and after addition of nanoparticles into the system was also determined. Finally, core displacement test was accomplished to determine the effectiveness of nanoparticles in displacing the remaining oil trapped in the reservoir. It was found that CTAB could alter the wettability of oil-wet dolomite to water-wet and addition of nanoparticles has enhanced the contact angle reduction. Al_2O_3 nano solution was more stable than ZrO_2 and about 55% of Al_2O_3 and 52.5% of ZrO_2 could be recovered from the transport test. The IFT of the system was 0.077 mN/m and has reduced after addition of nanoparticles into the system. The reduction of IFT due to Al_2O_3 was greater as compared to ZrO_2. Oil recovery by water flooding was 55%, 62.7% and 56% for sand packs 1, 2, and 3 respectively. However, after injection of two pore volumes of Al_2O_3, ZrO_2 nano solutions, and CTAB surfactant additional 20%, 16.7% and 14.1% of oil were recovered from sand packs 1, 2 and 3, respectively due to wettability alteration. As the conclusion, favourable wettability must be obtained in order to produce more oil especially in carbonate and mature reservoirs.

ABSTRAK

Kebolehbasahan reservoir bergantung pada kehadiran komponen kutub (asid atau bes) yang larut dalam minyak mentah dan interaksi masing-masing pada permukaan pepejal. Pengubahsuaian kebolehbasahan batuan oleh agen kimia misalnya surfaktan dan nanopartikel, ialah satu daripada kaedah realistik untuk mengubah suai kebolehbasahan batu karbonat dari keadaan basah minyak ke keadaan basah air. Kajian tentang perubahan kebolehbasahan apabila terdedah kepada surfaktan setiltrimetil ammonium bromida (CTAB) dan nanopartikel yang tersebar dalam CTAB telah dilaksanakan. Disamping itu, kestabilan koloid nanopartikel juga ditentukan menerusi ujian pemendapan dan ujian pengangkutan. Sebagai tambahan, tegangan antara muka (IFT) sebelum dan selepas penambahan nanopartikel turut diteliti. Akhir sekali, ujian penyesaran teras dilaksanakan bagi memerhatikan keberkesanan nanopartikel dalam menyesarkan baki minyak yang terperangkap di dalam reservoir. Hasil kajian menunjukkan bahawa CTAB boleh mengubah kebolehbasahan dari basah minyak dolomit ke basah air, dengan penambahan nanopartikel mampu mengurangkan lagi sudut sentuhan. Larutan nano Al_2O_3 lebih stabil berbanding larutan nano ZrO_2 dengan 55% Al_2O_3 dan 52.5% ZrO_2 mampu diperoleh semula menerusi ujian pengangkutan. Nilai IFT sistem ialah 0.077 mN/m dan berjaya diturunkan menerusi penambahan nanopartikel ke dalam sistem terbabit. Pengurangan IFT yang disebabkan penambahan Al_2O_3 adalah lebih besar berbanding ZrO_2. Perolehan minyak menerusi banjiran air ialah 55%, 62.7% dan 56% bagi pek pasir 1, 2 dan 3. Walau bagaimanapun, selepas suntikan dua isi padu liang larutan nanopartikel Al_2O_3 dan ZrO_2, serta surfaktan CTAB, tambahan masing-masing 20%, 16.7% dan 14.1% minyak baki berjaya dikeluarkan daripada pek pasir 1, 2 dan 3 berikutan berlakunya perubahan kebolehbasahan. Kesimpulannya, kebolehbasahan yang sesuai mesti diperoleh bagi mengeluarkan lebih banyak minyak terutama dari reservoir karbonat dan reservoir matang.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

EOR	-	Enhanced oil recovery
IFT	-	Interfacial tension
CTAB	-	Cetyltrimethylammonium bromide
WAG	-	Water alternated gas
IOR	-	Improved oil recovery
CMC	-	Critical micelles concentration
EA	-	Ethoxylated alcohol
DTAB	-	Dodecyltrimethylammonium bromide
Na_2CO_3	-	Sodium carbonate
SDS	-	Sodium dodecyl sulphate
MCA	-	Minimum contact angle
PZC	-	Point of zero charge
LHP	-	Lipophobic-hydrophilic polysilicon
PSNP	-	Polysilicon nanoparticles
NWP	-	Neutrally wet polysilicon
HLP	-	Hydrophobic-lipophilic polysilicon
FESEM	-	Field emission scanning electron microscope
NP	-	Nanoparticles
ppm	-	Part per million
PV	-	Pore volume
rpm	-	Revolutions per minute

