

Effects of Salt on Interfacial Tension of Surfactant-Brine-Oil System

by

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CERTIFICATION OF APPROVAL

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Approved by,

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TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

(Chin Ze Shen)

ABSTRACT

The concept of interfacial tension is very important surfactant flooding under the field of chemical enhanced oil recovery. Using the spinning drop tensiometer, this work aims to determine the interfacial tension between the mixture of brine with surfactant and oil, using different salts at different concentrations and temperatures. It is found that the oil-brine interfacial tension increases with decreasing salt concentration, increasing temperature, and use of NaCl instead of MgCl₂; while it decreases with use of surfactant and decreases further with use of surfactant added with salt.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

Oil and gas are produced from porous media in underground hydrocarbon reservoirs. At the end of primary and secondary recovery which generally only involves natural drive and pressure maintenance, usually more than 50% of the original oil in place (OOIP) is left in the reservoir unproduced. (Sheded, 2006)

Specifically for water flooding as a secondary recovery method, it can be said categorically that a waterflood that covers 100% of a given oil zone leaves a residual oil of approximately 30%, which value correlates to the end-point relative permeability of oil at zero. Oil cannot be produced at this saturation because of the high interfacial tension between oil and water, as water pressure alone is insufficient to overcome the high capillary pressure required to displace oil from very small pores.

The function of surfactant is to reduce the interfacial tension between oil and water. With the use of surfactant, much of the residual oil can be recovered as lowering the oil-water interfacial tension reduces the capillary pressure and thus allows water to displace additional oil. Theoretically, the residual oil can be reduced to zero if the interfacial tension can be reduced to zero, although it is impossible to achieve a 100% recovery factor in practice. (Emegwalu, 2009)

Thus, it is important to understand the effect of salt on the interfacial tension between brine, surfactant, and oil especially in the application of chemical enhanced oil recovery in order to have the most efficient usage of surfactant giving the highest recovery factor.

1.2 PROBLEM STATEMENT

Surfactant/brine IFT has proved to be an important area for study, especially with applications including surfactant EOR. Many surfactant-brine-oil IFT correlations have been studied and reported for a wide range of surfactants and brines. However, there has yet to be a study which explains in general the effect of different salts of different concentrations and temperatures on the IFT between surfactant, brine and

oil. Thus, this project aims to bring such vital information into light for the benefit of the above stated applications.

1.3 OBJECTIVE

This project aims to investigate and determine the salinity effects of different salts at different concentrations and temperatures on the interfacial tension (IFT) between surfactant, brine, and oil.

1.4 SCOPE OF STUDY

The interfacial tension will be measured between brine and oil followed by brine mixed with surfactant and oil. The project will involve, two types of salt most commonly found in reservoir fluids, i.e. Sodium Chloride (NaCl), and Magnesium Chloride ($MgCl_2$) at different concentration levels up to 0.34 mol/l. Temperatures will be set to 30°C and 50°C.

CHAPTER 2

THEORY

2.1 CONCEPT OF INTERFACIAL TENSION

When two immiscible fluids are in contact, the forces acting on the interface between the two fluids are the interfacial tension, also known as surface tension when the two fluids are liquid and gas. Considering two immiscible fluids of gas and liquid in the figure below: a liquid molecule which is remote from the interface is surrounded by other liquid molecules, thus having a resulting net attractive force on the molecule of zero; while a molecule at the interface has a force acting from it from the gas molecules lying immediately above the interface and from liquid molecules lying below the interface. (Ahmed, 2002)

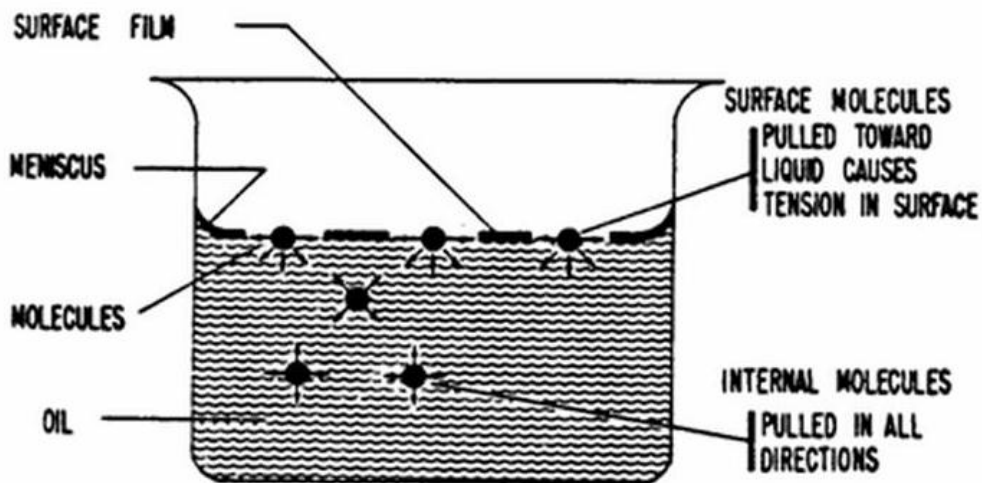


Figure 1: Illustration of gas-liquid interfacial tension. (Clark, 1969)

2.2 LITERATURE REVIEW

Wilson et al. (1976) investigated the effects of sulfonate molecular weight and salt concentration on the interfacial tension of oil-brine-surfactant systems. Comparing the IFTs of NaCl, $\text{Na}_5\text{P}_3\text{O}_{10}$, Na_2SO_4 , and Na_2CO_3 , it is found that the IFTs between the brine solutions and oil decreases rapidly with increasing concentration up till approximately 0.2mol/l, but increases rapidly immediately after. It is also found that NaCl reduces to the lowest IFT compared to all the other salts.

