The Effect of Surfactant Characteristics on IFT to Improve Oil Recovery in Tempino Light Oil Field Indonesia

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Abstract. Water injection has been employed in the Tempino oil field since 1996. The current oil recovery factor is 35% of OOIP. Even though the pressure is still high, the oil production rate has declined rapidly and the water cut is approaching 89%. In order to mobilize the oil from the reservoir more effectively, surfactant flooding is one of the solutions that can reduce residual oil saturation. Interaction between crude oil and compatible surfactant generates microemulsion, as an indication of low interfacial tension. Hence the oil is expected to move out of the pore throat easily. In this research, thirty types of surfactants were evaluated. The hydrophilic lipophilic balance (HLB) was calculated and the interfacial tension (IFT) with the reservoir fluid was measured. HLB criteria were established as an indicator of low IFT, which was then tested for Berea core flooding. The results indicate that an HLB between approximately 2.7 and 3.1 (on Davies' Scale) or greater than 11.5 (on Griffin's Scale) gives low IFT (~10^{-3} dynes/cm). This characteristic is possesed by surfactant ethoxy carboxylate with a linear hydrophobic structure. This surfactant produces a high incremental oil recovery according to Berea core flood tests. The AN2NS and AN3 surfactants recovered 90% and 86% of OOIP respectively.

Keywords: *ethoxy carboxylate; hydrophilic lipophilic balance (HLB); interfacial tension (IFT); light oil; recovery; surfactant flooding.*

1 Introduction

Many oil fields are being produced with water flooding as a secondary recovery process. Water flooding can produce a final oil recovery of around 35-50% of the original oil in place, leaving some remaining oil in the reservoir. After water flooding, the remaining oil could either be residual oil from the area swept by water or by-passed oil that could not be swept by the flooding. Surfactant flooding is an enhanced oil recovery (EOR) mechanism aimed at reducing the residual oil in water-swept zones of a reservoir.

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Surfactants are usually organic compounds that are amphiphilic, meaning they are composed of a hydrocarbon chain (hydrophobic group, the ‘tail’) and a polar hydrophilic group (the ‘head’). Therefore, they are soluble in both organic solvents and in water. They adsorb or concentrate on the surface or fluid/fluid interface, altering the surface properties significantly; in particular, they reduce the surface tension or interfacial tension (IFT) [1]. Surfactants may be classified according to the ionic nature of the head group as anionic, cationic, nonionic, and zwitterionic [2].

The mechanism of surfactant flooding to improve oil recovery works by reducing the IFT to mobilize the residual oil. A low IFT can be obtained with a specific type of surfactant that is compatible with the reservoir and must also satisfy several other stringent requirements [3-5].

The hydrophilic-lipophilic balance (HLB) is one of the indicators used to characterize surfactants. This number indicates the relative tendency to solve in oil or water and thus the tendency to form water-in-oil or oil-in-water emulsions. Low HLB numbers are assigned to surfactants that tend to be more soluble in oil and to form water-in-oil emulsions. When the formation salinity is low, a low HLB surfactant should be selected [1]. The HLB value is also used as a primary designing and screening of surfactants [6]. The range of values is around 6-9 because this is roughly between W/O emulsifier and O/W emulsifier [7].

In this study the process design of surfactant flooding was investigated for application in the Tempino oil field at a temperature of 68°C. A screening method that considers the surfactant structure, the type of surfactant and the HLB was used to understand the complexities of surfactant mechanism. The information and evaluation obtained from the HLB value and the IFT test was then used to design and optimize the formulation of surfactant for the Tempino field. A laboratory test was described by Levitt, *et al.*, which starts with the characterization and screening of surfactants and then advances to core flood testing with the best formulations [8,9]. These techniques were built on information from previous research. It was stated that a well-established relationship exists between the micro-emulsion formation, phase behavior and IFT. It is common in the industry to screen surfactants and their formulation for low IFT through laboratory-based oil/water phase behavior testing [10].