LIST OF SYMBOLS

q_e	-	Adsorption capacity at equilibrium
q_t	-	Adsorption capacity at time
c_o	-	Initial concentration
c_e	-	Equilibrium concentration
v	-	Volume of solution in liter
w	-	Weight of adsorbent in gram
t	-	Time
R^2	-	Correlation coefficient
θ	-	Contact angle
σ	-	Interfacial tension
ρ	-	Density
h	-	Height
k_{ro}	-	Relative permeability to oil
k_{rw}	-	Relative permeability to water
S_{or}	-	Residual oil saturation
δ_o	-	Displacement by oil
δ_w	-	Displacement by water

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Generally, oil recovery occurs through two main processes, which are primary recovery and secondary recovery. Primary recovery commonly comes from natural drives; which are rock and liquid expansion drive, depletion drive, gas cap drive, water drive, and gravity drainage drive. Meanwhile, secondary recovery refers to the introduction of additional energy into the reservoir. One of most common technique in secondary recovery is water injection or waterflooding. Briefly, the purpose of this waterflooding is to maintain the reservoir pressure and displace the remaining oil in the reservoir. Satter *et al.* (2008) mentioned that waterflooding technique has been widely used mainly due wide availability of water, inexpensive, and lower capital investment and operating costs. Ordinarily, maximum total oil recovery after primarily and secondary stage is 40% to 60% (Farouq and Thomas, 1996). The remaining oil is trapped mostly because of the heterogeneity of reservoir, unfavorable wettability and capillary trapped. To recover this remaining oil, advanced methods, which have become known as enhanced oil recovery (EOR) methods is necessary.

About more than 60% world's oil reserves are held in carbonate reservoirs (Sheng *et al.,* 2010). It is noted that oil recovery in these reservoirs is lower ascribed by two leading factors that are fractured reservoir and oil-wet rock. Therefore, many researchers have been focusing on wettability alteration of the rock and apparently, there is an increasing interest in using chemical for this purpose. Adding chemical agents such as surfactants can modify the wettability of carbonate rock system from oil-wet to water-wet condition (Mohammadi *et al.,* 2014). Wettability alteration of rock by surfactants was studied and the usage of ionic surfactants has been considered as feasible method for the recovery of oil reservoirs by modifying the wettability of rock surface from oil-wet to water-wet.

Chabert *et al.* (2010) perceived 80 % of carbonate reservoir classified as neutral to oil-wet due to the positive zeta potential of the rock surface. The adsorption of polar organic component presents in crude oil has been identified to be the main factor for the wettability alteration of carbonate surfaces to oil wet condition (Mahvash *et al.,* 2015). Cationic surfactant was observed to perform better than anionic surfactant in changing wettability of carbonate rock from oil-wet to more water-wet. This is due to the formation of ion pairs between the cationic heads of the surfactants molecules and the acidic components of the crude oil absorbed on the surface of carbonate rock (Austad *et al.,* 1997). However, according to Salehi *et al.* (2008) anionic surfactant molecules form a monolayer on the surface of carbonate rock through hydrophobic interaction of the tails of the surfactants molecules with the absorbed crude oil components on the rock surfaces. In addition, the hydrophobic interactions are much weaker than ion pair interaction, this explains why cationic surfactants have better performance than anionic surfactants in altering carbonate rock's wettability to a more water-wet state.

