EFFECTS OF TYPE OF SALT ON NANOPARTICLES-STABILIZED CARBON DIOXIDE FOAM IN ENHANCED OIL RECOVERY

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To my beloved mother and father

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ABSTRACT

Foam is employed to improve the efficiency by which the displacing fluid sweeps the reservoir and contacts and recovers oil. However, it is known that foam are both thermodynamically and kinetically unstable systems that readily destruct as a result of film drainage, drying, film breakup and gas diffusion. Study had found that solid nanoparticle may promote foam stabilization. The foams stability depends on the particle size, shape, concentration and hydrophobicity, as well as on the type of surfactant used. The objectives of this study are to determine the effectiveness of different type of salt on CO_2 foam stability by using various concentrations of nanoparticle at fixed surfactant concentration (AOS) and dispersion salinity, and to determine oil recovery performance of each type of salt and compare the results. Three types of salt (Sodium Chloride, Calcium Chloride and Magnesium Chloride) were used to create six different compositions of brine with total salinity of 3 wt%. A silicon dioxide nanoparticle was used in this study at four different concentrations; 0 wt%, 0.1 wt%, 0.5 wt% and 1.0 wt%. Alpha olefin surfactant (AOS) was used as the foaming agent at fixed concentration of 0.5 wt%. Red dye paraffin oil is used to represent the oil in formation. In the foam stability test, it was found that different type of salt requires different concentration of SiO_2 to give optimum stabilization on foam. From this study, it was found that different type of salt would affect the stability of nanoparticle-stabilized foam. The 3 wt% $CaCl_2$ at 0.5 wt% SiO_2 gave most stable foam and highest oil recovery because of the greater stability of micelles to cause enhanced foam stability. Thus, one can conclude that the foam stabilities can only be enhanced by packing micelles of high stability in the foam lamellae.

ABSTRAK

Busa digunakan untuk meningkatkan kecekapan bendalir anjakan menyapu reservoir dan menyentuh dan mengeluarkan minyak. Walau bagaimanapun, sistem busa secara termodinamik dan kinetiknya adalah tidak stabil, dan mudah musnah akibat daripada saliran filem, pengeringan, pepecahan filem dan peresapan gas. Kajian telah mendapati bahawa nanopartikal pepejal boleh menggalakkan penstabilan busa. Kestabilan busa bergantung kepada saiz partikal, bentuk, kepekatan dan hidrofobisiti, dan juga jenis surfaktan yang digunakan. Objektif kajian ini adalah untuk menentukan keberkesanan berlainan jenis garam ke atas kestabilan busa CO_2 pada perlbagai kepekatan nanopartikal dengan kepekatan tetap bagi surfaktan (AOS) dan kemasinan larutan; dan untuk menentukan prestasi perolehan minyak bagi setiap jenis garam dan membandingkan keputusannya. Tiga jenis garam (Natrium Klorida, Kalsium Klorida dan Magnesium Klorida) telah digunakan untuk menghasilkan enam komposisi yang berbeza dengan jumlah kemasinan 3% berat. Nanopartikal silika dioksida digunakan dalam kajian ini pada kepekatan yang berbeza; 0% berat, 0.1% berat, 0.5% berat dan 1.0% berat. Surfaktan Alfa Olefina (AOS) digunakan sebagai ejen pembusa pada kepekatan tetap 0.5% berat. Minyak parafin diwarnai merah untuk mewakili minyak dalam formasi. Dalam ujian kestabilan, didapati bahawa kompisisi air garam yang berbeza akan memberi kesan kepada kestabilan busa yang distabilkan oleh nanosilika. 3% berat $CaCl_2$ pada 0.5% berat SiO_2 menghasilkan busa yang paling stabil dan perolehan minyak yang paling tinggi kerana misela yang lebih stabil mempertingkatkan kestabilan busa. Dengan itu, boleh disimpulkan bahawa kestabilan busa hanya boleh dipertingkatkan dengan kepadatan misela yang berkestabilan tinggi dalam lamela busa.

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AOS	-	Alpha Olefin Sulfonate
$CaCl_2$	-	Calcium Chloride
CMC	-	Critical Micelle Concentration
CO_2	-	Carbon Dioxide
EOR	-	Enhanced Oil Recovery
HCPV	-	Hydrocarbon Pore Volume
IFT	-	Interfacial Tension
$MgCl_2$	-	Magnesium Chloride
NaCl	-	Natrium Chloride
NBF	-	Newton Black Film
OOIP	-	Oil Originally In Place
SC	-	Stable Supercritical
WAG	-	Water Alternating Gas

CHAPTER 1

INTRODUCTION

1.1 Background

World production capabilities of oil by conventional means will no longer meet energy demands. As a result, oil price will continue to soar. The soaring of oil price is speculated could make enhanced oil recovery very economically attractive, and could be the beginning of an era when unconventional petroleum sources become economic. These potential oil resources include heavy oils, tar sands, oil shale, and enhanced recovery from know reservoirs. Despite the convenience and adaptable of petroleum as energy resource, it is non-renewable. However, through enhanced oil recovery technique, it is possible to increase or maintain the current levels of production further for many years to come.