2 Experimental Procedure

In this study, an experiment was performed to analyze the relationship between the characteristics of the surfactant, phase behavior and IFT, and to analyze their influence on the oil recovery by using a surfactant with low IFT through a core flood system. All of the experiments were done using brine and oil from the Tempino field and the Berea core. The characteristics of the oil and brine from the Tempino field are shown in Table 1 and 2.

Table 1 Characteristics of oil from Tempino field.

The characteristics of oil from Tempino Field	Tempino (TPN) oil value
SARA:	
Saturated	71.60 %
Aromatics	25.49 %
Resins	2.14 %
Asphaltenes	0.78 %
EACN (Equivalent Alkane Carbon Number)	8.29
TAN (Total Acid Number)	-
Viscosity	0.90 cP (66°C)
API Gravity	42

Table 2 Characteristics of brine from Tempino field.

Analysis Parameter	Tempino Brine Value
TDS (ppm)	15540
Salinity (ppm)	8670
pH	8.571
Na^+ (ppm)	3906
K^+ (ppm)	21.22
Ca^{2+} (ppm)	78.96
Mg^{2+} (ppm)	109
Cl^- (ppm)	5244
CO_3^{2-} (ppm)	411
SO_4^{2-} (ppm)	30.66
Total Organic Carbon (TOC) (ppm)	999

2.1 Surfactant Characterization

The chemical structure of the surfactant was determined by using FTIR (Fourier Transform Infra Red) spectroscopy, NMR (Nuclear Magnetic Resonance) spectroscopy and mass spectroscopy (MS). The results from this analysis indicate the type and structure of the surfactant.

2.2 HLB calculation

The HLB is determined by calculating values for the different regions of the molecule, as described by Griffin [11,12]. Other methods have been suggested, notably by Davies [13]. Griffin's equation to calculate HLB for nonionic surfactants is

$$HLB = 20MW_h/MW \quad (1)$$

where MWh is the molecular mass of the hydrophilic portion of the molecule and MW is the molecular mass of the whole molecule, giving a result on an arbitrary scale of 0 to 20. An HLB value of 0 corresponds to a completely hydrophobic molecule and a value of 20 corresponds to a molecule made up completely of hydrophilic components. The HLB value can be used to predict the following surfactant properties:

1. A value from 0 to 3 indicates an antifoaming agent.
2. A value from 4 to 6 indicates a W/O emulsifier.
3. A value from 7 to 9 indicates a wetting agent.
4. A value from 8 to 18 indicates an O/W emulsifier.
5. A value from 13 to 15 is typical of detergents.
6. A value of 10 to 18 indicates a solubilizer or hydrotrope.

In 1957, Davies suggested a method for calculating a value based on the chemical groups of the molecule. The advantage of this method is that it takes into account the effect of strongly and less strongly hydrophilic groups. The equation is

$$HLB = 7 + mH_h\text{-}nH_l \quad (2)$$

where m is the number of hydrophilic groups in the molecule, H_h is the value of the hydrophilic groups, n is the number of lipophilic groups in the molecule, and H_l is the value of the lipophilic groups. For ethoxylated amphiphiles, the HLB is one-fifth the weight of the ethylene oxide portion of the molecule [14].

2.3 Solubility Test

Precipitation during flooding has to be avoided in order to guarantee the performance of the process. Therefore good solubility of the surfactants at the reservoir temperature and salinity is essential. All solubility tests were performed with a total dissolved salinities value of 15000 ppm and a temperature of 68°C at reservoir conditions. If no precipitate was formed within 2 days, the surfactants were used for further investigation.

2.4 Phase Behavior Test

Phase behavior studies were performed to assess the potential of each surfactant sample at the salinity and temperature of the Tempino field. The surfactants were dissolved in Tempino brine. 10 ml of oil was added to 10 ml of the surfactant solution. The samples were mixed in small 5 ml pipettes and the top of the pipettes was sealed using a flame. The formation of microemulsion was observed visually to look for the Winsor type III phase at 68°C. The phase behavior of microemulsion can be divided into three classes: lower-phase microemulsion, upper-phase microemulsion and middle-phase microemulsion, called Winsor type III. Figure 1 illustrates the relationship between salinity and phase behavior.

