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Correlation Study Between Streaming Potential Signal and Waterfront Progression During Water Alternate Gas (WAG) Injection

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Abstract: Spontaneous Potential (SP) is commonly measured during reservoir characterization. The SP signals are also generated during hydrocarbon production due to the streaming potential occurrence. Measurement of streaming potential has been previously proposed to detect the water encroachment towards a production well. The objectives of this study are to quantify the magnitude of the SP signal during production by WAG injection and to investigate the possibility of using SP measurements to monitor the sweep efficiency. The peak of the signal corresponds to the waterfront, where there is a change of saturation from ionic water to non-polar hydrocarbon. Similar trend is predicted in the case of WAG, where we have several interfaces between the injected water and the injected gas. This project involves numerical modeling and experimental work. Results from the experimental work will be used in the simulation work to correlate the measured SP signals with the distance of the waterfront in the WAG process. These observations suggest that WAG displacement process can be monitored indirectly from the signal acquired. Water or gas override can be detected and controlled if wells were equipped with inflow-control valves. This study is significant because monitoring the progress of water and gas in a WAG process is key in the effectiveness of this enhanced oil recovery method. Measurement of the streaming potential provides another method besides using tracers to monitor the WAG profile. Better monitoring will lead to more efficient displacement and great benefits in term of economy and environment.

Key words: Streaming potential, water alternate gas, enhanced oil recovery

INTRODUCTION

It is estimated that around 70% of the world oil production are produced from the matured oil fields. These oilfields that have been producing oil for 40 years are undergoing a declining stage. Therefore, technology development is required in order to improve and maximize the oil recovery. The best way is by applying an Enhanced Oil Recovery (EOR) method (Memon and Shuker, 2011).

Water Alternate Gas (WAG) process is a process where a gas slug is followed by a water slug and also can be referred as combined water/gas injection. WAG injection is recommended to improved gas injection sweep efficiency by using water to control the displacement mobility and also to stabilize the front. Besides that, produced hydrocarbon gas also can be re-injected into the water injection wells to improve oil production and to maintain the reservoir pressure or pressure maintenance. WAG injection process has become an imperative method in EOR throughout the suitable fields/reservoirs because it is capable to control gas fingering and also enhance the vertical sweep efficiency (Memon and Shuker, 2011).

However, WAG process need to be monitor to prevent viscous fingering which can lead to early breakthrough. Tracer have been used successfully to monitor and retrieve flow parameters, inter-well formation heterogeneity such as high permeability region and inter-zone communication regime. By using the tracer system, the understandings of fluid flow and WAG injection efficiency have been improved. Tracers are best describes as a unique reservoir compatible species that is foreign to the system. 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 which namely as radioactive, chemical and fluorescent (Abdullah *et al*., 2011). However, by using tracer, it takes too long to get the data. Thus, the alternative method to monitor WAG process is by using streaming potential measurement.

In the exploration and production segment of the oil industry, streaming potential is usually encountered as a component of the Spontaneous Potential (SP) log. The electromotive force measured by the SP log arises mainly from two types of phenomenon, electrokinetic and electrochemical (Doll, 1949). Although, the

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electrochemical component is generally considered to be dominant phenomenon (Wyllie, 1949), the electrokinetic or streaming potential component is sometimes important. Streaming potentials in porous media arise from the electrical double layer which can forms at solid-fluid interfaces (Hunter, 1981). Streaming potential measurements have been proposed as a method to characterize flow in fractures, adjacent to a borehole and the pressure response of a reservoir during transient production test (Jaafar *et al*., 2009). However, this research will be focused on the use of the streaming potentials to detect and characterize water and gas encroaching on a well during production.

The objectives of this study are to quantify the magnitude of the streaming potential during production by WAG process, to correlate the measured SP signals with the distance of the waterfront in the WAG process and to monitor water encroachment on intelligent well and sweep efficiency during WAG process.