Enhanced oil recovery technique can improve the percentage of discovered oil that can be used. It can be classified into thermal processes, chemical processes, and miscible displacement. One of the techniques of enhanced oil recovery is miscible gas injection. Usually, conventional gas or water-drive will leave 25-50% of the original oil in the reservoir. A portion of this oil can be recovered if the oil is contacted by a fluid with which it is miscible. Carbon dioxide (CO_2) and flue gas has become recognised as a useful substitute for light hydrocarbon gases in enhance oil recovery of crude oil where CO_2, know to be highly soluble in crude oils, and in water, causing 20 to 90% reduction in crude oil viscosities, and also an appreciable swelling (up to 50%) of crude oil when it is saturate with CO_2 above about 700 psi. However, most gas flooding field projects often faced with problem of early CO_2

breakthrough, poor sweep efficiency, and inefficient oil recovery due to viscous fingering resulted from low gas phase viscosity and an unfavourable mobility control.

One potential solution for reducing gas mobility is the use of foam. By the use of foam, the gas mobility is reduced by liquid films trapping gas in the porous media and reducing the gas fraction available for flow. Foam are also much efficient than water in controlling gas fingering. It can also decrease aqueous permeability by increasing gas saturation. Furthermore, the surfactant concentration required to formed foams is low, thus resulted in a potential cost effective process. Foam system is also reversible and is best suited where total blockage is not desired or feasible. However, it is known that foam are both thermodynamically and kinetically unstable systems that readily destruct as a result of film drainage, drying, film breakup and gas diffusion.

Solid particles may promote foam stabilization. Studies found that foams stability depends on the particle size, shape, concentration and hydrophobicity, as well as on the type of surfactant used. Much study had been conducted to study the stability of CO_2 foam. This study focused on the effects of different type of salt with various concentrations of nanoparticle on stabilized CO_2 foam for mobility control in immiscible flooding with fixed concentration of anionic surfactant (AOS) and brine salinity.

1.2 Problem Statement

Gases used in gas-flooding (such as CO_2, Hydrocarbons, N_2, etc.) are normally less viscous (more than one order of magnitude less) and less dense than both water and crude oil, which results in gas channelling through the high permeability zones and gravity overriding. Thus, gas flooding normally has poor volumetric sweep efficiency, especially in an immiscible displacement, with the displacing phase being a lower viscosity. The main advantage of gas is its better microscopic sweep leading to lower residual oil saturation in the pores compared to waterflood however, the major challenge associated with gas injection is its poor volumetric sweep efficiency, as a result of which gas does not contact a large fraction of oil and, thus, the overall recovery remains low.

A need for mobility control in gas flooding has led to the use of foam for sweep improvement and profile modification. Foam is employed to improve the efficiency by which the displacing fluid sweeps the reservoir and contacts and recovers oil.

Foam stability and mobility reduction characteristics depend on the properties of rock and fluids and process-design parameters such as formation permeability, injection foam quality and the size of the chemical slug. The effects of these parameters on the performance of the foam flooding process needs to be ascertained in order to determine its optimal potential for EOR. Most foam owes its existence to the presence of surfactants, that is, materials which are surface active.

They are concentrated at the interface of a fluid and act to reduce the surface tension between interfaces. More importantly for preventing foam termination, they stabilize the thin fluid film against rupture. In aqueous foams, surfactant molecules are amphiphilic; their two parts are hydrophobic and hydrophilic so that they can stay on the water surface. In porous media, foam exists as gas bubbles whose shapes conform to the solid matrix. Hirasaki (1989) defined foam in porous media as “a dispersion of a gas in a liquid such that the liquid phase is continuous and at least some part of the gas phase is made discontinuous by thin liquid films called lamellae.”

Solid-stabilized emulsions, known as “pickering emulsions”, have drawn active research interest for use under harsh conditions, because solid particles are generally more stable than surfactant under high temperature, and/or high salinity conditions. Their application in the upstream oil has been limited because the solids available to use were colloidal size with wide size distribution; and consequently it is not feasible for them to propagate long distance in oil reservoir formations with pore throat having similar sizes to those particles. It was also difficult to make with those colloids very stable and dense emulsions that are useful for upstream applications.

With the recent rapid nanotechnology advancement, nanoparticles with uniform size and shape and desired surface properties can be produced in large quantities at economic cost. The surface properties ("wettability") of the nanoparticle can be adjusted to generate desired types of emulsion droplet with desired uniform sized. Being solid particles, the nanoparticles can not only endure the harsh reservoir conditions, but also carry some additional functionality, such as paramagnetism or as a catalyst. Very stable emulsions and foams with desired internal structure and functionality can now be accordingly produced for potential oil recovery applications.

1.3 Objective of study

The objectives of this study are:

a) To determine the effectiveness of different type of salt on CO_2 foam stability by using various concentration of nanoparticles at fixed surfactant concentration (AOS) and dispersion salinity.
b) To determine oil recovery performance of each type of salt and compare the results.