Badakshan, A. and Bakes, P. (1990) did experimental work to study the influence of temperature and surfactant concentration on interfacial tension of saline water and

hydrocarbon systems. It was found that the IFT between N-hexane and NaCl solution decreases linearly with temperature from 20°C to 65°C, and increases with increasing weight percentage from 0 wt% to 15 wt%. The same applied to the IFT between cyclohexane or toluene and NaCl solution. However, as for the IFT between N-hexane and brine, the IFT decreased with increasing temperature from 20°C to 60°C regardless of the salt used, in this case NaCl, Na₂SO₄, NaHCO₃, and CaCl₂.

Ye et al. (2007) studied the effect of temperature on the interfacial tension between crude oil and gemini surfactant solution. It is reported that for surfactants 14-4-14 and 16-4-14 at a concentration of 1g/l, the interfacial tension decreased linearly from 30°C to 70°C but suddenly increased from 70°C to 80°C. However, when the both surfactants 14-4-14 and 16-4-14 were mixed, the interfacial tension stayed relatively constant from 30°C to 80°C.

Al-Sahhaf et al. (2007) studied the influence of temperature, pressure, salinity, and surfactant concentration on the interfacial tension of the N-Octane-Water System. It is reported that the surfactant-brine-oil IFT decreases slightly with increasing salt concentration from 0 -3.1 wt%. Surfactant-oil IFT also decreases linearly with increasing temperature from 24°C to 65°C.

Bera et al. (2011) measured the interfacial tension of excess brine microemulsion system involving NaCl as brine solution with Tergitol 15-S-9 as surfactant using Auto tensiometer (Rigosha & Co. Ltd., Model: 6801ES with platinum ring) under atmospheric pressure by the ring method. It is found that for the range of NaCl weight percentage of 1.6 to 2.7, the interfacial tension increases rapidly with increasing salinity but the rate of increase decreases rapidly.

CHAPTER 3

METHODOLOGY

3.1 RESEARCH METHODOLOGY AND PROJECT ACTIVITIES

Various techniques can be used to determine the interfacial tension between fluid phases. For this project, the spinning drop video tensiometer, a special purpose optical instrument for measuring of conventional to extremely low interfacial tensions is used. The IFT values of the samples are calculated by the control/data analysis software which is designed for intuitive use and fast access to all control elements.

Using the spinning drop tensiometer, the IFT will be measured by imaging an oil capsule injected through the needle in a surfactant/brine phase.

Several variables were manipulated in this experiment: salt type, concentration, and temperature. Two salts will be used: Sodium Chloride (NaCl) which is covalent, and Magnesium Chloride ($MgCl_2$) which is divalent. It will be conducted under temperatures of 30° and 50°C, with concentrations of 0.342 mol/l, 0.171 mol/l, and 0.086 mol/l, with and without the addition of surfactant Sodium Dodecyl Sulfate ($CH_3(CH_2)_{11}OSO_3Na$).

3.2 CHEMICALS

Component	Purity (%)	Supplier	Phase
H ₂ O	Distilled	Own	Liquid
NaCl	99.9%	Avantis Laboratory Supply	Solid
MgCl ₂ ·6H ₂ O	99.9%	Avantis Laboratory Supply	Solid
CH ₃ (CH ₂) ₁₁ OSO ₃ Na	-	-	Solid

3.3 EXPERIMENTAL APPARATUS

The measurement of IFT will be done using the spinning drop video tensiometer (SVT 20N) equipment.

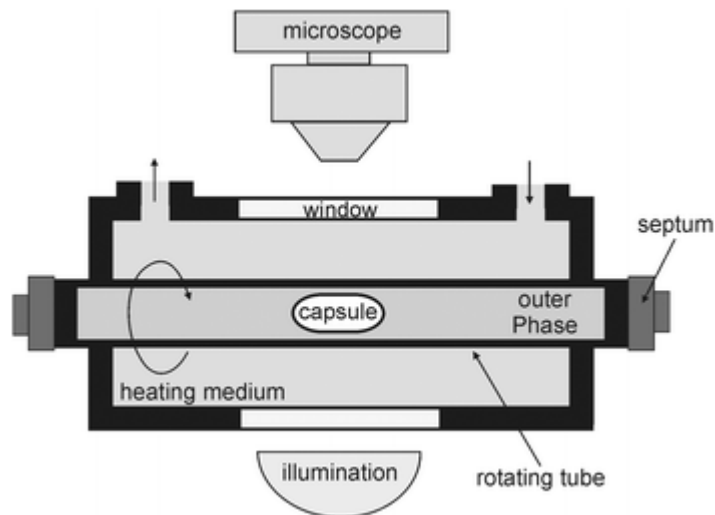


Figure 2 Diagram of a spinning drop tensiometer. (Leick, 2010)

In the diagram above, the rotating tube will house the outer phase liquid, in this case the brine solution, and there will be a drop of oil inside which is the capsule. The entire rotating tube will be spinning up to a frequency such that the capsule is flattened from round shape to oblong shape. It will be heated according to the temperature of interest. In order to view it from the computer, the illumination will be lighted up and the capsule will be captured via video using the microscope which as per the diagram. The software will then calculate the interfacial tension based on the image of the capsule.