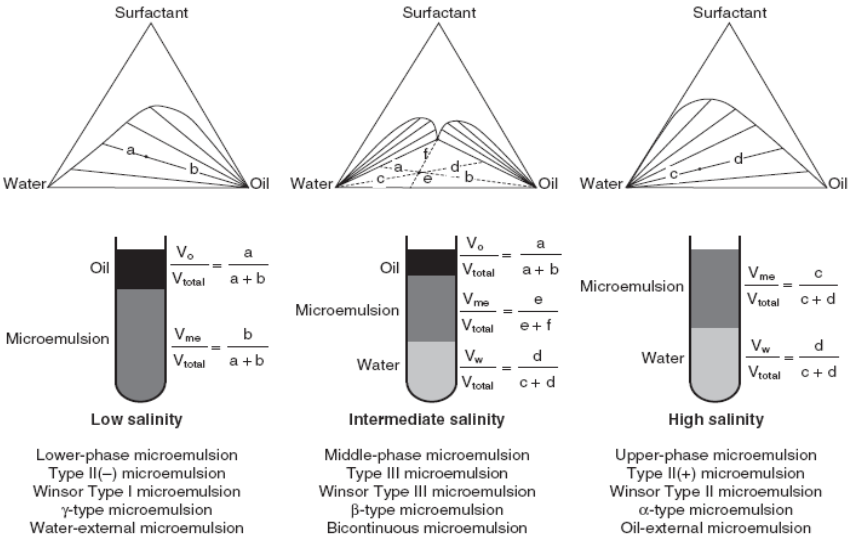

Figure 1 Three Types of Microemulsion and the Effect of Salinity on Phase Behavior [1].

2.5 IFT Test

The IFTs were measured using a TX 500C spinning drop tensiometer. The surfactants were added to the brines in a concentration of 2% w/w. The surfactant solution was brought into contact with the oil phase. IFT values were measured during 30 minutes. The average IFT value was taken as the result. Equilibration and measurement were performed at 68°C, which is the Tempino field temperature.

2.6 Core Flooding

The coreflooding system was set vertically to obtain oil recovery after injecting surfactant into the core. A syringe pump with 50-ml syringe was used to inject the fluids (brine, oil, and surfactants). A nitrogen pump was used to maintain the confining (overburden) pressure inside the core holder. To establish the required reservoir condition, the heated mantel around the core holder was used that was connected to a temperature controller. The effluent fluids were collected in a small 5 ml tube and the amount of the recovered oil was measured.

3 Result and Discussion

3.1 Surfactant Characterization

In this study, we have examined 30 samples of surfactants, which were provided by several domestic commercial suppliers and from suppliers outside Indonesia. The collected surfactants are classified as ethoxylates, carboxylate, sulfate, sulfonate, and ethoxycarboxylate (Table 3). The hydrophilic-lipophilic balance (HLB) value can be estimated from the structure of each surfactant. By determining the HLB value, the interaction strength between the head group with the brine and the tail group with the oil may be inferred. For a low IFT, an equal interaction strength between the head group with the brine and the tail group with the oil is needed [15].

Table 3 Samples of Surfactant.

Samples of Surfactant	Structure of Chemical	Type of Surfactants	Hydrophilic	Hydrophobic
9B	Derivative palm oil ethoxylate	Nonionic	ethoxylate	linear olefin
9Bl1	Blending of palm oil ethoxylates	Blending Nonionic	ethoxylate	linear
9BNS	Derivative palm oil ethoxylate	Nonionic	ethoxylate	linear
AN1	Blending ethoxylate and ethoxy-carboxylate	Nonionic + Anionic	ethoxy-carboxylate	linear
AN2	Blending ethoxylate and ethoxy-carboxylate	Nonionic + Anionic	ethoxy-carboxylate	linear
AN3	Blending ethoxylate and ethoxy-carboxylate	Nonionic + Anionic	ethoxy-carboxylate	linear
AN4	Blending ethoxylate and ethoxy-carboxylate	Nonionic + Anionic	ethoxy-carboxylate	linear
AN1NS	Blending ethoxylate and ethoxy-carboxylate	Nonionic + Anionic	ethoxy-carboxylate	linear
AN2NS	Blending ethoxylate and ethoxy-carboxylate	Nonionic + Anionic	ethoxy-carboxylate	linear