1.4 Scope of study

In this thesis, the interested parameters to enhance the performance of foam are type of salt (Sodium chloride (NaCl), Calcium chloride ($CaCl_2$) and Magnesium Chloride ($MgCl_2$)) and nanoparticles concentration (0 wt%, 0.1 wt%, and 0.5 wt%, 1.0 wt %) with fixed concentration of 0.5 wt% anionic surfactant (AOS) and 3 wt% water salinity.

For the purpose of this study, glass bead pack models with 30.5 cm of length and 5.4 cm of diameter made from Acrylic (Perspex) were used and packed with granule sized of glass bead in range between 90 to 150 µm. Porosity and permeability of glass bead packs were measured.

The stability test was prepared and modified based on ASTM-D 6082-62, D892-06 and D1881-87 (Borole and Caneba, 2013). In this study, the stability of the aqueous foam was evaluated by the Ross-Miles method, using half-life measurements. The technique used in to generate the foam is air expansion this technique was used to evaluate the stability of foam in presence of nanoparticles, surfactant and brine.

Displacement tests were performed by using seven unconsolidated glass bead pack models. The glass bead packs were located in the horizontal position to neglect the effect of gravity forces. Initially, the glass bead pack was saturated with 3 wt% NaCl brine for measurement of porosity and absolute permeability. Then, the glass bead pack models were saturated with red dye paraffin oil to create the initial oil saturation. Next, water flooding was done by injection of 2 PV of 3 wt% brine at flow rate of 3 cc/min. The oil recovery after water flooding was calculated. Finally, the glass bead pack model were subjected to foam flooding by injecting aqueous nanoparticles dispersion with flow rate 3 cc/min followed by co-injection of CO_2 gases with 9 cc/min for further oil recovery and better volumetric sweep efficiency.

REFERENCES

Abdel-Wali, A. A. (1996). *Effect of Simple Polar Compounds and Salinity on Interfacial Tension and Wettability of Rock/Oil/Brine System*. Journal of King Saud University-Engineering Science, 8(2): 153-163.

Adkins, S.S., Chen, X., Chan, I., Torino, E., Nguyen, Q., and Sanders, A. (2010). *Morphology and Stability of CO_2-In-Water Foams with Nonionic Hydrocarbon Surfactants.* Langmuir, Vol 26, No 8, 5335-5348.

Agbalaka, C.C., Dandekar, A. Y., Patil, S. L., Khataniar, S. And Hemsath, J. R. (2009). *Coreflooding Studies to Evaluate the Impact of Salinity and Wettability on Oil Recovery Efficiency*. Transport In Porous Media 76(1):77-94.

Alkan, H., Goktekin, A., and Satman, A. (1991). *A Laboratory Study of CO_2-Foam Process for Bati Raman Field.* Turkey. SPE Middle East Oil Show, Kingdom Of Bahrain.

Alotaibi, M. B. And Nasr-El-Din, H. A. (2009). *Effect of Brine Salinity on Reservoir Fluids Interfacial Tension*. Paper SPE 121569, Presented At SPE Europec/Eage Annual Conference and Exhibition Held In Amsterdam, the Netherlands.

Alotaibi, M. B., Nasralla, R. A., and Nasr-Ei-Din, H. A. (2011). *Wettability Studies Using Lowsalinity Water In Sandstone Reservoirs*. SPE Reservoir Evaluation & Engineering, 713-725.

Alvarez, J. M., Rivas, H. J. & Rossen, W. R. (1999). *Unified Model for Steady-State Foam Behaviour at High and Low Foam Qualities*. SPE Annual Technical Conference and Exhibition. Houston, Texas: Society of Petroleum Engineers.

Anderson, W. G. (1986). *Wettability Literature Survey—Part 1: Rock/Oil/Brine Interactions And The Effects Of Core Handling On Wettability*. Journal of Petroleum Technology, 159.

Apaydin, O.G., and Kovscek, A.R. (2000). *Transient Foam Flow in Homogeneous Porous Media: Surfactant Concentration and Capillary End Effects*. SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Asghari, K., and Khalil, F. (2005). *Effect of Operational Parameters on CO_2-Foam Process, Petroleum Science and Technology*, Vol 23, 189-198.

Ashraf, A., Hadia, N. J., Torstæer, O. And Tweheyo, M. T. (2010). *Laboratory Investigation of Low Salinity Waterflooding as Secondary Recovery Process: Effect of Wettability*. Paper SPE 129012, Presented At the SPS Oil and Gas India Conference and Exhibition Held in Mumbai, India.

Bagci, S., Kok, M. V. And Turksoy, U. (2001). *Effect of Brine Composition on Oil Recovery by Waterflooding. Petroleum and Technology*. 19(3&4), 359-372.

Bai, B., Grigg, R.B., Liu, Y., and Zeng, Z. (2005). *Adsorption Kinetics Of Surfactant Used In CO_2-Foam Flooding Onto Berea Sandstone*. Annual Technical Conference and Exhibition, Dallas, Texas, USA.

Bai, B., Grigg, R.B., Svec, Y., and Wu, Y. (2010). *Adsorption of a Foam Agent on Porous Sandstone and Its Effect on Foam Stability, Colloids and Surfaces*. A: Physicochemical And Engineering Aspects, Vol 353, 189-196.

Bergeron V. (1997). Langmuir 13 3474.