Nanotechnology is developing in oil and gas industry due to its potential to solve or manage several problems in the petroleum industries. EOR is one of the potential areas of nanotechnology application. Nanoparticles have the ability to alter certain factors in the formations and oil properties and this can be advantageous to enhance oil recovery (Ogolo *et al.,* 2012). The authors also reported that the wettability of a formation could be changed by applications of nanoparticles. Several studies have been conducted and the applications of nanoparticles to change rock wettability and its subsequent effects on oil recovery have been documented by several authors (Karimi *et al.,* 2012; Ogolo *et al.,* 2012; and Hendraningrat *et al.,* 2013). Nanoparticles can enhance the recovery through two major mechanisms, via interfacial tension reduction or wettability alterations (Roustaei *et al.,* 2012). In 2013, Hendraningrat *et al.* stated that the displacement mechanism by nanoparticles is called as structural disjoining pressure mechanism. Brownian motion and electrostatic repulsion between the nanoparticles are the energies that drive this mechanism in which smaller size nanoparticles would cause a bigger repulsion force. Structural disjoining pressure is associated to the fluids ability to spread along the surface of a substrate due to the imbalance interfacial forces among solid, oil phase and aqueous phase, which is the nanofluids. The interfacial forces will cause the nanofluids contact angle to decrease and the result is called as wedge film and this wedge film will act to separate formation fluids such as oil from the formation surface (Liu *et al.,* 2012).

Nanoparticles have high energy surface and therefore the adsorption of nanoparticles on a solid surface can change the surface energy and subsequently change the wettability of the rocks. In this research, the introduction of nanofluids to alter the wettability of carbonate rock is studied by experimental approach in which the experiment is also covering the stability of nanofluids and the effect of nanofluids on IFT.

1.2 Problem Statement

Current world oil production mostly comes from mature fields and over the past decades, oil-based companies are maximizing the oil production from these fields. However, stagnant oil production and unimpressive recovery by primary and secondary recovery caused the situation to be more precarious (Roustaei *et al.,* 2012). Enhanced oil recovery (EOR) technologies are necessary to meet the energy demand in many more years to come.

There is a huge interest to enhance recovery from the carbonate rock system by considering the remaining amount of oil in place. The addition of some chemical agents such as surfactants and nanoparticles into the injecting water can modify the wettability of the rock surface. In spite of all reported studies, the performance of nanoparticles in cationic surfactant i.e cetyltrimethylammonium bromide (CTAB) to alter wettability of oil-wet dolomite to water-wet condition has not yet well studied. Even though CTAB surfactant is expensive and toxic, this research is still in the preliminary study and further study need to be conducted in order to be implemented in the real application.

Therefore, this research is carried out to investigate and identify the types of nanoparticles that are effective as wettability modifiers. The challenging part in this study is to understand the mechanisms involved in this alteration. Parameters such as nanofluids concentrations, and stability of the colloids are very important and is investigated in order to achieve an optimized condition in this study.

1.3 Objectives of Study

The objectives of this research are as follows:

I. To study the stability of nanoparticles in cationic surfactant i.e CTAB and the quantities of nanoparticles deposition during the transport through dolomite rock.
II. To investigate the wettability alteration of dolomite rock system after introduction of nano solution.
III. To study the effect of wettability alteration on the oil recovery

REFERENCES

Abbas, Z., Labbez, C., Nordholm, S., Ahlberg, E. (2008). Size-dependent surface charging of nanoparticles. *Journal of Physical Chemistry C*. 112. 5715-5723

Abdallah, W., Buckley, J., Carnegie, A., Edwards J., Herold, B., Fordham, E., Graue, A., Habashy, T., Seleznez, N., Signer, C. (2007). Fundamentals of wettability. Schlumberger Wettability Workshop. May. Bahrain. 44-61

Abdelfatah, E. R., Kang, K., Pournik, M., Shiau, B., Harwell, J., Haroun, M. R., Rahman, M. M. (2017). Study of nanoparticle adsorption and release in porous media based on the DLVO theory. *SPE Latin America and Caribbean Petroleum Engineering Conference*. May 17-19. Buenos Aires, Argentina. 1-16

Abhijit, Y. D. (2013). *Petroleum reservoir rock and fluid properties*. (2nd edition). Boca Raton, Florida. Taylor & Francis Group, LLC

Ahmed, T. (2010). *Reservoir engineering handbook*. (4th edition). Burlington, MA. Gulf Professional Publishing.