Samples of Surfactant	Structure of Chemical	Type of Surfactants	Hydrophilic	Hydrophobic
AN4NS	Blending ethoxylate and ethoxy-carboxylate	Nonionic + Anionic	ethoxy-carboxylate	linear
21	Branched alkyl sulfate	Anionic	sulfate	branch
9A	Derivative palm oil ethoxylate	Nonionic	ethoxylate	linear
9F	Derivative palm oil ethoxylate	Nonionic	ethoxylate	linear
9G	Derivative palm oil ethoxylate	Nonionic	ethoxylate	linear
9Bl2	Blending of palm oil ethoxylates	Nonionic	ethoxylate	linear
9D2	Derivative palm oil ethoxylate	Nonionic	ethoxylate	linear
24B	Coconut oil ethoxylate	Nonionic	ethoxylate	saturated, unsaturated
C	Internal olefin sulfonate C19-23	Anionic	sulfonate	olefin
5	Sodium alkyl benzene sulfonate	Anionic	sulfonate	linear, aromatic
20	Branched alkane sulfonate	Anionic	sulfonate	branch
22	Branched alkyl sulfosuccinate	Anionic	sulfosuccinate	branch
5A	Derivative sodium alkyl benzene sulfonate	Anionic	sulfonate	linear, aromatic
5B	Derivative sodium alkyl benzene sulfonate	Anionic	sulfonate	linear, aromatic
31B	Derivate of benzene sulfonate	Anionic	sulfonate	linear, aromatic
31C	Derivate of benzene sulfonate	Anionic	sulfonate	linear, aromatic
31D	Derivate of benzene sulfonate	Anionic	sulfonate	linear, aromatic
31E	Derivate of benzene sulfonate	Anionic	sulfonate	linear, aromatic
13	Polynaphtalene sulfonate	Anionic	sulfonate	aromatic
19	Linear olefin sulfonate	Anionic	sulfonate	linear olefin
27	Carboxylates surfactant	Anionic	carboxylate	Linear

The HLB value was computed using empirical approaches, i.e. by two methods, proposed by Davies and Griffin respectively. By using Davies' method, the HLB was computed to give values ranging from 1.5 to 38.1, while Griffin's method yielded an HLB from 3.3 to 11.7 (on a scale of 0 to 20). The results from both methods are shown in Table 4. The value of IFT is shown in Table 5.

Table 4 Calculation of HLB.

Samples of Surfactant	DAVIES		GRIFFIN		HLB	
	mH_h	nH_l	MW_h	MW	Davies	Griffin
9B	10.4	14.725	325	564	2.7	11.5
9Bl1	10.4	14.725	325	564	2.7	11.5
9BNS	10.4	14.725	325	564	2.7	11.5
AN1	11.2	14.725	353	592	3.1	11.7
AN2	11.2	14.725	353	592	3.1	11.7
AN3	11.2	14.725	353	592	3.1	11.7
AN4	11.2	14.725	353	592	3.1	11.7
AN1NS	11.2	14.725	353	592	3.1	11.7
AN2NS	11.2	14.725	353	592	3.1	11.7
AN4NS	11.2	14.725	353	592	3.1	11.7
21	38.7	7.6	96	321	38.1	6
9A	10.4	14.725	325	564	2.7	11.5
9F	10.4	14.725	325	564	2.7	11.5
9G	10.4	14.725	325	564	2.7	11.5
9Bl2	10.4	14.725	325	564	2.7	11.5
9D2	10.4	14.725	325	564	2.7	11.5
24B	10.4	15.2	325	578	2.2	11.3
C	11	9.975	81	376	8.0	4.3
5	11.2	14.725	353	592	9.9	4.9
20	11	7.6	81	306	10.4	5.3
22	15.5	7.6	198	423	14.9	9.4
5A	11	8.075	81	320	9.9	5.1
5B	11	8.075	81	320	9.9	5.1
31B	11	8.075	81	320	9.9	5.1
31C	11	8.075	81	320	9.9	5.1
31D	11	8.075	81	320	9.9	5.1
31E	11	8.075	81	320	9.9	5.1
13	22	9.5	162	414	19.5	7.8
19	11	7.6	81	306	10.4	5.3
27	2.1	7.6	45	270	1.5	3.3