3.4 EXPERIMENTAL PROCEDURE

1. Make sure the equipment is clean and in usable condition
2. Fill up the rotating tube with brine solution fully using a 5ml syringe, and make sure there are no bubbles inside.
3. Tighten the rotating tube with the septum and insert it into the spinning drop tensiometer, and lock the rotating tube into position.
4. Set the frequency of the rotating tube to 200 rpm.
5. Fill a 1ml syringe with oil, and together with the needle insert the syringe into the rotating tube and produce a drop of oil.
6. Increase the frequency of the rotating tube until the capsule has an oblong shape, with its length at least twice its height.
7. Record the IFT readings and tabulate.
8. Repeat all above steps for NaCl and MgCl₂, with concentrations 0.342 mol/l, 0.171 mol/l, and 0.086 mol/l, at temperatures of 30° and 50°C, and with 1 g/l of CH₃(CH₂)₁₁OSO₃Na.

3.5 KEY MILESTONE

Milestone	Status
Project background research	Completed
Literature review	Completed
Experimental work	Completed
Results analysis	Completed
Report compilation	Completed
Submission of project paper	Completed

3.6 GANTT CHART

FYP 1

No.	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Work														
2	Preliminary Research Work														
3	Submission of Extended Proposal														
4	Proposal Defence														
5	Project Work Continues														
6	Submission of Interim Draft Report														
7	Submission of Interim Report														

Mid Semester Break

FYP 2

No.	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	
1	Project Work Continues								Mid Semester Break								
2	Submission of Progress Report																
3	Project Work Continues																
4	Pre-SEDEX																
5	Submission of Draft Report																
6	Submission of Dissertation (soft bound)																
7	Submission of Technical Paper																
8	Oral Presentation																
9	Submission of Project Dissertation (hard bound)																

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 MEASUREMENT OF DENSITY AND REFRACTIVE INDEX

Measurement of IFT using the spinning drop requires three input data: density of outer phase, refractive index (Ri) of outer phase, and density of capsule; all measured at the specific temperature set for the experiment. The measured data is as follows:

Fluid	Density (kg/l)		Ri	
	30°C	50°C	30°C	50°C
Water	0.99564	0.98804	1.3318	1.3287
Water + surfactant	0.99721	0.98967	1.3319	1.3288
NaCl 5g/l	1.00046	0.99303	1.3327	1.3296
NaCl 10g/l	1.00332	0.99584	1.3334	1.3304
NaCl 20g/l	1.01033	1.0023	1.3353	1.3322
NaCl 5g/l + surfactant	1.00067	0.99324	1.333	1.3298
NaCl 10g/l + surfactant	1.00394	0.99634	1.3337	1.3307
NaCl 20g/l + surfactant	1.01021	1.00257	1.3352	1.3323
MgCl ₂ 17g/l	1.00101	0.99534	1.3338	1.3309
MgCl ₂ 35g/l	1.01025	1.00108	1.3359	1.3328
MgCl ₂ 70g/l	1.01887	1.00988	1.3398	1.3371
MgCl ₂ 17g/l + surfactant	1.00392	0.99633	1.3339	1.3308
MgCl ₂ 35g/l + surfactant	1.01038	1.00295	1.3358	1.3331
MgCl ₂ 70g/l + surfactant	1.02417	1.01653	1.3413	1.3399
Masila	0.84684	0.83343	-	-
Dubai	0.87484	0.86022	-	-

Table 1 Density and Ri values for all fluids used.

