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Relationship between Foam Stability and the Generated Electrokinetic Signals during FAWAG (Foam Assisted Water Alternate Gas) Processes

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Abstract: The natural pressure in hydrocarbon reservoirs is only sufficient in producing small amount of hydrocarbon at the end of the depletion stage. Therefore, in order to enhance or increase the hydrocarbon recovery, water or other fluids are injected into the formation to extract the hydrocarbon from the pore space. This common practice is known as Improved or Enhanced Oil Recovery (IOR or EOR). Foam is purposely used in some of the EOR displacement processes in order to control the mobility ratio, hence improving the volumetric sweep efficiency. The efficiency of a foam displacement process in EOR depends largely on the stability of the foam films. In laboratory, foam stability is usually measured through physical observation of the foam bubble in a glass tube. Unfortunately, this direct observation is not possible in the reservoir. Therefore, indirect measurement such as the measurement of electrokinetic signal would be a better alternative. This study aims to determine the correlation between the foam stability and the associated electrokinetic potential signals which resulted from the flowing fluid in Foam Assisted Water Alternate Gas (FAWAG) process. The investigation includes sample preparation, sample analysis, displacing fluid formation, rheological properties test, foam stability test and electrokinetic signal measurement by using NI Data Acquisition System (NIDAS). It is expected that the variations of foam bubble stability will change the pattern of the electrokinetic signals. The research findings could lead to a new approach in monitoring a FAWAG process. Application in the real field could benefit the oil and gas industry in term of making the EOR process more efficient and more economic.

Key words: Foam stability, electrokinetic signals, FAWAG, hydrocarbon

INTRODUCTION

Carbon dioxide (CO_2), nitrogen (N_2), air and hydrocarbon are common media used in gas flooding or gas injection. The primary mechanism of gas injection is focusing on sweep efficiency and gas flooding has better microscopic sweep efficiency as compared to water flooding. However, the major challenge in this type of gas injection is poor volumetric sweep efficiency. This inconvenient situation would lead to no contact between gas and a large area of hydrocarbon in reservoir (Farajzadeh *et al*., 2012). As a result, overall hydrocarbon recovery remains low.

There are several causes associated with the low recovery problem namely gravity segregation due to the large density difference between gas and oil, viscous fingering in which the more viscous oil is by-passed by less viscous gas and channelling due to gas flowing in the high permeable streaks in heterogeneous reservoir (Farajzadeh *et al*., 2012). Therefore, foam flooding or foam displacement process is a potential solution to encounter those challenges. Foams may be defined as a relatively homogeneous dispersion of gas in a foaming-surfactant solution. At some shear rates, certain foams exhibit non-newtonian fluid properties (Al-Attar, 2011).

Indirect measurement for foam stability by using electrokinetic potential is proposed in this study. The aim of the project is to find the relationship between the foam quality in the reservoir and the generated electrokinetic potentials during the displacement process. Measurement of electrokinetic potential has been previously proposed as a detecting tool for the water encroachment towards a production well (Jackson *et al*., 2012). The dynamics of electrically charged fluids such as formation or injected fluid in porous media could be measured by electrodes installed downhole (Jaafar *et al*., 2009).

Foams are always formed under dynamic conditions (Malysa and Lunkenheimer, 2008). The longevity of foam is determined by the stability of single foam films, depending on the physicochemical quantities and processes like surfactant concentration, salt concentration, adsorption kinetics and gravitational

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drainage. Other factors such as gas diffusion through foam films, surface forces, capillary pressure and mechanical fluctuations could also be significant (Salleh and Ismail, 2012; Wiggers *et al*., 2000). Both the formability and stability are the key factors to ensure high performance of recovery (Hou *et al*., 2012). It is expected that electrokinetic potential signal can be correlated with some of these parameters.

This study could reveal the correlation between the foam stability and electrokinetic potential. This correlation is based on the foam film properties and characteristics. This study is significant because it could help in monitoring the macroscopic and microscopic efficiency of an EOR process. By using electrokinetic signal, foam stability could be monitored from the surface. This will give great advantages in term of time, economy and environment.