Bergeron, V., Fagan, M.E., And Radke, C.J. (1993). *Generalized Entering Coefficients: A Criterion for Foam Stability against Oil in Porous Media*, Langmuir, Vol 9, No 7, 1704.

Bertin, H.J.; Apaydin, O.G., Castanier, L.M., and Kovscek, A.R. (1998). *Foam Flow in Heterogeneous Porous Media: Effect of Crossflow*. SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Blauer, R.E., and Kohlhaas, C.A. (1974). *Formation Fracturing With Foam*. Fall Meeting of the Society of Petroleum Engineers of Aime, Houston, Texas, USA.

Borchardt, J.K. (1988). *Structure-Property Relationships for Mobility-Control Surfactants, Ch. 9 of Surfactant-Based Mobility Control-Progress in Miscible Flood Enhanced Oil Recovery*. Edited By Duane Smith, ACS Symposium Series 373, ACS, Washington Dc, 181-204.

Buckley, J. S., Liu, Y., And Monsterleet, S. (1998). *Mechanisms of Wetting Alteration by Crude Oils*. SPE Journal, 54-61.

Buckley, J. S., Takamura, K. And Morrow, N. R. (1989). *Influence of Electrical Surface Charges on the Wetting Properties of Crude Oils*. SPE Reservoir Engineering, 4 (3): 332-342.

Cai, B., Yang, J. And Guo, T. (1996). *Interfacial Tension Of Hydrocarbon + Water/Brine Systems Under High Pressure*. Journal Of Chemical And Engineering Data 41 (3):493-496.

Cao, H., Tsai, F. T-C. And Rusch, K. A. (2010). *Salinity And Soluble Organic Matter On Virus Sorption In Sand And Soil Columns*. Ground Water, 48(1), 2010, 42-52.

Casteel, J.F., And Djabbarah, N.F. (1988). *Sweep Improvement In CO_2 Flooding By Use Of Foaming Agents*. Journal Of Reservoir Engineering Of Society Of Petroleum Engineers, Vol 3, No 4, 1186-1192.

Chang, S.H., And Grigg, R.B. (1999). *Effects Of Foam Quality And Flow Rate On CO_2-Foambehavior At Reservoir Temperature And Pressure*. Reservoir Evaluation And Engineering Journal, Vol 2, No 3, 248-254.

Chang, Shih-Hsien, And Grigg, Reid B. (1998). *Effects Of Foam Quality And Flow Rate On CO_2-Foam Behaviour At Reservoir Conditions*. SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Chang, Shih-Hsien, Martin, F.D., and Grigg, R.B. (1994). *Effect of Pressure on CO_2 Foam Displacements: A Micromodel Visualization Study*. SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Chen, Q., Gerritsen, M.G., And Kovscek, A.R. (2010). *Improving Steam-Assisted Gravity Drainage Using Mobility Control Foams: Foam Assisted-SAGD (FA-SAGD).* SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Chou, S.I. (1991). *Conditions For Generating Foam In Porous Media*. 66th SPE Annual Technical Conference And Exhibition, Dallas, Texas, USA.

Cohen D., Patzek T.W., Radke C.J. (1997). *Transp. Porous Media.*

D. Xing, B. Wei, W. McLendon, R. Enick, S. McNulty, J. Eastoe, S. Rogers, D. Crandall, B. Tennant, T. McLendon, V. Romanov, Y. Soong. (2012). *CO_2-Soluble, Nonionic, Water-Soluble Surfactants That Stabilize CO_2-in-Brine Foams.* SPE Symposium on improved Oil Recovery, Tulsa.

Dellinger, S.E., Patton, J.T., And Holbrook, S.T. (1984). *CO_2 Mobility Control.* SPE Journal, Vol 24, No 2, 191-196.

Derjaguin B.V., Landau L.D. (1941). *Theory of Stability of Liyophobic Colloids*. Elsevier Pub. Co., N.Y., 1948.

Djabbarah, N.F., Weber, S.L, Freeman, D.C., Muscateloo, J.A., And Covington, T.E. (1990). *Laboratory Design And Field Demonstration Of Steam Diversion With Foam*. The 60th california Regional Meeting, Ventura, California, USA.

Do, H. D. & Pinczewski, W. V. (1991). *Diffusion Controlled Swelling Of Reservoir Oil By Direct Contact With Injection Gas*. Chemical Engineering Science, 46, 1259-1270.

Dong, M., Huang, S. & Srivastava, R. (1999). *Effect Of Solution Gas In Oil On* CO_2 *Minimum Miscibility Pressure*. Annual Technical Meeting. Calgary, Alberta: Petroleum Society Of Canada.

Du D.X. (2007). Personal Communication.

Emadi, A., Sohrabi, M., Jamiolahmady, M., And Ireland, S. (2012). *Visualization Of Oil Recovery By* CO_2*-Foam Injection; Effect Of Oil Viscosity And Gas Type*. SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Emadi, A., Sohrabi, M., Jamiolahmady, M., Ireland, S. And Robert Son, G. (2011). *Visual Investigation Of Extra Heavy Oil Recovery By CO2 /N2 Foam Injection*. Eage 16th European Symposium On Improved Oil Recovery, Cambridge, UK.