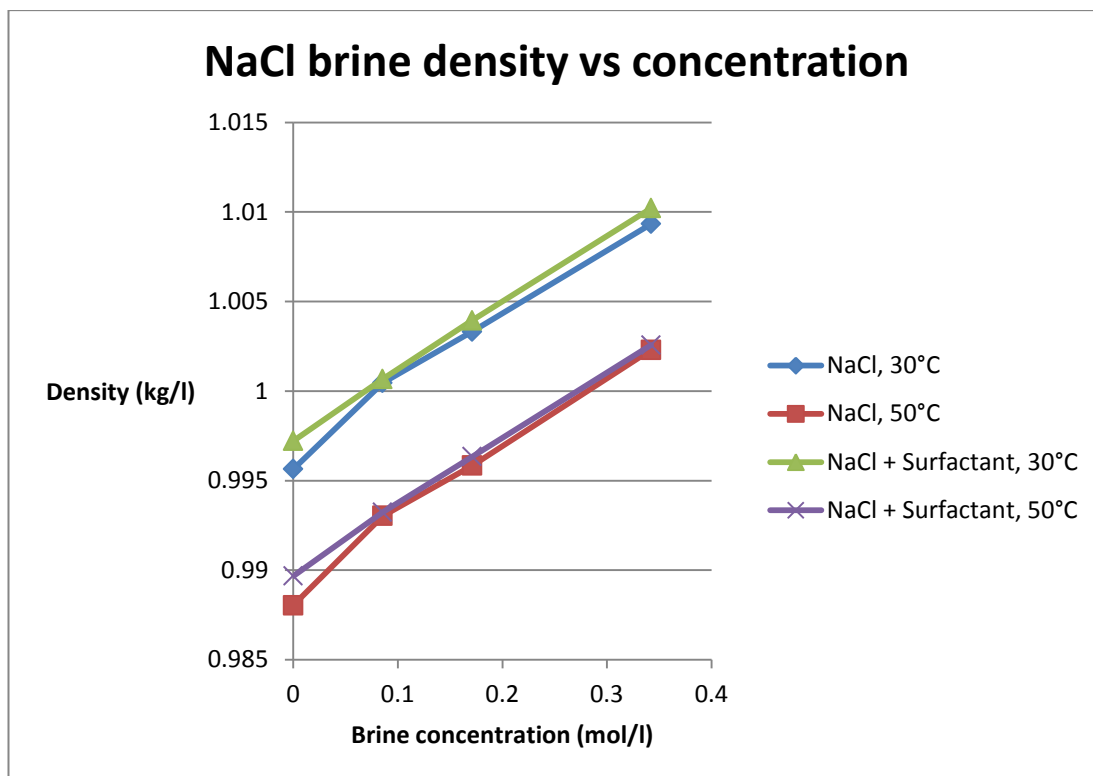


Figure 3 Graph of NaCl brine density vs concentration

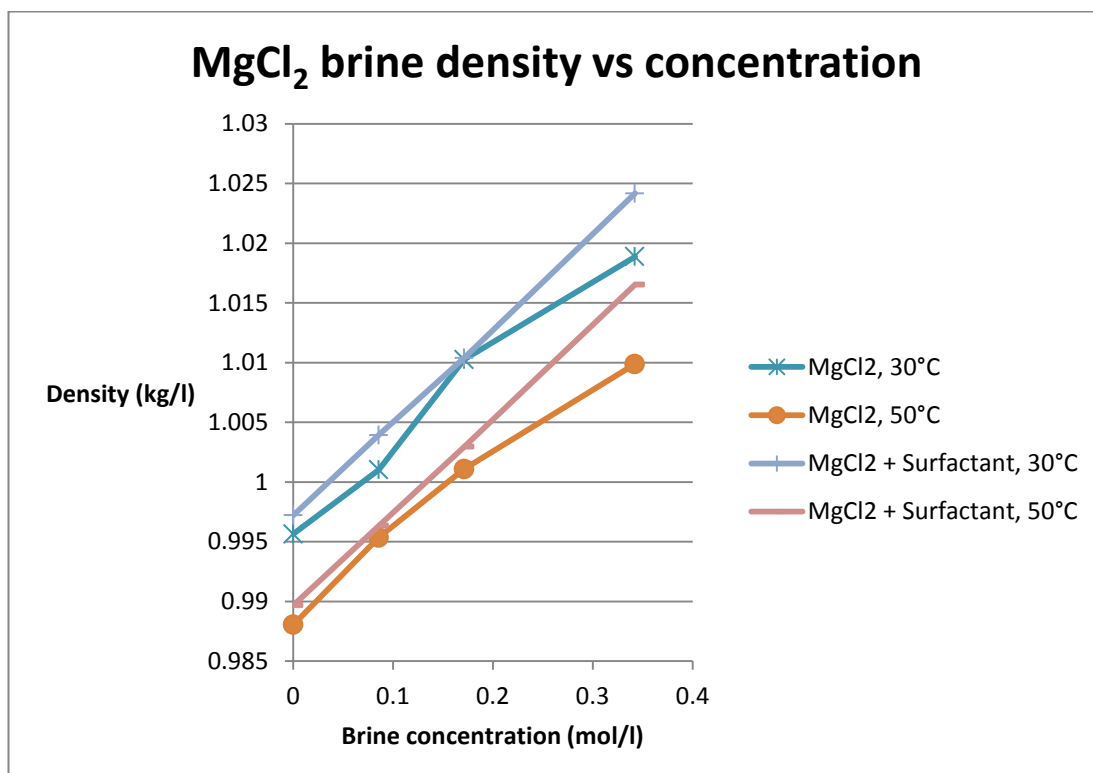


Figure 4 Graph of MgCl₂ brine density vs concentration

Both graphs above show density vs concentration of both brine solution, with and without surfactant, at both temperatures of 30°C and 50°C. The data are in line with

basic theories. First, density of brine increases linearly with concentration and with addition of surfactant. This is because salt and surfactant are heavier in terms of molecular weight compared to water of the same volume, and an increase in these molecules relative to lighter water molecules definitely leads to an increase in density.