The objectives of this study are to simulate the Foam Assisted Water Alternate Gas (FAWAG) process by using a sand pack model, to measure the changes in the electrokinetic potential as a result of the changes in the foam stability, to generate a correlation which enables the prediction of foam quality based on electrokinetic signals and to assess the effects of different reservoir and production conditions on the measurement of electrokinetic signals during FAWAG processes.

Foam Assisted Water Alternate Gas (FAWAG): Pressure in the reservoir becomes depleted after some time of hydrocarbon production, therefore EOR is the solution for this situation (Tunio and Chandio, 2012). One of the EOR techniques is by applying FAWAG process. FAWAG technique could improve sweep efficiency during gas injection while reducing Gas Oil Ratio (GOR) and maximizing hydrocarbon production rate in the production tubing (Tunio and Chandio, 2012). As mentioned earlier, foam can be used in EOR method in order to minimize the gravity overriding, viscous fingering and channelling problem. FAWAG also provides good mobility control of gas flow by delaying early gas breakthroughs (Skauge *et al*., 2002) and has come out as a new method for well flow improvement.

Foam stability: Foam is a dispersion of gas in a continuous liquid phase which volumetrically forming a fraction of foam. However, the gas phase is discontinuously organized in gas bubbles (Exerowa and Kruglyakov, 1998; Weaire and Hutzler, 1999). Besides that, foam can be generated by flowing gas in the porous medium with the presence of surfactant (Simjoo *et al*., 2011). The gas breaks into bubbles that are stabilized by the surfactant solution in a liquid phase (Holm, 1968; Schramm and Wassmuth, 1994). The formation of foam makes gas mobility become drastically decrease (Kovscek and Radke, 1994; Rossen, 1996; Zitha *et al*., 2006). Foam can be classified into three classes namely in-depth Mobility Control Foam (MCF), Blocking/Diverting Foam (BDF) or also known as injection profile improvement foam and Gas Oil Ratio (GOR) control foam (Turta and Singhal, 2002).

Structure of foam: The foam scale in bubble form is considered in this study. The bubbles connect each other by thin liquid films which are also known as foam films or lamellae. The foam films are direct with liquid phase and the neighbouring foam films via Plateau borders. These are interconnected throughout the foam channels which create a continuous liquid phase structure (Farajzadeh *et al*., 2012).

As mentioned by Bergeron *et al*. (1993) and Farajzadeh *et al*. (2008), the foam films are thin free staying layers aqueous solution surrounded by the gas from the both sides. Usually, surfactant molecules adsorb on both film sides and stabilize the film. The thickness of the foam films is only a few micro-meters but could be even only a few nano-meters based on the situation. However, for the “bulk” foam in porous media, the average bubble size exceeds the length of the system or in other words the foam can occupy more than one pore space (Kovscek and Radke, 1994; Rossen, 1996).

Farajzadeh *et al*. (2012) has describe the Plateau borders connecting the lamellae to water films wetting the rock surface. Therefore, the liquid phase becomes continuous throughout the porous formation. These wetting films on water on the rock can be stable only if the surface of the rock is hydrophilic (water-wet).

Foam injection modes: The most important factors in FAWAG process are foam placement technique in the reservoir (injection of pre-foamed foam, co-injection foam and Surfactant Alternating Gas (SAG) foam), reservoir pressure and permeability (Turta and Singhal, 1998). Therefore, in the field, the manner of foam placement is more diverse as compared to in the laboratory.

The foam placement technique is closely associated with the way by the foam is generated hence the terms of foam generation and foam injection mode are interchangeable. Generally, the foam is generated when a gas passing surfactant in aqueous solution which creates a stable dispersion of gas bubbles and lamellae trains in the liquid. There are three types of foam injection mode which are pre-foamed foam, co-injection foam and SAG foam.

Monitoring technique for FAWAG or foam stability: There are several methods in order to monitor the FAWAG process or foam stability. Basically, the data acquisitions are collected before, during and after the process. A tracer is used as one of the data collector along the FAWAG process (Blaker *et al*., 2002). Basically, the tracer have been used successfully on many oil field systems to monitor and retrieve flow parameters, inter-well formation heterogeneity such as high permeability region and inter-zone communication regime. Once the reservoir has been injected by any fluid, the tracer will monitor the injected fluid and allows important information to be retrieved. Tracer can be divided into three categories namely; radioactive, chemical and fluorescent (Abdullah *et al*., 2011).