WATER ALTERNATE GAS (WAG) PROCESS

Since, 1950, the use of carbon dioxide for improving oil recoveries in petroleum reservoirs has been investigated. It is not surprising that the idea of using CO_2 to remove oil from underground reservoir is becoming more popular as carbon dioxide is one of the most plentiful and useful compounds on the planet (Holm, 1982). Hence the use of CO_2 for enhanced oil recovery becomes popular.

The major advantages of CO_2 miscible process are low MMP (Minimum Miscibility Pressure), swelling of reservoir oil and the reduction in viscosity of reservoir oil. Despite the advantages of CO_2 flooding, the poor sweep efficiency and high operation cost are two main disadvantages of using CO_2. The poor sweep efficacy results in the early breakthrough of gas. The low viscosity of CO_2 compared to reservoir oil causes viscous fingering that results in early breakthrough. The operation cost of CO_2 flooding is high compared to the oil price. Therefore, controlling the mobility of CO_2 to improve sweep efficiency and incremental oil recovery is a solution to reduce the unit costs of incremental oil due to CO_2.

The main problems affecting the effectiveness of CO_2 WAG process are early breakthrough, gravity segregation, viscous fingering, heterogeneity effects and phase behaviours (Stone, 1982), hence resulting in poorer sweep efficiency and therefore inefficient oil recovery. Consequently to improve WAG process, breakthrough and viscous fingering should be controlled. A schematic of typical CO_2 WAG flooding process by alternate water and CO_2 is presented in Fig. 1.

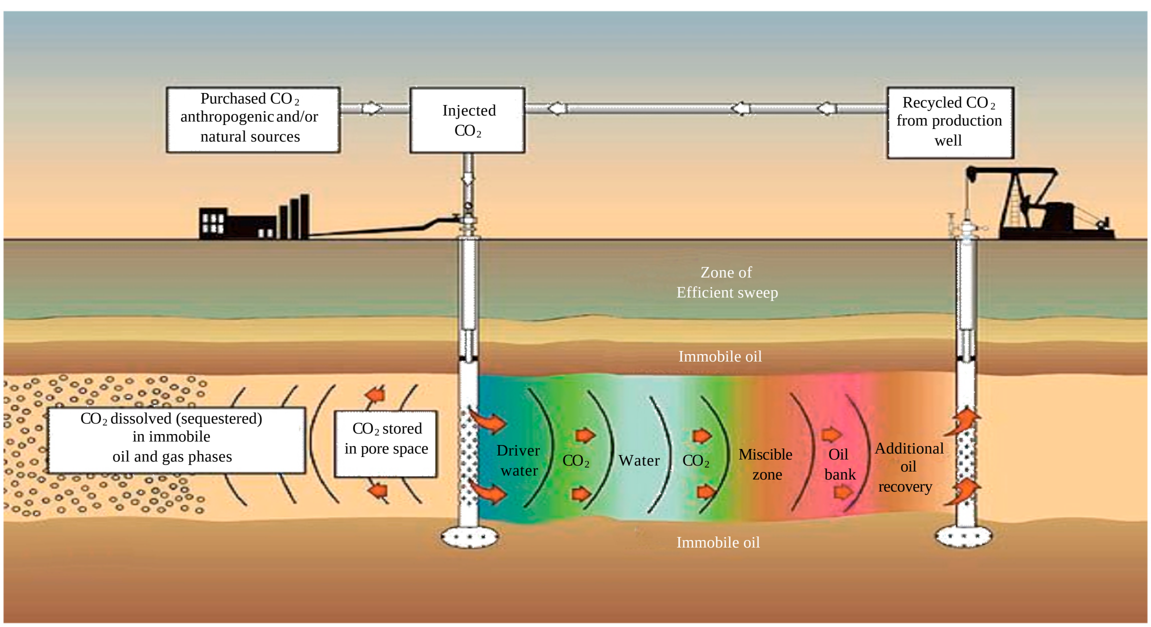

Fig. 1: Schematic of typical WAG injection (ARI and Melzer Consulting, 2010)