Emadi, A., Sohrabi, M., Jamiolahmady, M., Ireland, S., And Robertson, G. (2011). *Mechanistic Study Of Improved Heavy Oil Recovery By* CO_2*-Foam Injection*. SPE Enhanced Oil Recovery Conference, Kuala Lumpur, Malaysia.

Enick R., M., And Olsen, D., K. (2012). *Mobility And Conformance Control For Carbon Dioxide Enhanced Oil Recovery (*CO_2*-EOR) Via Thickeners, Foams, And Gels* – A Detailed Literature Review Of 40 Years Of Research. National Energy Technology Laboratory.

Espinosa, D., Caldesas, F., Johnston, K., Bryant, S.L., and Huh, C. (2010). *Nanoparticle-Stabilized Supercritical CO_2, Foams for Potential Mobility Control Applications*. SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma. USA.

Exerowa D., Kruglyakov P.M. (1998). *Foam and Foam Films*. Elsevier Science.

Farajzadeh R., Du D.X., Zitha P.L.J. (2007). unpublished data.

Farajzadeh, R., Andrianov, A. & Zitha, P. L. J. (2009). *Foam Assisted Enhanced Oil Recovery At Miscible And Immiscible Conditions*. Kuwait International Petroleum Conference And Exhibition. Kuwait City, Kuwait: Society Of Petroleum Engineers.

Farajzadeh, R., Andrianov, A., Krastev, R., Hirasaki, G. & Rossen, W. R. (2012). F*oam-Oil Interaction In Porous Media: Implications For Foam Assisted Enhanced Oil Recovery*. SPE EOR Conference At Oil And Gas West Asia. Muscat, Oman: Society Of Petroleum Engineers.

Farajzadeh, R., Wassing, L. B. M. & Boerrigter, P. M. (2010). *Foam Assisted Gas Oil Gravity Drainage In Naturally-Fractured Reservoirs*. SPE Annual Technical Conference And Exhibition. Florence, Italy: Society Of Petroleum Engineers.

Farzaneh S. A. And Sohrabi M. (2013). *A Review Of The Status Of Foam Application In Enhanced Oil Recovery*. Heriot-Watt University, Edinburgh, UK.

Farzaneh, S.A., and Sohrabi, M. (2010). *Report on Enhanced Heavy Oil Recovery*. Technical report, Heriot-Watt University, Edinburgh, Scotland, and UK (unpublished).

Fjelde, I., Zuta, J., And Berenb Lyum R. (2011). *Retention Of CO_2-Foaming Agent In CO_2-Foam Flooding Of Heterogeneous Carbonate Reservoirs*. Brasil Offshore, Macaé, Brazil.

Friedmann, F., And Jensen, J.A. (1986). *Some Parameters Influencing The Formation And Propagation Of Foams In Porous Media*. California Regional Meeting Of Society Of Petroleum Engineers. Oakland, California, USA.

Friedmann, F.F., Smith, M.E., Guice, W.R., Gump, J.M., And Nelson, D.G. (1994). *Steam-Foam Mechanistic Field Trial In The Midway-Sunset Field.* SPE Reservoir Engineering.

Grigg, R.B., and Mikhalin, A.A. (2007). *Effects of Flow Conditions and Surfactant Availability on Adsorption*. International Symposium on Oilfield Chemistry of Society of Petroleum Engineers, Houston, Texas, USA.

Grogan, A. T. P., W.V. (1987). *The Role Of Molecular Diffusion Processes In Tertiary CO_2 Flooding*. Journal Of Petroleum Technology, 39, 591-602.

Guo, H., Faber, R., Buijse, M., And Zitha, P.L.J. (2011). *A Novel Alkaline-Surfactant-Foam EOR Process*. SPE Enhanced Oil Recovery Conference, Kuala Lumpur, Malaysia.

Hall, A. C., Collins, S. H. And Melrose, J. C. (1983). *Stability Of Aqueous Wetting Films In Athabasca Tar Sands*. Society Of Petroleum Engineers Journal, 249-258.

Hamouda, A. A. And Karoussi, O. (2008). *Effect Of Temperature, Wettability And Relative Permeability On Oil Recovery From Oil-Wet Chalk.* Energies, 1:19-34.

Handy, L.L., Amaefule, J.O., Ziegler, V.M., And Ershaghi, I. (1982). *Thermal Stability Of Surfactants For Reservoir Application*. SPE Journal, Vol 22, No 5, 722-730.

Hanssen, J.E., And Dalland, M. (1990). *Foams For Effective Gas Blockage In The Presence Of Crude Oil.* SPE/DOE Symposium On Enhanced Oil Recovery, Tulsa, Oklahoma, USA.

Haugen, A., Ferno, M. A., Graue, A., And Bertin, H.J. (2010). *Experimental Study Of Foam Flow In Fractured Oil-Wet Limestone For Enhanced Oil Recovery*. SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

He, L., Peng, Y., Wei, L., Li, S., And Yan Z. (2010). *Application Of Nitrogen Foam For Profile Modification In A Heterogeneous Multi-Layer Sandstone Oilfield*. SPE Asia Pacific Oil & Gas Conference And Exhibition, Brisbane, Queensland, Australia.