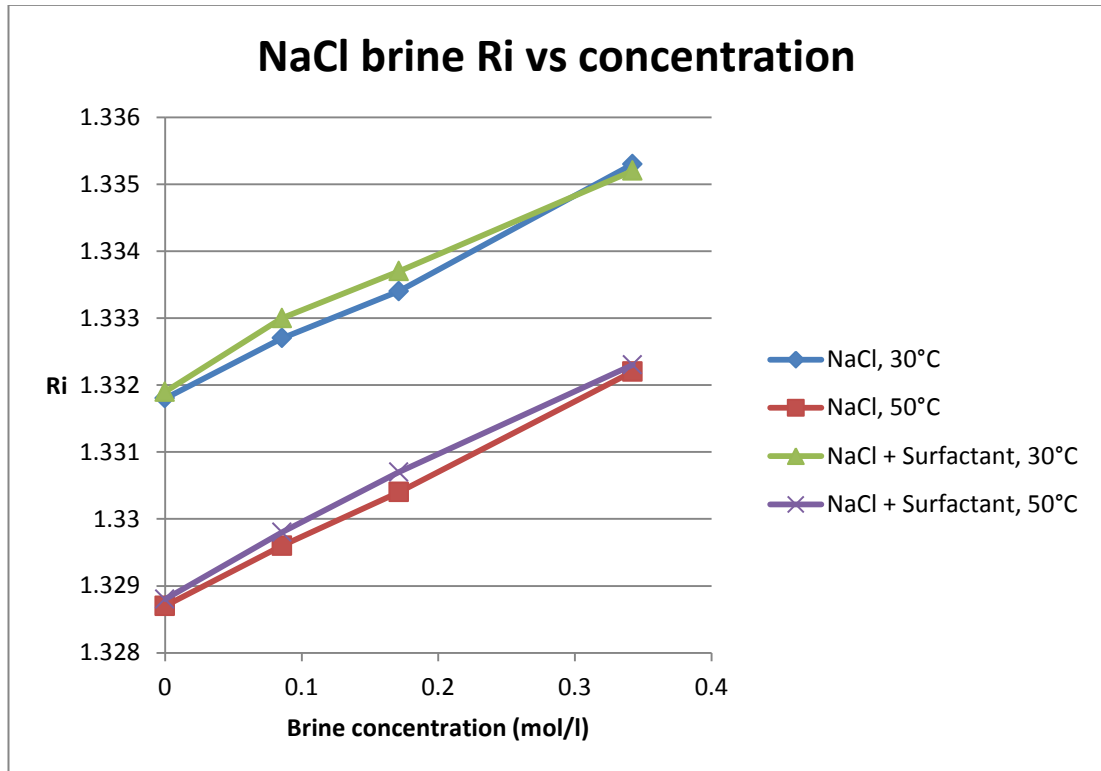


Figure 5 Graph of NaCl brine Ri vs concentration

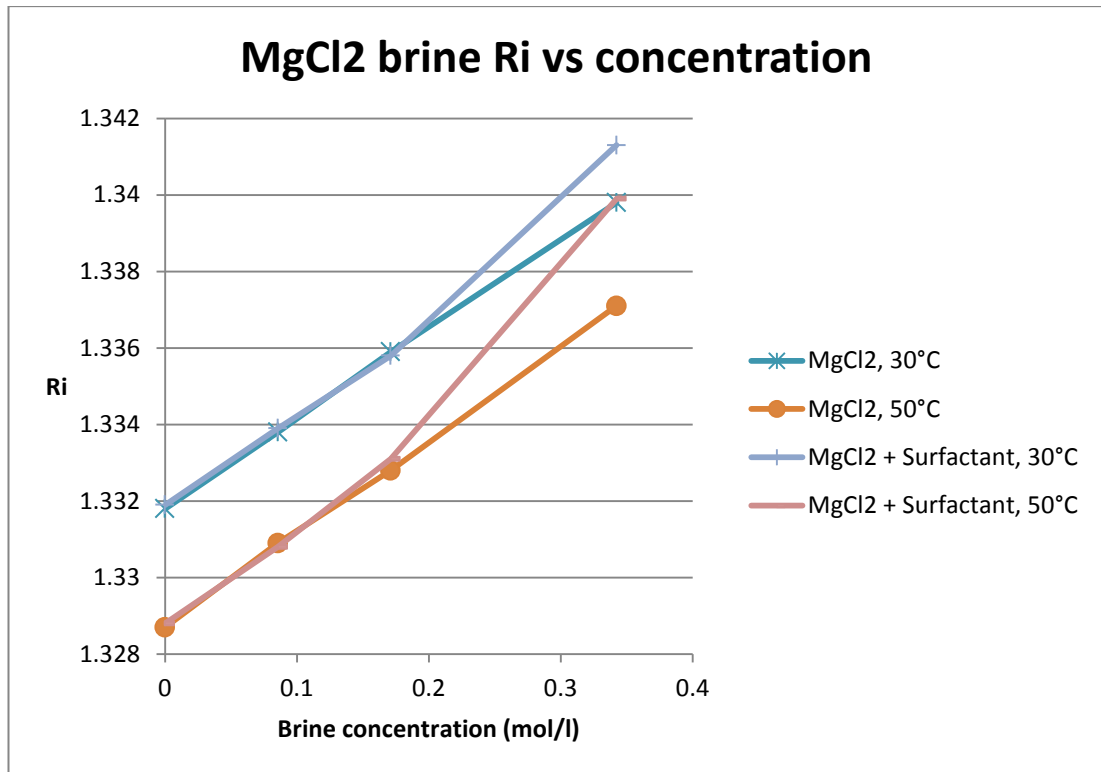


Figure 6 Graph of MgCl₂ brine Ri vs concentration

The refractive index of a phase is a function of the ratio between the speed of light in vacuum and the speed of light in the specific phase. The speed of light travelling through a phase is in turn a function of the density of the phase, where light travels slower through a denser phase and vice-versa. Therefore, the graph shows very similar density and Ri trends as density and Ri is directly proportional.