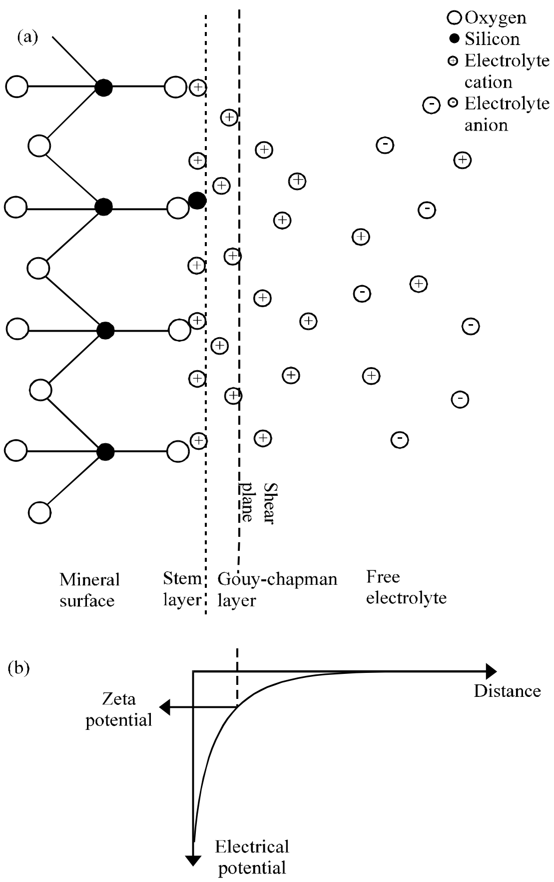

Fig. 2 (a-b): Electrical double layer formed at a mineral-fluid interface (Jackson *et al*., 2005)

THEORY OF THE ELECTOKINETIC POTENTIAL

The presence of the electrical double layer at the solid-fluid interface will resulted eletrokinetic phenomenon in fluid saturated rocks as shown in Fig. 2. The mineral surfaces become electrically charged when surface molecules undergo amphoteric reactions with the adjacent fluid. The surface becomes positively charge if the fluid pH values less than that of the point of zero charge of the mineral. Adjacent to the mineral surface is a layer of adsorbed counter-ions in the fluid, which have an opposite charge to that of the surface, termed Stern layer. These ions are attached to the mineral surface and immobile. However, there is an excess of counter-ions in the fluid adjacent to the Stern layer which are mobile; this is termed the diffuse or Gouy-Chapman layer. Within this layer, the concentration of excess counter-ions decreases away from the mineral surface until the fluid becomes electrically neutral; known as free electrolyte.

Some of the excess counter-ions within the diffuse layer are transported with the flow if the fluid is induced to flow relative to the mineral surfaces. At steady state, the advection of charge within the diffuse layer is countered by conduction of charge through the fluid and rock, if it is conductive. Thus, with an associated electrokinetic potential, a current is established. Shear plane is a closest plane to the mineral surface at which flow occurs in the diffuse layer. The potential at this plane is termed the zeta potential (Fig. 2b). The electrokinetic potential is a manifestation of this zeta potential.

ELECTROKINETIC MONITORING IN OIL FIELDS

There has been a little attention to electrokinetic phenomenon in oil fields. By using transient electrokinetic potential measurements to characterize permeability in core samples. Sprunt *et al*. (1994) were interested in the electrokinetic contribution to Spontaneous Potential (SP) log measurements. Compared to Jiang *et al*. (1998), he was suggested that electrokinetic measurements might be utilized as a hydrocarbon indicator. Electrokinetic measurements might be feasible as a permanent downhole monitoring strategy (Wurmstich and Morgan, 1994). They used numerical model techniques to simulate the electrokinetic potential measured at monitoring wells and at the surface during production.