Table 5 IFT Measurements.

Samples of Surfactant	**HLB**		**IFT (mN/m)**
	Davies	**Griffin**	
9B	2.7	11.5	0.0019
9Bl1	2.7	11.5	0.0021
9BNS	2.7	11.5	0.0034
AN1	3.1	11.7	0.0037
AN2	3.1	11.7	0.0079
AN3	3.1	11.7	0.0011
AN4	3.1	11.7	0.0021
AN1NS	3.1	11.7	0.0038
AN2NS	3.1	11.7	0.0018
AN4NS	3.1	11.7	0.0034
21	38.1	6	0.0485
9A	2.7	11.5	0.0529
9F	2.7	11.5	0.0529
9G	2.7	11.5	0.0354
9Bl2	2.7	11.5	0.0337
9D2	2.7	11.5	0.0119
24B	2.2	11.3	0.0559
C	8.0	4.3	0.0485
5	9.9	4.9	0.4170
20	10.4	5.3	0.5160
22	14.9	9.4	0.1640
5A	9.9	5.1	0.4170
5B	9.9	5.1	0.4960
31B	9.9	5.1	0.2460
31C	9.9	5.1	0.2450
31D	9.9	5.1	0.3160
31E	9.9	5.1	0.3470
13	19.5	7.8	12.9400
19	10.4	5.3	1.8000
27	1.5	3.3	1.0100

In the case of Tempino oil and brine, the optimum HLB value is between 2.7 and 3.1 (on Davies' Scale), where the IFT is the lowest (Figure 2). In this HLB range, the water-surfactant interaction and oil-surfactant interaction are approximately equal, which produces the lowest interfacial tension. At HLB values greater than 3.1, there is less water-surfactant interaction than oil-surfactant interaction. Conversely, at HLB values smaller than 2.7, water-surfactant interaction is greater than oil-surfactant interaction. This observation deviates from Davies' proposal, where an equal interaction between water-surfactant and oil-surfactant is expected at an HLB of about 7.