The density and Ri values were measured as they are the input data for the measurement of IFT using the spinning drop tensiometer software.

4.1 MEASUREMENT OF BRINE-SURFACTANT-OIL IFT

The same sets of measurements were used on two different oils, one from Dubai and another from Masila. The results are as below.

IFT between fluid and Masila oil (mN/m)				
Fluid	Concentration (mol/l)			
	0	0.08556	0.17112	0.34233
NaCl, 30°C	22.35	21.3	23.94	19.86
NaCl, 50°C	23.71	22.94	21.11	20.71
NaCl + Surfactant, 30°C	7.56	1.02	1.13	0.90
NaCl + Surfactant, 50°C	9.37	2.06	1.99	1.50
MgCl ₂ , 30°C	22.35	20.37	22.42	16.77
MgCl ₂ , 50°C	23.71	21.43	20.36	17.12
MgCl ₂ + Surfactant, 30°C	7.56	0.39	0.38	0.26
MgCl ₂ + Surfactant, 50°C	9.37	0.87	0.94	0.70

Table 2 Measured IFT values between Masila oil and different fluids.

IFT between fluid and Dubai oil (mN/m)				
Fluid	Concentration (mol/l)			
	0	0.08556	0.17112	0.34233
NaCl, 30°C	15.21	17.81	17.72	13.73
NaCl, 50°C	15.88	19.95	18.79	19.69
NaCl + Surfactant, 30°C	6.91	0.71	0.67	0.74
NaCl + Surfactant, 50°C	8.05	-	-	-
MgCl ₂ , 30°C	15.21	17.09	17.42	11.75
MgCl ₂ , 50°C	15.88	18.24	18.31	15.32
MgCl ₂ + Surfactant, 30°C	6.91	0.48	0.59	0.68
MgCl ₂ + Surfactant, 50°C	8.05	0.62	0.57	0.31

Table 3 Measured IFT values between Dubai oil and different fluids.

Graphs for the above tables are plotted as below.

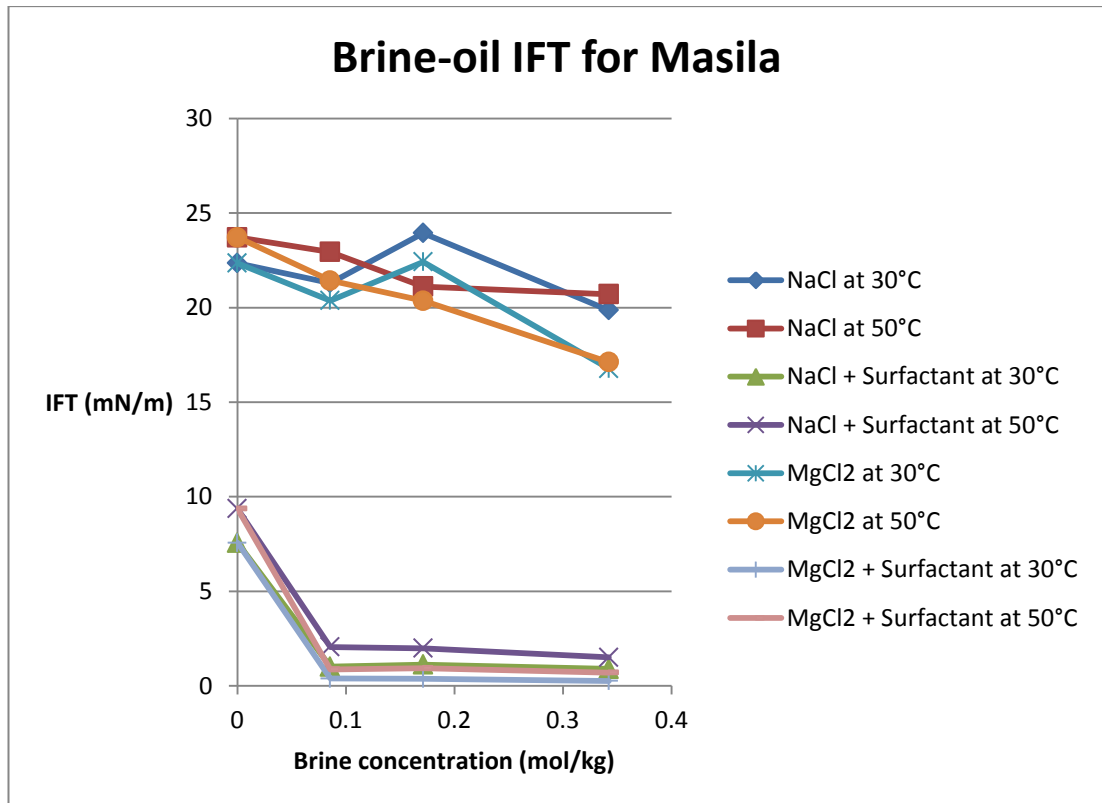


Table 4 Graph of measured IFT values between Masila oil and different fluids.