STREAMING POTENTIALS THEORY

The electrical double layer which forms at solid (mineral)-fluid interface was created streaming potentials in porous media (Hunter, 1981). A diffuse layer in the adjacent fluid (contains an excess of countercharge) was formed when the solid surfaces become electrically charged. If more than one fluid phase is present in the pore space, additional double layers may format fluid-fluid interfaces (Jaafar *et al*., 2009). If the fluid is persuade to flow tangentially to the interface by an external potential gradient and then some excess charge within the diffuse layer is transported with the flow, giving rise to a streaming current. Streaming potential is an accumulation of charge associated with divergence of the streaming current density establishes an electrical potential.

Measurements of streaming potential by using electrodes permanently installed downhole have recently been proposed as a promising new reservoir monitoring technology (Jackson *et al*., 2005; Jaafar *et al*., 2009). There are still significant uncertainties associated with the interpretation of the measurements, particularly concerning the magnitude and sign of the streaming potential coupling coefficient at high salinity

(Saunders *et al*., 2008). Streaming potential measurements have been proposed as a method to characterize flow in the fractures adjacent to a borehole and the pressure response of a reservoir during transient production test. However, in this research will focus on the use of streaming potential measurements to detect water and gas encroaching on a well during Water Alternate Gas (WAG) process.

MONITORING WAG PROCESS

Implementation of tracer application in the reservoir system had been applied in various applications throughout the world. 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 (Abdullah *et al*., 2011). By using the tracer system, the understandings of fluid flow and WAG injection efficiency have been improved.

Tracers are best describes as a unique reservoir compatible species that is foreign to the system. 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 which namely as radioactive, chemical and fluorescent (De Melo *et al*., 2001).

Radioactive tracer is the most commonly used system in the reservoir due to low detection level. Besides that, radioactive tracer is a molecule which contains one or more atoms that are radioactive. These atoms may emit radiation in extremely low energy beta particles. This radiation can be absorbed by even thin layer of plastic to more penetrating electromagnetic gamma radiation which can penetrate into several inches of metal.

Furthermore, halogen is the most widely used in chemical tracer. Its detection level requires larger volumes as compared to radioactive tracer. Fluorescent tracer is safe and can be easily detected visually and affordable to purchase. However, this tracer can react with reservoir rock and it is limited to the noticeable fault or channel reservoir.

However, by using tracer, its take too long to know the performance of WAG process. Since, the tracer was injected to the reservoir, we need to wait the tracer solution comes out at the producer. The process takes long time to finish since we need to wait the tracer comes out from the producing well. To save the time and cost, other alternative method for monitoring the WAG process is streaming potential signals.

METHODS

The experimental system is designed for observing displacement of water and gas and measure the streaming potential signals during WAG process. The numerical system is designed to observe SP signals resulted from fluids flow during WAG process.

Experimental set-up for streaming potential measurement: Glass bead and sand pack are used as porous media. The range selected for the glass bead is 90-150 μm. The advantage of using glass beads is enhancing visual observation and providing consistent permeability and porosity (represent homogeneous reservoir). Other than that, glass beads also provide clear visual observation of displacement front. For the sand pack, it represents a heterogeneous reservoir.

The linear model is designed to simulate flow in a horizontal cross section of the reservoir. The model is made of glass which permits visual observation of the displacement behaviour. The glass will glued to the cover by using araldite glue. The model is designed in order to have a packing volume (bulk volume). To tighten the inlet and outlet, three long stainless steel rods were used to prevent leakage. Besides, mesh screens are placed at the inlet and outlet to prevent glass beads from coming out together with the fluid during injection experiments.