Heller, J.P. (1994). *CO_2 foams In EOR. Chapter 5 In Foams: Fundamentals And Applications In The Petroleum Industry*. American Chemical Society, L.L. Schramm (Ed.), Washington DC.

Høgnesen, E. J., Strand, S. And Austad, T. (2005). *Waterflooding Of Preferential Oil-Wet Carbonates: Oil Recovery Related To Reservoir Temperature And Brine Composition*. Paper SPE 94166, Presented At The SPE Europec/Eage Annual Conference Held In Madrid, Spain.

Holm, L.W., and Garrison, W.H. (1988). *CO_2 Diversion with Foam in an Immiscible CO_2 Field Project*. SPE Reservoir Engineering, 112-118.

Iler, R. K. (1979). *The Chemistry Of Silica*. Wiley, New York.

Israelachvili J. (1991). *Intermolecular and Surface Forces.* Academic Press, London.

Israelachvili J., H. Wennerstrom, J. (1992). *Phys. Chem.*

Kang, W., Liu, S., Meng, L., Cao, D., And Fan H. (2010). *A Novel Ultra-Low Interfacial Tension Foam Flooding Agent To Enhance Heavy Oil Recovery*. SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Khalil, F., And Asghari, K. (2006). *Application Of CO_2-Foam As A Means Of Reducing Carbon Dioxide Mobility*. Jcpt, Vol 45, No 5, 37-42.

Kovscek, A. R., Patzek, T. W. & Radke, C. J. (1993). *Fundamentals Of Foam Transport In Porous Media*. SPE Annual Technical Conference And Exhibition. Houston, Texas.

Kristiansen, T.S., And Holt, T. (1992). *Properties Of Flowing Foam In Porous Media Containing Oil*. SPE/DOE Symposium On Enhanced Oil Recovery, Tulsa, Oklahoma, USA.

Kuehne, D.L., Frazier, R.H., Cantor, J., Horn, Jr., W. (1992). *Evaluation Of Surfactants For CO_2 Mobility Control In Dolomite Reservoirs*. SPE/DOE Eighth Symposium On Enhanced Oil Recovery, Tulsa, Oklahoma, USA.

Kuhlman, M.I., Lau, H.C., and Falls, A.H. (2000). *Surfactant Criteria for Successful Carbon Dioxide Foam in Sandstone Reservoirs*. SPE Reservoir Evaluation and Engineering, Vol 3, No 1, 35-41.

Lau, H.C., And O'brien, S.M. (1988). *Effects Of Spreading And Non Spreading Oils On Foam Propagation Through Porous Media*. spere, 893.

Le, V. Q. SPE, Nguyen Q. P., SPE (2008). *A Novel Foam Concept with CO_2 Dissolved Surfactants*. SPE /DOE Improved Oil Recovery Symposium held in Tulsa, Oklahoma, U.S.A., 9–3.

Li, B., Hirasaki, G.J., And Miller, C.A. (2006). *Upscaling Of Foam Mobility Control To Three Dimensions*. SPE Symposium On Improved Oil Recovery, Tulsa, Oklahoma, USA.

Li, R.F., Yan, W., Liu, S., Hirasaki, G.J., And Miller, A. (2010). *Foam Mobility Control For Surfactant Enhanced Oil Recovery*. SPE Journal, Vol 15, No 4, 928-942. Literature Review Of 40 Years Of Research And Pilot Tests. SPE

Improved Oil Recovery Symposium. Tulsa, Oklahoma, USA: Society Of Petroleum Engineers.

Liu, R., Liu, H., Li, X., And Fan, Z. (2008). *The Reservoir Suitability Studies Of Nitrogen Foam Flooding In Shengli Oilfield*. SPE Asia Pacific Oil And Gas Conference And Exhibition, Perth, Australia.

Liu, Y., Grigg, R.B., And Bai, B. (2005). *Salinity, pH, And Surfactant Concentration Effects On Co2-Foam*. SPE International Symposium On Oilfield Chemistry, Woodlands, Texas, USA.

Liu, Y., Grigg, R.B., And Svec, R.K. (2005). *CO_2 foam Behaviour: Influence Of Temperature, Pressure, And Concentration Of Surfactant*. SPE Production Operations Symposium, Oklahoma City, Oklahoma, USA.

Liu, Y., Grigg, R.B., and Svec, R.K. (2006). *Foam Mobility and Adsorption in Carbonate Core*. SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Lobo, L., And Wasan, D.T. (1993). *Mechanisms Of Aqueous Foam Stability In The Presence Of Emulsified Non-Aqueous-Phase Liquids: Structure And Stability Of The Pseudoemulsion Film*. Langmuiri, Vol 9, No 7, 1668.

Manlowe, D.J., And Radke, C.J. (1990). *A Pore-Level Investigation Of Foam/Oil Interactions In Porous Media*. SPE Reservoir Engineering Journal, Vol 5, No 4.

Mannhardt, K., Novosad, J.J., And Schramm, L.L. (2000). *Comparative Evaluation Of Foam Stability To Oil*. SPE Reservoir Evaluation And Engineering, Vol 3, No1, 23-34.