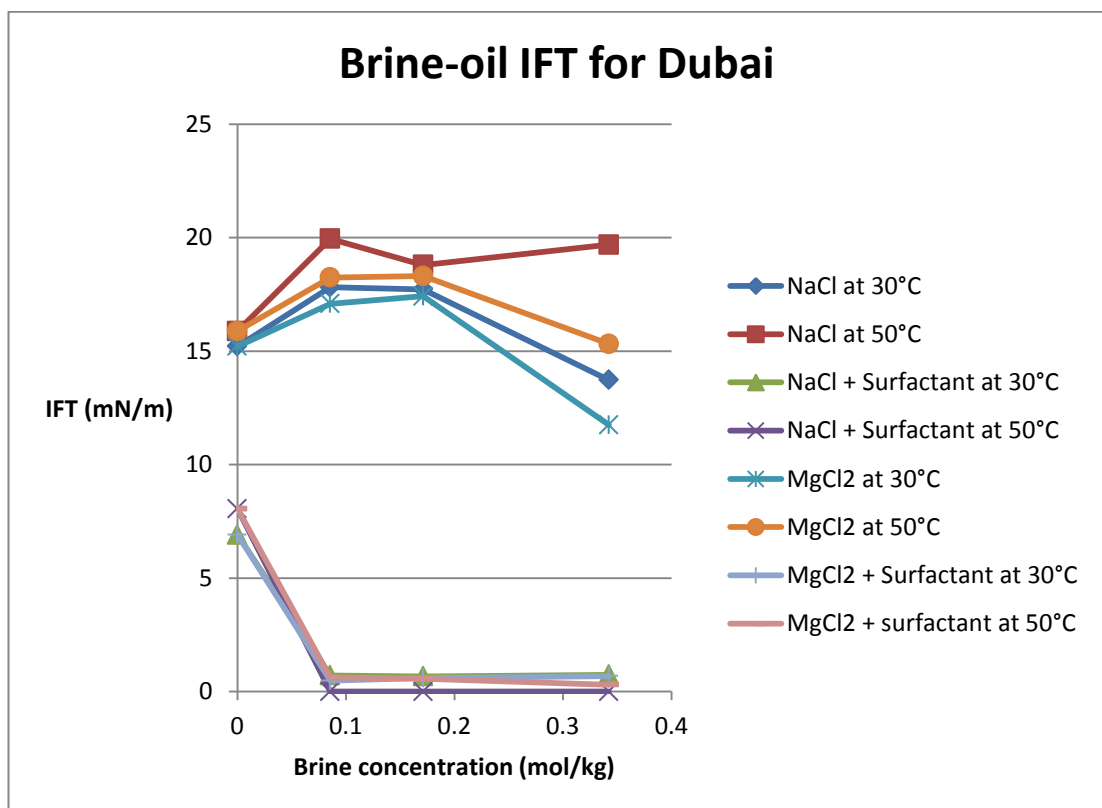


Table 5 Graph of measured IFT values between Dubai oil and different fluids.

It is observed that the general trend of the IFT results for both Masila and Dubai oil are generally similar, thus the results will be analyzed collectively.

The most obvious finding from the data is that the use of surfactant greatly reduces brine-oil IFT. Without surfactant, brine-oil IFT ranges from 15 mN/m to 20 mN/m, but with the addition of a mere 1g/l of $\text{CH}_3(\text{CH}_2)_{11}\text{OSO}_3\text{Na}$ surfactant into the brine, the IFT mostly reduced to less than 1 mNm, which is at least 10 times lower. This is because surfactant molecules come with hydrophobic and hydrophilic ends, which causes them to diffuse in water and adsorb at interfaces between brine and oil. The surfactant used, Sodium Dodecyl Sulfate, is also an anionic surfactant, thus reacts positively to water hardness i.e. presence of sodium ions. Therefore, it is definitely expected that addition of surfactant into brine leads to greatly reduced IFT.

However, without the presence of salt, the surfactant-brine IFT was significantly higher than when salt was present. Thus the use of surfactant in salt-present solution will enhance the effect of surfactant by decreasing the IFT further. This is due to the fact that the IFT is strongly dependent on the salinity of the aqueous phase, and at a critical salt concentration the IFT approaches its minimum value. (Donaldson, 1989) At zero salt concentration, most of the surfactant stays in the aqueous phase and very little of the surfactant partitions into the interface or oil phase; whereas as the salt concentration increases, the surfactant preferentially dissolves in the oil phase due to the “salting out” process where surfactant molecules move towards the oil/brine interface thus lowering IFT. (Chan, 1980)

As for the IFT for surfactant-brine-oil, no clear trend can be deduced about the relationship between brine concentration and IFT as the values are too low and uncertainty is high. Based on literature review though, it can be inferred that there is an optimum salinity where the surfactant concentration is equal in the oil and brine phase lowering the IFT the most implying that the surfactant molecules have the same affinity for oil and brine. (Chan, 1980)

Next, it is observed that generally brine-oil IFT is slightly lower for NaCl compared to MgCl_2 . This could be related to the Hofmeister series which provides a qualitative ranking of salt anions and cations which is originally based on their effectiveness as protein precipitates, but subsequently found to be applicable to many other processes in which water-accessible surface area (ASA) changes significantly. It is found that

the higher the ranking of salt ions in the Hofmeister series, the higher the IFT produced. (Pegram, 2007) The thermodynamic description of Hofmeister effects, and all other effects of electrolyte and nonelectrolyte solutes, on biopolymer processes is most fundamentally based on preferential interaction coefficients which quantify the thermodynamic consequence of the local accumulation or exclusion of the solute from the vicinity of the hydrated biopolymer surface as a function of solute concentration. (Timasheff, 1998)