Besides that, 3D Vertical Seismic Profiling (VSP) also may be used as a monitoring system before and after FAWAG process. The seismic is shot on the sea surface and geo-phones are placed in a well, may give sufficiently high resolution to identify gas saturation changes in the reservoir. The operation may be repeated after the foam injection is completed in an attempt to observe the changes in gas saturation (Blaker *et al*., 1999).

Simulations with a foam mechanistic simulator, STARS with in addition to conventional simulations also may be performed to establish the baseline for gas production before and after the foam (Aarra *et al*., 2002). STARS may clarify the influence of different foam parameters (Skauge *et al*., 2002). The STARS simulations indicate weak to moderate foam properties of the foam generated in the reservoir (Aarra *et al*., 2002).

A new device has been proposed for registering thin film drainage around a single foam bubble based on the increase of the electrical resistance of the draining film. Initially, a small bubble is expended inside an electrically conductive liquid bridge that is formed between two vertically aligned metallic electrodes. Then the liquid of the bridge is withdrawn at a pre-selected flow rate until rupture of the bridge or bubble system while monitoring its electrical resistance across the electrodes. The research concluded that this potential new device is suitable for assessment of foam stability with respect to coalescence. (Kostoglou *et al*., 2010). Therefore, by using the same principle, it is believed that the foam stability in FAWAG process can be monitor by using electrokinetic signal. It is estimated that the flowing of FAWAG process in the porous medium will produce an electric current and the changes of foam stability will generate different electrokinetic signal pattern.

Electrokinetic potential: Electrokinetics is the study of the phenomena where tangential electric field interacts with a charged surface immersed in electrolyte solution (Shaw, 1992; Dukhin *et al*., 1974; Lyklema, 1995). The electrokinetic effects in a porous system are defined as the movement of part of the Electric Double Layer (EDL) from the charged pore surfaces when a liquid is forced through the system. The movement of liquid through the capillaries carries a net charge (mobile part of the EDL) and it gives rise to streaming current, consequently, a potential difference (streaming potential). The electrokinetic behaviour depends on the potential at the surface of shear between the charged surface and the electrolyte solution. This potential is called the electrokinetic or zeta potential (Dukhin *et al*., 1974; Lyklema, 1995).

The electrokinetic properties of a porous medium are often determined by the mean of streaming potential measurements. In low electrolyte concentration, such as petroleum fluids, the surface conductivity will dominate streaming potential measurements and therefore any derived electrokinetic potentials (Minor *et al*., 1998). In the case of oil reservoirs, it arises from the existence of double layers involving excess charges that move under the influence the electric fields applied tangentially to the rock pore surfaces. It is possible to account for the surface conductivity by estimating the total electric conductivity by measuring the plug and bulk conductivities independently (Briggs, 1928; Minor *et al*., 1998; Alkafeef and Alajmi, 2006).

In reservoir rocks there exists a thin charged double layer at the interface between the rock matrix and the water in the pores. The matrix surface is usually negatively charged. When the water moves under a pressure gradient, an electrical current is generated. This electric current is the source of the streaming potential (Chen *et al*., 2006). Electrokinetic techniques have proven to be a valuable tool in providing direct information on charged solid or liquid interface (Alkafeef *et al*., 2007).

Generally, self-potential or spontaneous potential are divided into four which are thermoelectric, electrokinetic, redox potential and electrochemical. From the point of view of non-equilibrium thermodynamics, Electrokinetic Phenomena (EKP) are typically cross phenomena because thermodynamic forces of a certain kind create fluxes of another type. For instance, in electro osmosis and electrophoresis, an electric force leads to a mechanical motion and in streaming potential and sediment potential, an applied mechanical force produces an electric current (potential) (Delgado *et al*., 2007). Figure 1 shows that the summary of the spontaneous potential.