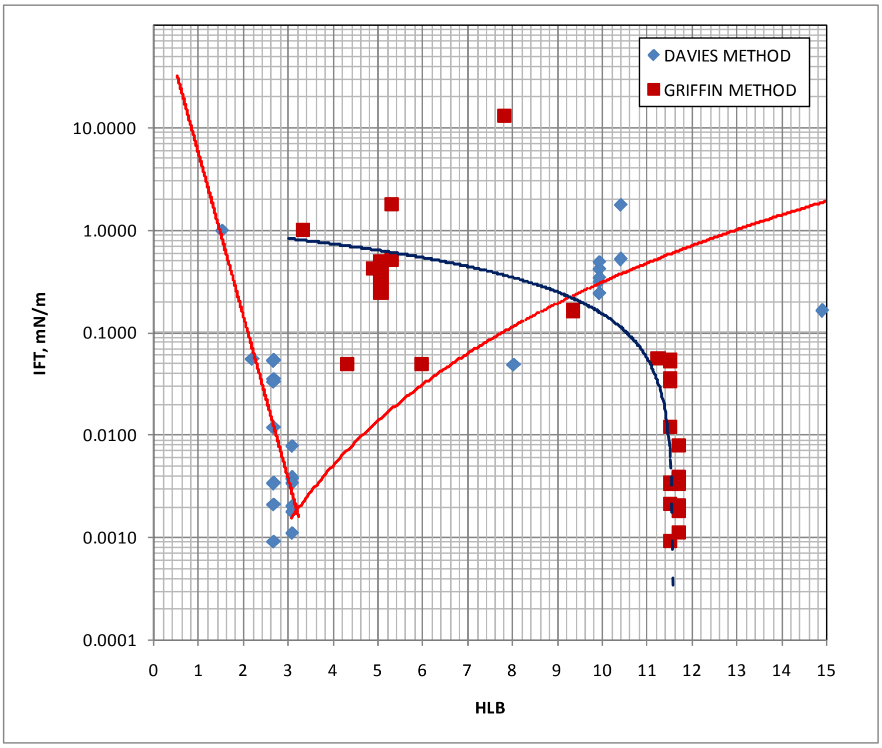

Figure 2 Plot HLB versus IFT.

On Griffin's scale, the lowest HLB occured at about 11.7. This is relatively close to the expected value of 10 obtained from Griffin's formula for the balance of hydrophilic and lipophilic groups. However, the balance value of 10 is roughly approximate, as it is only based on the surfactant properties and it does not consider the properties of brine and oil.

Base on the results above, Griffin's formula may be used as an indicator for surfactant formulation. Meanwhile, further modification and calibration is needed for Davies' formula to be used for the same purpose.

3.2 Solubility and Phase Behavior Test

All surfactant samples gave a one-phase solution when mixed with reservoir brine. Furthermore, all samples were tested for their compatibility with reservoir oil by conducting a phase behavior test. It can be shown that a surfactant sample can form microemulsion of Winsor type III (Table 6), but there are several surfactants that show an increasing microemulsion viscosity and form a turbid solution at the water phase from visual observation. This can be caused by the hydrophobic group having a linear straight chain so the micelles formed are very compact and rigid.

Table 6 Observation of Phase Behavior.

Samples of Surfactant	Structure of Chemical	Aqueous Stability	Phase Behavior	Viscosity of Emulsion
9B	Derivative palm oil ethoxylate	One Phase	Type III	Not Viscous
9Bl1	Blending of palm oil ethoxylates	One Phase	Type III	Not Viscous
9BNS	Derivative palm oil ethoxylate	One Phase	Type III	Not Viscous
AN1	Blending ethoxylate and ethoxy-carboxylate	One Phase	Type III	Viscous
AN2	Blending ethoxylate and ethoxy-carboxylate	One Phase	Type III	Not Viscous
AN3	Blending ethoxylate and ethoxy-carboxylate	One Phase	Type III	Viscous
AN4	Blending ethoxylate and ethoxy-carboxylate	One Phase	Type III	little Viscous
AN1NS	Blending ethoxylate and ethoxy-carboxylate	One Phase	Type III	Not Viscous
AN2NS	Blending ethoxylate and ethoxy-carboxylate	One Phase	Type III	Not Viscous
AN4NS	Blending ethoxylate and ethoxy-carboxylate	One Phase	Type III	Not Viscous
21	Branched alkyl sulfate	One Phase	Type III	Not Viscous
9A	Derivative palm oil ethoxylate	One Phase	Type III	Viscous
9F	Derivative palm oil ethoxylate	One Phase	Type III	Not Viscous
9G	Derivative palm oil ethoxylate	One Phase	Type III	Not Viscous