Mcguire, P. L., Chatham, J. R., Paskvan, F. K., Sommer, D. M. And Carini, F. H. (2005). *Low Salinity Oil Recovery: An Exciting New EOR Opportunity For*

Alaska's North Slope. Paper SPE 93093, Presented At The SPE Western Regional Meeting Held In Irvine, Ca, USA.

Nguyen, Q.P. (2004). *Dynamics Of Foam In Porous Media*. Phd Dissertation, Delft University, Netherlands.

Nikolov, A.D., Wasan, D.T., Huang, D.W., And Edwards, D.A. (1986). *The Effect Of Oil On Foam Stability: Mechanisms And Implications For Oil Displacement By Foam In Porous Media*. SPE Annual Technical Conference And Exhibition. New Orleans, Louisiana, USA.

Noaa, (2013). *Greenhouse Gases* Http://Www.Ncdc.Noaa.Gov/Oa/Climate/Gases.Html [Online]. [Accessed (Accessed 26.02.2013).

Okasha, T. M. And Al-Shiwaish, A. A. (2009). *Effect Of Brine Salinity On Interfacial Tension In Arab-D Carbonate Reservoir, Saudi Arabia*. Paper SPE 119600, Presented At The SPE Middle East Oil & Gas Show And Conference In The Bahrian International Exhibition Centre, Kingdom Of Bahrain.

Patil, S., Dandekar, A. Y., Patil, S. L., And Khataniar, S. (2008*). Low Salinity Brine Injection For EOR On Alaska North Slope (Ans)*. Paper Iptc 12004, Presented At The International Petroleum Technology Conference, Kuala Lumpur, Malaysia.

Pei, H., Zhang, G., Ge, J., Wang, J., Ding, B., And Liu, X. (2010). *Investigation Of Polymer-Enhanced Foam Flooding With Low Gas/Liquid Ratio For Improving Heavy Oil Recovery*. Canadian Unconventional Resources And International Petroleum Conference, Calgary, Alberta, Canada.

Robertson E. P. (2007). *Low-Salinity Waterflooding To Improve Oil Recovery-Historical Field Evidence*. Paper SPE 109965, Presented At The SPE Annual Technical Conference And Exhibition, Anaheim, California, USA.

Rossen, W. R. (1996). *Foams - Theory, Measurements And Application, Chapter 11: Foams In Enhanced Oil Recovery*.

Samir Pandey, Rahul P. Bwage, and Dinesh O. Shah (2002). *Effect of Counterions on Surface and Foaming of Dodecul Sulfate.* Journal of Colloid and Interface Science. 263 (2003) 160-166.

Schramm, L.L. (1994). Foam *Sensitivity To Crude Oil In Porous Media In Foams*, Fundamentals And Applications In The Petroleum Industry,

Schramm, L.L., And Novosad, J.J. (1990). *Microvisualization Of Foam Interactions With A Crude Oil, Colloids Surf*. Vol 46, No 21.

Schramm, L.L., Turta, A.T., And Novosad, J.J. (1993). *Microvisual And Coreflood Studies Of Foam Interactions With A Light Crude Oil*, spere, 201.

Schramm. L.L. (1994). Foam*: Fundamentals and Applications in the Petroleum Industry*. Advances in Chemistry, Series 242.

Seccombe, J. C., Lager, A., Webb, K., Jerauld, G. And Fueg, E. (2008). *Improving Waterflood Recovery: Losaltm EOR Field Evaluation.* Paper SPE 113480, Presented At The SPE/DOE Improved Oil Recovery Held In Tulsa, Oklahoma, USA.

Sharma, M. M. And Filoco, P. R. (2000). *Effect Of Brine Salinity And Crude-Oil Properties On Oil Recovery And Residual Oil Saturations*. SPE Journal 5(3), P.293-300.

Skauge, A., Aarra, M.G. And Surguchev, L.M. Et Al. (2002). *Foam- Assisted WAG: Experience From The Snorre Field*. SPE/DOE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Skjæveland, S. M. & Kleppe, J. (1992). *Spor - Recent Advances In Improved Oil Recovery Methods For North Sea Sandstone Reservoirs*. Norwegian Petroleum Directorate, Chapter 9, 207-250.

Skrettingland, K., Holt, T., Tweheyo, M. T. And Skjevrak, I. (2011). *Snorre Low-Salinity-Water Injection—Coreflooding Experiments And Single-Well Field Pilot*. SPE Reservoir Evaluation & Engineering, 182-192.

Stig André Winter Langlo (2013). *Enhanced Oil Recovery By CO_2 And CO_2-Foam Injection In Fractured Limestone Rocks.* Department Of Physics And Technology University Of Bergen.

Sunil Kokal And Abdulaziz Al-Kaabi (2010*). Enhanced Oil Recovery: Challenges & Opportunities.* Expec Advanced Research Centre, Saudi Aramco.

Sweatman, R. E., Crookshank, S. & Edman, S. (2011). *Outlook And Technologies For Offshore CO_2 EOR/CCS Projects*. Offshore Technology Conference. Houston, Texas, USA.