SP measurement technique: Logging tools employ SP technique in order to make a measurement. This

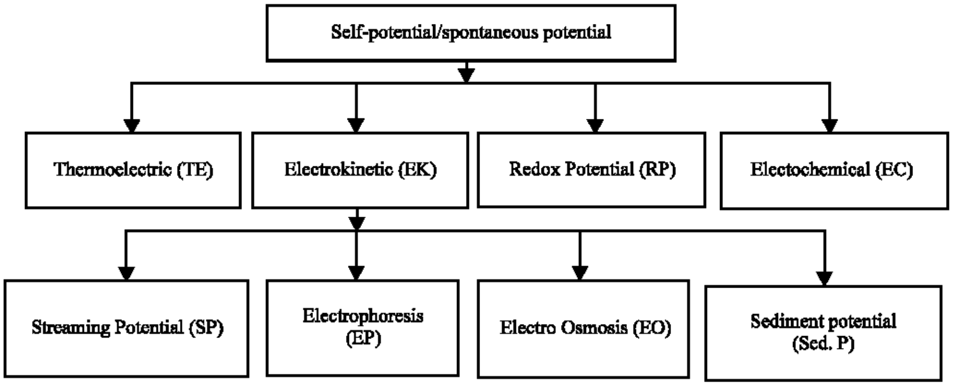

Fig. 1: Summarization of spontaneous potential

measurement is relatively simple and usually SP downhole electrode is used in the logging tools. SP can be affected by several factors that complicate the interpretation. Beside petrochemical component, SP is also affected by electrokinetic potential and bimetallism. In addition, SP is also affected by the bed thickness and true resistivity of the reservoir.

Furthermore, for the spontaneous potential during production, it can be measured by placing one probe of a voltmeter at the earth's surface (called surface electrode) and the other probe in the borehole (called downhole electrode). The electrokinetic signal produces an electric current which can be seen at the surface on the data acquisition system as a voltage data type.

MATERIALS AND METHODS

The experimental works consists of five parts which are sample and model preparation, FAWAG formulation, rheological properties test, foam stability test and electrokinetic potential signal measurement.

Foam stability test: The foam stability evaluation is used to determine the coalescence time of the foam. The foam stability of aqueous foam can be evaluated using Ross-Miles method which based on half-life measurement. The technique of air expansion will be used in order to generate foam. Tensiometer will be used with the aim of surface tension measurement.

Electrokinetic potential signal measurement: After foam is generated by using pre-foamed foam technique, two pair of non-polarizing Ag/AgCl electrodes will be installing in the foam generation model. The pressure difference across the sample will be measured using a pair of pressure transducers and the voltage across the sample will be measured using two pairs of non-polarizing Ag/AgCl electrodes. One pair of electrodes will be positioned out of the flow path, to eliminate spurious potential drift and electrode flow effects. The other pair of electrodes will be located on each face of the sand pack model. The voltage measurements will be recorded continuously at a sampling rate of 1 Hz by using National Instrument (NI) data acquisition system. This system will directly connect to the computer by using Labview software (Fig. 2).

PRELIMINARY RESULT

The experiments are performed with deionised water and Sodium Dodecyl Sulphate (SDS) solutions. Experiments are conducted using four concentrations of SDS (0.0025, 0.005, 0.0075, 0.01 and 0.0125 mL) in 100 mL deionised water. A small amount of NaCl (4×10^{-3} M) is added to the deionised water to yield the ionic strength that is met in applications where foams are produced from fresh water but avoiding the fouling problems created by calcium and magnesium salts. This small concentration of salt does not affect interfacial properties. During the experiments, the electrokinetic signal are recorded and stored in the NIDAS.

The experiments are conducted by using four nominal drainage rates which are 20, 50, 100 and 200 μL h^{-1}. Figure 3 shows that the foam ruptured time versus drainage rate and SDS concentration. The foam ruptured time increases with increasing SDS concentration and decreases with higher flow rate. The subsequent stability of the size of the bubble during the drainage experiments is monitored by a very sensitive differential pressure transducer which connected to the bubble via the hole in the model. The rupture time includes the effect of the resistance to film thinning (elasticity), film elongation, surfactant diffusion from the bulk through the film and the rupture