Aishah, M. (2016). Methylene blue adsorption onto crosslinked sago starch. Master of Engineering. Universiti Teknologi Malaysia. Skudai

Alaskar, M. N., Ames, M. F., Connor, S. T., Liu, C., Cui, Y., Li, K., Horne, R. N. (2012). Nanoparticle and microparticles flow in porous and fractured media - An experimental study. Society of Petroleum Engineer. 17(4). 1160-1171

Alexander, C. M., Dabrowiak, J. C., Goodisman, J. (2013). Gravitational sedimentation of gold nanoparticles. *Journal of Colloid and Interface Science*. 396. 53-62

Al-Maamari, R., Buckley, J. (2003). Asphaltene precipitation and alteration of wetting: the potential for wettability changes during oil production. SPE Reservoir Evaluation & Engineering. 6(4). 210-214

Alotaibi, M. B., Nasralla, R. A., Nasr-El-Din, H. A. (2010). Wettability challenges in carbonate reservoirs. *SPE Improved Oil Recovery Symposium*. 24-28 April. Tulsa, Oklahoma. 1-20

Anderson, W. (1986). Wettability literature survey-part1: rock/oil/brine interactions and the effect of core handling on wettability. *Journal of Petroleum Technology*. 38(10). 1125-1144

Anderson, W. (1986). Wettability literature survey-part 2: Wettability measurement. *Journal of Petroleum Technology*. 38(11). 1246-1262

Atkin, R., Craig, V. S. J., Wanless, E. J., Biggs, S. (2003). Mechanism of cationic surfactant adsorption at the solid-aqueous interface. *Advances in Colloid and Interface Science*. (103). 219-304

Austad, T. and Milter, J. (1997). Spontaneous Imbibition of Water into Low Permeable Chalk at Different Wettabilities Using Surfactants. *SPE International Symposium on Oilfield Chemistry*. 18-21 February. Houston, USA. 257-266

Bayat, A. E. (2015). *Effective parameter in metal oxide nanoparticles transportation through porous media packs for enhanced oil recovery*. Doctor Philosophy, Universiti Teknologi Malaysia, Skudai.

Ben-Moshe, T., Dror, I., Berkowitz, B. (2010). Transport of metal oxide nanoparticles in saturated porous media. *Chemosphere*. 81. 387-393

Bizmark, N., Ioannidis, M. A. (2015). Effects of ionic strength on the colloidal stability and interfacial assembly of hydrophobic ethyl cellulose nanoparticles. *Langmuir*. 31(34). 9282-9289

Bryant, E. M., Bowman, R. S., Buckley, J. S. (2006). Wetting alteration of mica surface with polyethoxylated amine surfactants. *Journal of Petroleum Science and Engineering*. 52. 244-252

Buckley, J. S., and Liu, Y. (1998). Some mechanisms of crude oil/brine/solid interactions. Journal of Petroleum Science and Engineering. 20(3-4). 155-160

Buckley, S. E. and Leverett, M. C. (1942). Mechanism of Fluid Displacement in Sands. *Petroleum Transactions, AIME*.146, 187-196.

Chabert, M., Morvan, M., and Tabary, R. (2010). Fractured Carbonates: A Methodology to Evaluate Surfactant Performances. *SPE Improved Oil Recovery Symposium*. 24-28 April. Tulsa, Oklahoma, USA. 1-8

Chengara, A., Nikolov, A. D., Wasan, D. T., Trokhymchuk, A., Henderson, D. (2004). Spreading of nanofluids driven by the structural disjoining pressure gradient. *Journal of Colloid and Interface Science*. 280(1). 192-201

Cherifi, H., Fatiha, B., Salah, H. (2013). Kinetic studies on the adsorption of methylene blue onto vegetal fiber activated carbons. *Applied Surface Science.* 282. 52-59.

Chowdhury, I., Walker, S. L. (2011). Deposition mechanisms of TiO_2 nanoparticles in a parallel plate system. *Journal of Colloid and Interface Science*. 369. 16-22

Cuiec, L., Bourbiaux, B., Kalaydjian, F. (1994). Oil recovery by imbibition in low permability chalk. *SPE Formation Evaluation*. 9(3). 200-208

Ehtesabi, H., Ahadian, M. M., Taghikhani, V., Ghazanfari, M. H. (2014). Enhanced heavy oil recovery in sandstone cores using TiO_2 nanofluids. *Energy Fuels*. 28(1). 423-430.