Taber, J. J., Martin, F. D., Seright, R. S. (1997a). *EOR Screening Criteria Revisited - Part I: Introduction to Screening Criteria and Enhanced Oil Recovery Projects* (SPE-35385). SPE Reservoir Engineering, V. 12, No.3, August 1997. pp 189-198.

Taber, J. J., Martin, F. D., Seright, R. S. (1997b). *EOR Screening Criteria Revisited - Part II: Applications and Impact of Oil Prices* (SPE-39234). SPE Reservoir Engineering, V.12, No.3. pp 199-205.

Takamura, K. And Chow, R. S. (1989). *The Electric Properties Of The Bitumen/Water Interface Part II. Application Of The Ionizable Surface-Group Model*. Colloid And Surfaces, 15: 35-48.

Tang, G. Q. And Morrow, N. R. (1997). *Salinity, Temperature, Oil Composition, And Oil Recovery By Waterflooding*. SPE Reservoir Engineering, November: 269-276.

Torino, E., Reverchon, E., And Johnston, K.P. (2010). *Carbon Dioxide/Water, Water/Carbon Dioxide Emulsions And Double Emulsions Stabilized With A Nonionic Biocompatible Surfactant*. J. Colloid Interface Science, Vol. 348, 469-478.

Tsau, J.S., And Heller, J. P. (1996). *How Can Selective Mobility Reduction Of CO_2-Foam Assist In Reservoir Floods*. The Permian Basin Oil And Gas Recovery Conference, Midland, Texas, USA.

Tsau, J.S., and Heller, J.P. (1992). *Evaluation of Surfactants for CO_2-Foam Mobility Control*. Permian Basin Oil and Gas Recovery Conference, Midland, Texas, USA.

Tsau, J.S., Syahputra, A.E., Yaghoobi, H., Et Al. (1999). *Use Of Sacrificial Agents In CO_2 Foam Flooding Application*. SPE Annual Technical Conference And Exhibition, Houston, Texas, USA.

Vijapurapu, C. S. And Rao, D. N. (2004). *Compositional Effects Of Fluids On Spreading, Adhesion And Wettability In Porous Media*. Colloids And Surfaces A: Physicochemical And Engineering Aspects, 241, 335-342.

Vikingstad, A. K., Skauge, A., Høiland, H. & Aarra, M. (2005). *Foam-Oil Interactions Analysed By Static Foam Tests*. University Of Bergen.

Wang, G.C. (1984). A *Laboratory Study Of CO_2 Foam Properties And Displacement Mechanism*. SPE Enhanced Oil Recovery Symposium, Tulsa, Oklahoma, USA.

Webb, K. J., Black, J. J And Al-Ajeel, H. (2004). *Low Salinity Oil Recovery-Log-Inject-Log*. Paper SPE 89379, Presented At The SPE/DOE Fourteen Symposium On Improved Oil Recovery Held In Tulsa, Oklahoma, USA.

Xing, D., Wei, B., Trickett, K., Mohamed, A., Eastoe, J., Soong, Y., And Enick R. (2010). *CO_2-Soluble Surfactants For Improved Mobility Control*. SPE Improved Oil Recovery Symposium , Tulsa, Oklahoma, USA.

Xu, W. (2005). *Experimental Investigation Of Dynamic Interfacial Tensions At Reservoir Conditions*. M.S. Thesis, Louisiana State University At Baton Rouge.

Yaghoobi, H., And Heller, J.P. (1994). *Laboratory Investigation Of Parameters Ffecting CO_2-Foam Mobility In Sandstone At Reservoir Conditions*. SPE Eastern Regional Meeting, Charleston, West Virginia, USA.

Yaghoobi, H., Tsau, J.S., And Grigg, R.B. (1998). *Effect Of Foam On CO_2 Breakthrough: Is This Favorable To Oil Recovery?*. SPE Permian Basin Oil And Gas Recovery Conference, Midland, Texas, USA.

Yin, G., Grigg, R.B. , And Svec, Y. (2009). *Oil Recovery And Surfactant Adsorption During CO_2-Foam Flooding*. Offshore Technology Conference, Houston, Texas, USA.

Yu Zheng (2012). *Effect Of Surfactants And Brine Salinity And Composition On Spreading, Wettability And Flow Behaviour In Gas-Condensate Reservoirs*. Graduate Faculty Of The Louisiana State University And Agricultural And Mechanical College,

Zhang, Y., Xie, X And Morrow, N. R. (2007). *Waterflood Performance By Injection Of Brine With Different Salinity For Reservoir Cores*. Paper SPE 109849, Presented At The SPE Annual Technical Conference And Exhibition,, Anaheim, California, USA.

Ziegler, Victor M., Handy, And Lyman L. (1981). *Effect Of Temperature On Surfactant Adsorption In Porous Media*. SPE Journal, Vol 21, No 2, 218-228.

Zuta, J., And Fjelde, I. (2010b). *Transport Of A CO_2-Foaming Agent During CO_2-Foam Processes In Fractured Chalk Rock*. SPE Reservoir Evaluation & Engineering, Vol 13, No 4, 710-719.