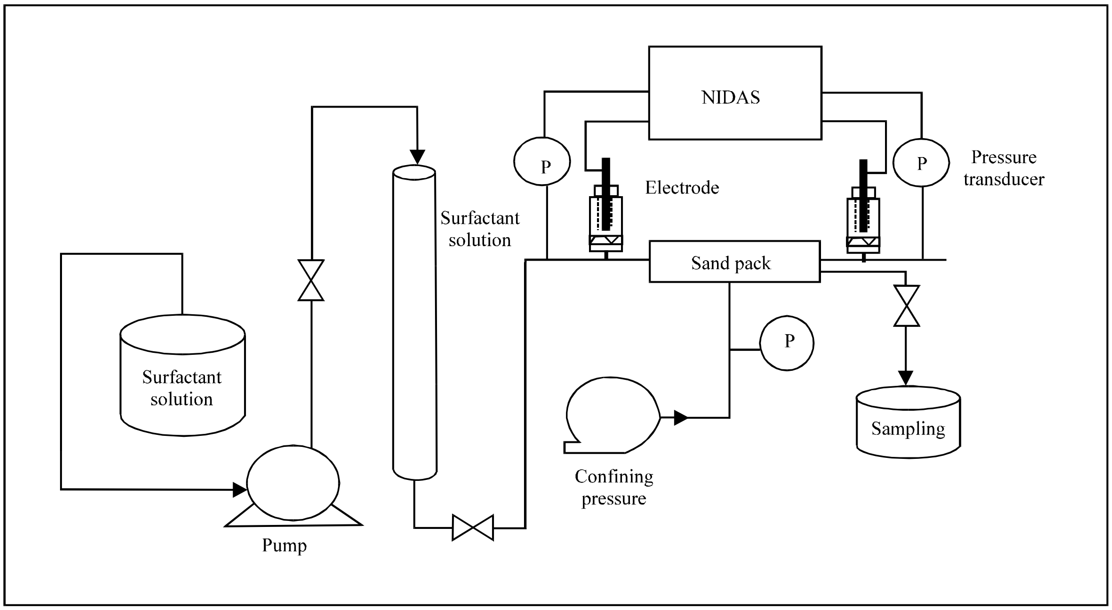

Fig. 2: Schematic diagram for experimental set-up

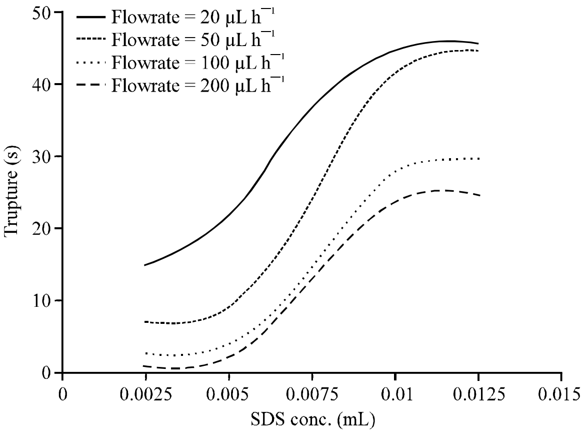

Fig. 3: Relationship between foam ruptured time and SDS concentrations with different flowrates

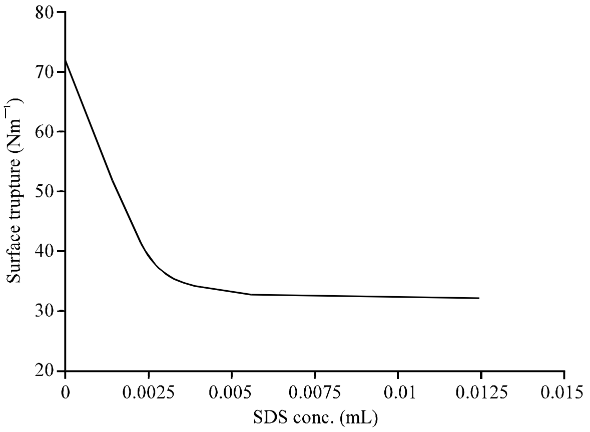

Fig. 4: Relationship between surface tension of foam and SDS concentration

driving force. Higher surfactant concentrations lead to the appearance of elasticity at thicker films (Kostoglou *et al.*, 2010).