Erle, D., and Waqi, D. (2008). Wettability. Houstan, Texas. Gulf Publishing Company

Fan, W., Jiang, X., Lu, Y., Huo, M., Lin, S., Geng, Z. (2015). Effects of surfactants on graphene oxide nanoparticles transport in saturated porous media. *Journal of Environmental Sciences*. 35. 12-19

Farouq Ali, S.M., and Thomas, S. (1996) The promise and problems of enhanced oil recovery methods. *Journal of Canadian Petroleum Technology*, 1996. 35(7). 57-63

Ganguly, S., Chakraborty, S. (2011). Sedimentation of nanoparticles in nanoscale colloidal suspensions. *Physics Letters A*. 375. 2394-2399

García-García, S., Wold, S., Jonsson, M. (2009). Effects of temperature on the stability of colloidal montmorillonite particles at different pH and ionic strength. *Applied Clay Science*. 43(1). 21-26

Giraldo, J., Benjumea, P., Lopero, S., Cortés, F. B., Ruiz, M. A. (2013). Wettability alteration of sandstone cores by alumina-based nanofluids. *Energy Fuels*. 27(7). 3659-3665

Godinez, I. G., & Darnault, C. J. (2011). Aggregation and transport of nano-TiO2 in saturated porous media: Effects of pH, surfactants and flow velocity. *Water Research,*45(2), 839-851

Green, D. W., and Willhite, G. P. (1998). *Enhanced oil recovery*. Richardson, Texas. Society of Petroleum Engineers

Guzman, K. A., Finnegan, M. P., Banfield, J. F. (2006). Influence of surface potential on aggregation and transport of Titania nanoparticles. *Environmental Science & Technology,*40(24), 7688-7693

Han, Y., Hwang, G., Kim, D., Bradford, S. A., Lee, B., Eom, I., Kim, P. J., Choi, S. Q., Kim, H. (2016). Transport, retention, and long-term release behavior of ZnO nanoparticle aggregates in saturated quartz sand: Role of solution pH and biofilm coating. *Water Research*. 90. 247-257

Hari, M., Joseph, S. A., Mathew, S., Nithyaja, B., Nampoori, V. P. N., Radhakrishnan. (2013). Thermal diffusivity of nanofluids composed of rod-shaped silver nanoparticles. *International Journal of Thermal Sciences*. 64. 188-194

Hirasaki, G. J., Miller, C., and Puerto, M. (2011). Recent advance in surfactant EOR. *SPE Annual Technical Conference and Exhibition*. 21-24 September. Denver, Colorado. 1-35

Hendraningrat, L., Li, S., Torsæter, O. (2013). A coreflood investigation of nanofluids enhanced oil recovery. Journal of Petroleum Science and Engineering. 111. 128-138

Ho, Y., & Mckay, G. (1998). A Comparison of Chemisorption Kinetic Models Applied to Pollutant Removal on Various Sorbents. *Process Safety and Environmental Protection,76*(4), 332-340

Hognesen, E., Standes, D., Austad, T. (2004). Scaling spontaneous imbibition of aqueous surfactant solution into preferential oil-wet carbonates. *Energy Fuels*. 18 (6). 1665-1675

Hou, B. F., wang, Y. F., Huang, Y. (2015). Mechanistic study of wettability alteration of oil-wet sandstone surface using different surfactants. *Applied Surface Science*. 330. 56-64

Jarrahian, Kh., Vafie-Sefti, M., Ayatollahi, Sh., Moghadam, F., Mousavi Moghadam, A. (2010). Study of wettability alteration mechanisms by surfactants. *International Symposium of The Society of Core Analysts*. 4-7 October. Halifax, Nova Scotia, Canada

Jarrahian, K., Seiedi, O., Sheykhan, M., Sefti, M. V., Ayatollahi, S. (2012). Wettability alteration of carbonate rock by surfactants: A mechanistic study. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 410. 1-10

Jiang, W., Ding, G., Peng, H., Hu, H. (2010). Modelling of nanoparticles' aggregation and sedimentation in nanofluids. *Current Applied Physics*. 10. 934-941

Jiang, X., Tong, M., Lu, R., Kim, H. (2012). Transport and deposition of ZnO nanoparticles in saturated porous media. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 401. 29-37

Jolivet, JP., Froidefond, C., Pottier, A., Chanéac, C., Cassaigon, S., Tronc, E., Euzen, P. (2004). Size tailoring of oxide nanoparticles by precipitation in aqueous medium. A Semi-quantitative modelling. *Journal of Materials Chemistry*. 3281-3288