As for temperature, it is observed that brine-oil IFT values are generally higher at 50°C than 30°C, indicating a proportionate relationship between IFT and temperature, solely taking into account the behaviour of the fluids at these two reference points. This finding is also in contrary to literature review where it is generally found that IFT reduces with an increase in temperature, 30°C to 60°C (Ye, 2007); as well as findings that increase in temperature decreases IFT linearly for a variety of salt-surfactant combinations (Al-Sahhaf, 2007); and another report that for any salt, IFT reduces linearly with an increase in temperature within the range 30°C to 60°C. (Badakshan, 1990) It would be expected that an increase in temperature will lead to increase in molecular activity between the brine-oil interface, which leads to a reduction in interfacial tension. Besides, there is a considerable possibility of experimental inaccuracy having not all results showing an increase in IFT with an increase in temperature.

As for concentration, the data from the experiment largely fluctuates but most results point towards the conclusion that higher salt concentration leads to lower brine-oil IFT. It is noted from literature review that for high salt concentrations, the coexistence of water-in-oil micro-emulsion with excess of water results in an increase in IFT values with an increase in salinity. (Ruckenstein, 1987) This is also confirmed by experimental study that for a system of surfactant micro-emulsion/water with excess brine, higher salinity leads to higher IFT values. (Bera, 2011); as well as another study which states reported IFT as directly proportional to salt concentration. (Pegram, 2007) Thus, the results of this experiment could again be credited to a high level of error.

CHAPTER 5

CONCLUSION

5.1 CONCLUSION AND RECOMMENDATIONS

Several conclusions are drawn from this project:

- The use of surfactant reduces the IFT between water and oil, and the addition of salt into the surfactant further reduces the brine-oil IFT.
- The brine-oil IFT of NaCl solution is generally higher than that of MgCl₂.
- Brine-oil IFT increases with increasing temperature from 30°C to 50°C, but results due to experimental error possible.
- Brine-oil IFT decreases with increasing salt concentration, results due to experimental error also possible.

It is recommended for more study to be done on this subject by using different types of salts at more concentration levels to better understand the effects of salt and the concentration on brine-oil IFT and if there is a relationship between IFT and the number of valence electron the salt molecule has. It is also recommended that the temperature ranges to be conducted is greater, preferably from room temperature up to temperatures of that of reservoir conditions to determine clearly the effect of temperature on brine-oil IFT. As for IFT measurements which involve brine and surfactant together, it is recommended for more accurate equipment to be used to see in more detail the effect of surfactant, salt, and temperature on brine-oil IFT.

REFERENCES

- Ahmed, T. (2002). *Reservoir Engineering Handbook* (2 ed.). Gulf Professional Publishing.
- Al-Sahhaf, T. E. (2007). The Influence of Temperature, Pressure, Salinity, and Surfactant Concentration on the Interfacial Tension of the N-Octane-Water System. *Chemical Engineering Communications* , 667-684.
- Badakshan, A. B. (1990). The influence of temperature and surfactant concentration on interfacial tension of saline water and hydrocarbon systems in relation to enhanced oil recovery by chemical flooding. *Society of Petroleum Engineers* .
- Bera, A. O. (2011). Interfacial tension and phase behavior of surfactant-brine-oil system. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* , 383, 114-119.
- Chan, K. S. (1980). The Molecular Mechanism for Achieving Ultra Low Interfacial Tension Minimum in a Petroleum Sulfonate/Oil/Brine System. *J. Dispersion Science and Technology* , 55-95.
- Clark, N. (1969). *Elements of Petroleum Reservoirs*. Society of Petroleum Engineers, AIME.
- Donaldson, E. (1989). *Enhanced Oil Recovery II, Processes and Operations*. New York: Elsevier Science Publishers B.V.
- Emegwalu, C. (2009). *Enhanced Oil Recovery: Surfactant Flooding as a Possibility for the Norne E-Segment*. Norwegian University of Science and Technology.
- Leick, S. H. (2010). Deformation of liquid-filled calcium alginate capsules in a spinning drop apparatus. *Physical Chemistry Chemical Physics* , 2950-2958.
- Pegram, L. R. (2007). Hofmeister salt effects on surface tension arise from partitioning of anions and cations between bulk water and the air-water interface. *Journal of Physical Chemistry* , 5411-5417.
- Ruckenstein, E. R. (1987). Interfacial tension of oil-brine systems in the presence of surfactant and cosurfactants. *Journal of Colloid and Interface Science* , 104-119.

Sheded, A. (2006). Influences of fracture orientation on oil recovery. *J. Pet. Sci. Eng.* (50), 285-292.

Timasheff, S. (1998). "Control of protein stability and reactions by weakly interacting cosolvents: The simplicity of the complicated. *Advanced Protein Chemistry* , 355-432.

Wilson, P. M. (1976). The effects of sulfonate molecular weight and salt concentration on the interfacial tension of oil-brine-surfactant systems. *Society of Petroleum Engineers of AIME* , 202-216.

Ye, Z. Z. (2007). The effect of temperature on the interfacial tension between crude oil and gemini surfactant solution. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* , 322, 138-141.