Equilibrium surface tension is measured by the tensiometer. The surface tension of the foam formulation is presented Fig. 4. The surface tension of foam decreases with increasing surfactant solution. In this situation, surfactant acts in two ways in the process which are by reducing the equilibrium surface tension and by stabilizing the resulting thin film through the Gibbs elasticity.

FUTURE WORK

In order to correlate the electrokinetic signal and foam stability during FAWAG process, the foam formulation will be flowed into the porous media model. The voltage of the solution will be measured and plotted on the data acquisition system while it is flowing in the porous media model by using different SDS concentrations.

Figure 5 shows the relationship between voltage (electrokinetic potential) and SDS concentrations. It is estimated that voltage decreases with the increases of

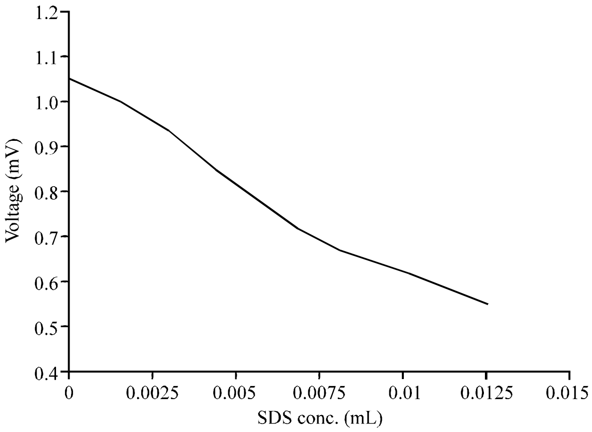

Fig. 5: Relationship between voltage and SDS concentrations

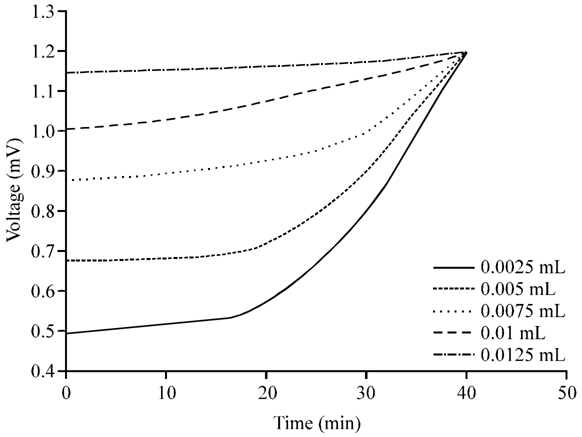

Fig. 6: Relationship between electrokinetic signal and foam stability with time

SDS solution concentration. The withdrawal of liquid from the foam cluster at a controlled flow rate generates drainage of the liquid layers between the small inner bubble and the outer bridge surface which is registered by electrokinetic potential measurements. Depending on the employed surfactant and also on the liquid withdrawal rate, one can examine the drainage of either stable or unstable inter-bubble films (Kostoglou *et al.*, 2010).

Electrokinetic methods have been extensively employed for both understanding the conductive properties of foams and for the investigation of the initial expansion and subsequent stability of various foams. Electrodes geometry or arrangement and electric current excitation frequency are the most important parameters affecting the sensitivity and accuracy of the measurements. In addition, the bubble size is estimated to affect the electrokinetic signal measurement (Kostoglou *et al.*, 2010).

Figure 6 shows that the relationship between electrokinetic potential (voltage) and foam stability (SDS concentration) during the FAWAG process in the porous media. It is estimated that the voltage decreases with the increasing of foam stability. However, when the foam solution flowing in the porous media, the foam stability start to decrease because of the instability structure of sand pack model. Each SDS concentration will give a different pattern of signal yet lastly they will lump together because all foams are converted into the liquid.

CONCLUSION

This project could present new findings in the relationship between foam stability and electrokinetic signals generated in the foam assisted water alternate gas process. This fundamental knowledge could lead to developing new approach in monitoring FAWAG process. The indirect measurement could be very useful for monitoring the efficiency of the (EOR) method in real-time. Application in the real field could benefit the oil and gas industry in term of making the EOR process more efficient and more economic. This project could also contribute to better energy and natural resources management.

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