Joonaki, E., Ghanaatian, S. (2014). The application of nanofluids for enhanced oil recovery: Effects on interfacial tension and core flooding. *Petroleum Science and Technology*. 32. 2599-2607

Ju, B., Dai, S., Luan, Z., Zhu, T., Su, X., Qiu, X. (2002). A study of wettability and permeability change caused by adsorption of nanometer structured polysilicon on the surface of porous media. *SPE Asia Pacific Oil and Gas Conference and Exhibition*. 8-10 October. Melbourne, Australia. 1-12

Ju, J., Fan, T., Ma, M. (2006). Enhanced oil recovery by flooding with hydrophilic nanoparticles. *China Particuology*. 4(1). 41-46

Juliana, G., Pedro, B., Sergio, L., Farid, B. C., Marco, A. R. (2013). Wettability alteration of sandstone cores by alumina-based nanofluids. *Energy Fuels*. 27(7). 3659-3665

Kanel, S. R., Al-Abed, S. R. (2011). Influence of pH on the transport of nanoscale zinc oxide in saturated porous media. *Journal of Nanoparticles Research*. 13(9). 4035-4047

Kapusta, S., Balzano, L., Paul, T. R. (2011). Nanotechnology application in oil and gas exploration and production. *International Petroleum Technology Conference*. 7-9 February. Bangkok Thailand. 1-5

Karimi, A., Zahra, F., Alireza, B., Nahid, P. K., Jabar, B. D., Reza, A., Sharareh, A. (2012). Wettability alteration in carbonates using zirconium oxide nanofluids: EOR implications. *Energy Fuels*. 26(2). 1028-1036

Khairul, M. A., Shah, K., Doroodchi, E., Azizian, R., Moghtaderi, B. (2016). Effects of surfactant on stability and thermo-physical properties of metal oxide nanofluids. *International Journal of Heat and Mass Transfer*. 98. 778-787

Kirtiprakash, K., Alex, D. N., Darsh, W., Liu, K. L. (2012). Dynamic spreading of nanofluids on solids. Part 1: Experimental. *Langmuir*. 28(41). 14618-14623

Kumari, J., Mathur, A., Rajeshwari, A., Venkatesan, A., Satyavati, S., Pulimi, M., Chandrasekaran, N., Nagarajan, R., Mukherjee, A. (2015). Individual and co transport study of titanium dioxide NPs and Zinc oxide NPs in porous media. *PLoS ONE*. 10(8). 1-18

Leong, K. Y., Mohd Hanafi, N., Mohd Sohaimi, R., Amer, N. H. (2016). The effect of surfactant on stability and thermal conductivity of carbon nanotube based nanofluids. *Thermal Science*. 20(2). 429 - 436

Liu, L., Gao, B., Wu, L., Sun, Y., Zhou, Z. (2015). Effects of surfactant type and concentration on graphene retention and transport in saturated porous media. *Chemical Engineering Journal*. 262. 1187-1191

Liu, K, L., Kondiparty, K., Nikolov, A. D., Wasan, D. (2012). Dynamic spreading of nanofluids on solids part II: Modelling. *Langmuir*. 28(47). 16274-16284

Liu, X., Chen, G., Su, C. (2011). Effects of material properties on sedimentation and aggregation of titanium dioxide nanoparticles of anatase and rutile in the aqueous phase. *Journal of Colloid and Interface Science*. 363. 84-91

Lysons, W. and Plisga, G. (2004). *Standard handbook of petroleum & natural gas engineering*. (2nd edition). Burlington, MA. Gulf Professional Publishing

Maher, A. (2016). Kinetic models for adsorption on mineral particles comparison between Langmuir kinetics and mass transfer. *Environmental Technology & Innovation*. (6). 27-37

Mahvash, K., Rashid, S. A., Shahab, A., Nasir, M. (2015). Mechanistic study of wettability alteration of oil-wet calcite: The effect of magnesium ions in the presence and absence of cationic surfactant. *Colloids and Surfaces A: Physicochemical and Engineering Aspect*. 482, 403-415

McElfresh, P. M., Holcomb, D. L., Ector, D. (2012). Application of nanofluids technology to improve recovery in oil and gas wells. *SPE International Oilfield Nanotechnology Conference*. 12-14 June. Noordwijk, Natherlands

McGraw. M. A., Kaplan, D. I. (1997). *Colloid suspension stability and transport through unsaturated porous media* (PNNL-11565). Technical Report. Richland, Washington.