Samples of Surfactant	Structure of Chemical	Aqueous Stability	Phase Behavior	Viscosity of Emulsion
9Bl2	Blending of palm oil ethoxylates	One Phase	Type III	Not Viscous
9D2	Derivative palm oil ethoxylate	One Phase	Type III	Viscous
24B	Coconut oil ethoxylate	One Phase	Type III	Not Viscous
C	Internal olefin sulfonate C19-23	One Phase	Type III	Not Viscous
5	Sodium alkyl benzene sulfonate	One Phase	Type III	Not Viscous
20	Branched alkane sulfonate	One Phase	Type III	Not Viscous
22	Branched alkyl sulfosuccinate	One Phase	Type III	Not Viscous
5A	Derivative sodium alkyl benzene sulfonate	One Phase	Type III	Little Viscous
5B	Derivative sodium alkyl benzene sulfonate	One Phase	Type III	Little Viscous
31B	Derivate of benzene sulfonate	One Phase	Type III	Viscous
31C	Derivate of benzene sulfonate	One Phase	Type III	Viscous
31D	Derivate of benzene sulfonate	One Phase	Type III	Viscous
31E	Derivate of benzene sulfonate	One Phase	Type III	Viscous
13	Polynaphtalene sulfonate	One Phase	Type III	Not Viscous
19	Linear olefin sulfonate	One Phase	Type III	Not Viscous
27	Carboxylates surfactant	One Phase	Type III	Not Viscous

3.3 Interfacial Tension Test (IFT)

The surfactants that successfully passed the phase behavior test were evaluated by mixing them with brine and oil from the Tempino oil field. Tempino oil is a light oil with a gravity of 42 degree API. The surfactant concentration used in this study was 2% w/w. In Figure 2, the IFT values are displayed as a function of the HLB for both Davies' and Griffin's method. On Davies' scale, the surfactant samples with the lowest IFT had an HLB value of 3.1. These surfactants were AN3 and AN2NS, which have type ethoxy carboxylate and their hydrophobic group structure is linear. There were three other surfactants with an HLB of 2.7 that also yielded a low IFT (~10^{-3} mN/m). Their structure is composed of ethoxylate and linear olefin chains as hydrophobic groups (9B), a blending of ethoxylated surfactant (9Bl1), and the surfactant with ethoxylate and a linear olefins hydrophobic group but without co-solvent (9BNS). The existence of an olefin group has the effect of the surfactant tail group to interact more strongly with the oil. A low IFT is achieved at HLB values between 2.7 and 3.1. According to Davies' formula, the value should be around 7. This suggests that further calibration needs to be applied to Davies' formula in order to be used as an indicator for designing ultra-low IFT surfactants. With Griffin's method, the lowest IFT values (0.0011 mN/m and 0.0018 mN/m) were found at an HLB value of 11.7. This is somewhat closer to the value of 10 predicted by Griffin's formula.

It can be seen that the structure of surfactant that gives a low IFT value for the Tempino field is a blend of nonionic ethoxylate surfactant and anionic carboxylate surfactant with a linear chain as the hydrophobic group.

3.4 Core Flooding

The surfactant samples that gave the lowest IFT values were tested in core flood tests. In this study, the surfactant samples AN3 and AN2NS, with IFT values 0.0011 mN/m and 0.0018 mN/m respectively, were tested for core flooding using two Berea cores. Both surfactants showed good aqueous stability and had middle phase microemulsion (Winsor type III). The permeability of the Berea cores was 261.95 mD and 250.99 mD respectively. The temperature during the core flooding experiment was 68°C.

First the core was saturated by brine. Oil was then injected displacing the water until water was no longer produced. To preserve the oil saturation, the treated core was aged in oil for about 7 days at reservoir temperature. For oil recovery evaluation, the saturated core was injected with brine (waterflooding) for about 2.3 PV (pore volumes), at which no more oil was produced. The average oil recovery was 55% (Figure 3), which is a normal oil recovery by water flooding in sandstones with permeability around 250 mD.

Table 7 Recovery Factor.