Mohammadi, M. S., Moghadasi, J., Kordestany, A. (2014). A laboratory investigation into wettability alteration of carbonate rock by surfactant: The effect of salinity, pH and surfactant concentration. *Iranian Journal of Oil & Gas Science and Technology*. 3(3). 01-10

Mohammed, M., and Babadagli, T. (2015). Wettability alteration: A comprehensive review of material/methods and testing the selected ones on heavy-oil containing oil-wet systems. *Advances in Colloid and Interface Science*. 220. 54-77

Mohan, K., Gupta, R., Mohanty, K. K. (2011). Wettability altering secondary oil recovery in carbonate rocks. *Energy Fuels*. 25. 3966-3973

Mohsen, S. M., Jamshid, M., Amin, M. (2014). A laboratory investigation into wettability alteration of carbonate rock by surfactants: The effect of salinity, pH and surfactant concentration. *Iranian Journal of Oil & Gas Science and Technology*. 3. 01-10

Mui, J., Ngo, J., Kim, B. (2016). Aggregation and colloidal stability of commercially available Al_2O_3 nanoparticles in aqueous environments. *Nanomaterials*. 6 (90). 1-15

Munshi, A.M., Singh, V. N., Singh, J. P. (2008). Effect of nanoparticle size on sessile droplet contact angle. *Journal of Applied Physics*. 103. 1-6

Ogolo, N. A., Olafuyi, O. A., Onyekonwu, M. O. (2012). Enhanced oil recovery using nanoparticles. *SPE Saudi Arabia Technical Symposium and Exhibition*. 8-11 April. Al-Khobar, Saudi Arabia

Onyekonwu, M. O., Ogolo, N. A. (2010). Investigating the use of nanoparticles in enhancing oil recovery. *34th Annual SPE International Conference and Exhibition*. 31 July – 7 August. Tinapa-Calabar, Nigeria. 1-14

Park, Y., Whitaker, R. D., Nap, R. J., Paulsen, J. L., Mathiyazhagan, V., Doerrer, L. H., Song, Y-D., Hürlimann, M. D., Szleifer, I., Wong, J. Y. (2012). Stability of superparamagnetic iron oxide nanoparticles at different pH values: Experimental and theoretical analysis. *Langmuir*. 28. 6246-6255

Quintero, F., J. M. González, J. E. Arellano, M. Mas. (2014). Adsorption of surfactant with different degrees of ethoxylation on hematite weighting material and its effect on the tribological properties of water-based petroleum drilling fluids. In Biresaw G., K. L. Mittal. *Surfactants in trobology*. (349-384). Boca Raton, Florida. Taylor & Francis group, LLC

Ravari, R. R., Strand, S., Austad, T. (2011). Combined surfactant enhanced gravity drainage (SEGD) of oil and the wettability alteration in carbonates: The effect of rock permeability and interfacial tension (IFT). *Energy Fuels*. 25. 2083-2088

Rosen, M. J. (2004). *Surfactant and interfacial phenomena*. (3rd edition). New York. John Wiley & Sons

Rao, D. S., and Dash, R. K. (2015). Effect of nanomaterials sizes on the dispersion stability of biodiesel based nanofluids. *Advanced Materials Letters*. 6 (3). 247-251

Roustaei, A., Moghadasi, J., Bagherzadeh, H., & Shahrabadi, A. (2012). An Experimental Investigation of Polysilicon Nanoparticles' Recovery Efficiencies through Changes in Interfacial Tension and Wettability Alteration. *SPE International Oilfield Nanotechnology Conference*. 12-14 June. Noordwijk, Natherlands

Salehi, M., Johnson, S. J., Liang, J. T. (2008). Mechanistic study of wettability alteration using surfactants with applications in naturally fractured reservoirs. 24(24). 14099-14107

Santanu, P., Kartic., C. K. (2004). A review on experimental studies of surfactant adsorption at the hydrophilic solid-water interface. *Advances in Colloid and Interface Science*. (110). 75-95