Core	**Permeability (mD)**	**Porosity (%)**	**Surfactant**	**Total Recovery (%)**	
				Water Flooding	**Surfactant Flooding**
Core 1	261.95	23.41	AN2NS	53	90
Core 2	250.99	21.04	AN3	58	86

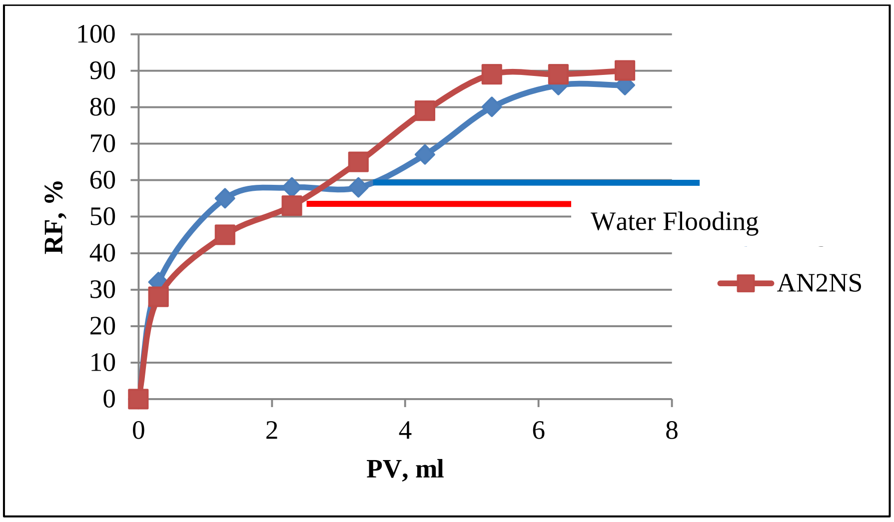

Figure 3 Plot of PV versus RF.

This was followed by continuous injection of surfactant solution for a total of 5 PV. The oil recovered during this stage was also recorded. As shown in Table 7 and Figure 2, the incremental oil recovery by the two surfactants (AN2NS and AN3) was quite high. Further examination showed that the incremental oil recovery by surfactant AN2NS (37%) was higher than the incremental oil recovery by surfactant AN3 (28%). This seems contrary to their IFT (a lower IFT value is expected to yield a higher incremental oil recovery). This can be attributed to other factors, such as core properties, that affect the oil recovery. Other mechanisms, such as the wettability effect, may need to be further investigated.

4 Conclusions

In this study, 30 samples of surfactant were compared using the HLB, phase behavior test, IFT and the core flooding test. The phase behavior tests were performed before applying the surfactant for enhanced oil recovery in order to find the optimal surfactant parameters. All of the tests were done for a surfactant concentration of 2 wt%.

The HLB values from Davies' and Griffin's methods in general showed relatively consistent behaviour for its relationship with the IFT. On Davies' scale, an ultra-low IFT was achieved at an HLB between 2.7 and 3.1. According to Davies' formula this value should be around 7, where hydrophilic and lipophilic equal balance occurs. This suggests that further calibration needs to be applied to Davies formula in order to be able to use it as an indicator for designing ultra-low IFT surfactants.

On Griffin's scale, the lowest HLB occured at about 11.7. This is relatively close to the expected value of 10 obtained from Griffin's formula for the balance of hydrophilic and lipophilic. Griffin's formula, therefore, may be used as an indicator for surfactant formulation.

Among the thirty tested samples, surfactants AN2NS and AN3 (mixes of non-ionic ethoxylate and anionic carboxylate surfactants) yielded the lowest IFT for oil-brine from the Tempino field. In the core flooding test, an injection of 2 wt% AN2NS surfactant solution into the core showed that oil recovery increased by 37% on top of waterflooding (total 90%), whereas the recovery by injecting AN3 surfactant increased oil recovery by 28% on top of waterflooding (total 86%). This significantly higher incremental oil recovery is correlable with the ultra-low IFT of the two surfactants.

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Nomenclature

MW_h = the molecular mass of the hydrophilic portion of the molecule
MW = the molecular mass of the whole molecule
m = the number of hydrophilic groups in the molecule
H_h = the value of the hydrophilic groups
n = the number of lipophilic groups in the molecule
H_l = the value of the lipophilic groups
PV = pore volume

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