Satter, A., Iqbal, G., and Buchwater, J. (2008). *Practical enhanced reservoir engineering*. Tulsa, Oklahoma. Pennwell

Seethepalli, A., Adibhatla, B., Mohanty, K. K. (2004). Wettability alteration during surfactant flooding of carbonate reservoirs. *SPE/DOE Fourteenth Symposium on Improved Oil Recovery*. 17-21 April. Tulsa, Oklahoma

Shamsijazeyi, H., Miller, C. A., Wong, M. S., Tour, J. M., Verduzco, R. (2014). Polymet-coated nanoparticles for enhanced oil recovery. *Journal of Applied Polymer Science*. 131 (15). 1-13

Sheng, J., Morel, D., Gauer, P. (2010). Evaluation of the effect of wettability alteration on oil recovery in carbonate reservoirs. *AAPG GEO Middle East Geoscience Conference & Exhibition*. 7-10 March. Manama, Bahrain

Somasundaran, P., and Krishnakumar, S. (1996). Adsorption of surfactants and polymers at the solid-liquid interface. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. (123-124). 491-513

Standes, D. C., and Austad, T. (2003). Wettability alteration in carbonates: Interaction between cationic surfactant and carboxylates as a key factor in wettability alteration from oil-wet to water-wet conditions. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 216(1). 243-259

Standnes, D. C., and Austad, T. (2000). Wettability alteration in chalk: 2. Mechanism for wettability alteration from oil-wet to water-wet using surfactants. *Journal of Petroleum Science and Engineering*. 28 (3). 123-143

Standnes, D. C., Nogaret, L. A. D., Chen, H. L., Austad, T. (2002). An evaluation of spontaneous imbibition of water into oil-wet carbonate reservoir cores using a nonionic and a cationic surfactant. *Energy Fuels*. 16(6). 1557-1564

Strand, D., Austad, T., Standnes, D. (2003). Spontaneous imbibition of aqueous surfactant solutions into neutral to oil-wet carbonate cores: Effect of brine salinity and composition. *Energy Fuels*. 17 (5). 1133-1144

Suleimanov, B. A., Ismailov, F. S., Velijev, E. F. (2011). Nanofluid for enhanced oil recovery. *Journal of Petroleum Science and Engineering*. 78. 431-437

Tabrizy, V., Hamouda, A. A., Denoyel, R. (2011). Influence of magnesium and sulfate ion on wettability alteration of calcite, quartz, and kaolinite: Surface energy analysis. *Energy Fuels*. 25. 1667-1680

Thomas, M. M., Clouse, J. A., Longo, J. M. (1993). Adsorption of organic compounds on carbonate minerals 1. Model compounds and their influence on mineral wettability. *Chemical geology*. 109. 201-213

Tripathi, I., and Mohanty, K. (2008). Instability due to wettability alteration in displacement through porous media. *Chemical Engineering Science*. 63(21). 277-282

Williams, W. C., Bang, I. C., Forrest, E., Hu, L. W., Buongiorno, J. (2006). Preparation and characterization of various nanofluids. *NSTI Nanotechnology Conference and Trade Show*. 7-11 May. Boston, USA. 408-411

Xia, G., Jiang, H., Liu, R., Zhai, Y. (2014). Effects of surfactant on the stability and thermal conductivity of Al_2O_3/de-ionized water nanofluids. *International Journal of Thermal Science*. 84. 118-124

Xu, X., Xu, N., Cheng, X., Guo, P., Chen, X., Wang, D. (2017). Transport and aggregation of rutile titanium dioxide nanoparticles in saturated porous media in the presence of ammonium. *Chemosphere*. 169. 9-17

Zhang, H., Nikolov, A., Wasan, D. (2014). Enhanced oil recovery (EOR) using nanoparticles dispersion: Underlying mechanism and imbibition experiments. *Energy Fuels*. 28. 3002-3009

Zhang, D. L., Liu, S., Puerto, M., Miller, C. A., Hirasaki, G. J. (2006). Wettability alteration and spontaneous imbibition in oil-wet carbonate formations. *Journal of Petroleum Science & Engineering*. 52(1). 213-226

Zhang, R., Somasundaran, P. (2006). Advances in adsorption of surfactant and their mixtures at solid/solution interfaces. *Advances in Colloid and Interface Science*. (123-126). 213-229