For the experimental set-up, the syringe pump can be used to set any desired injection rate. In addition the displacing fluids were pumped into one end of the model through injection port and the produced fluids were collected by collector tubes. The displaced fluids were displaced out through the other end of the model, collected and measured in collectors. The fluids produced are water and mixture of CO_2 and oil. Finally a refractometer was used to determine the fraction of the fluid produced. A few non-polarizing Ag/AgCl electrodes are used to measure the voltage across the model. The electrodes are installed along the WAG model. Streaming potential signals are measured by using National Instrument Data Acquisition System (NIDAS). A pair of pressure transducers will be measured the pressure differences across the WAG model and the voltage across the model will be measured by using Ag/AgCl electrodes. The experimental set-up is shown in Fig. 3.

Fluids system has to be chosen so as to avoid the necessity of a high pressure and temperature, but then each phase of reservoir fluid system must be presented by the substitute fluids. The liquid system used in this study is refined oil (paraffin), viscous water to represent oil,

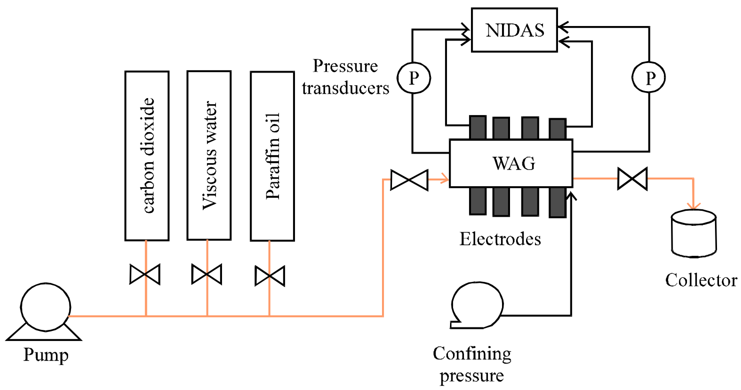

Fig. 3: Schematic diagram of WAG model with streaming potential measurements

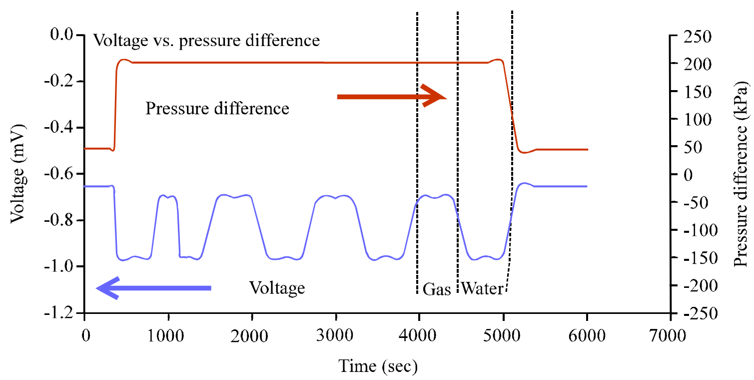

Fig. 4: Streaming potential profile. The voltage trend up and down due to the presence of water and gas

water and CO_2, respectively at reservoir condition. Scaling requirements established that the viscosity ratio and density difference of the various fluids in the model were the same as those in the reservoir. In this study, these properties of CO_2 were kept constant while the properties of water and oil were changed. The refined oil was a mixture of paraffin and kerosene. The kerosene was used to increase the viscosity of the paraffin oil. In addition, the viscous water was a mixture of glycerol and brine. The glycerol was used to increase the viscosity water and density as well. The viscosity and density for paraffin oil used are 16.8 cp and 0.81 g cc^{-1}. The desired viscosity and density of viscous water are 2.89 cp and 1.15 g cc^{-1}. The liquid system and background around the model were adjusted to have a clear visual observation. The liquid used in the study were dyed. The oil in red colour, water in green and CO_2 will be left colourless. These colours allowed visual observation of the shape of the displacement front.

PRELIMINARY RESULTS

The experiments are performed with viscous water, refined oil and carbon dioxide. Experiments are conducted by injected the viscous water and CO_2 alternately. During the experiments, the electrokinetic signal are recorded and stored in the NIDAS.

At t = 0, pressure difference and voltage are at the initial value (Fig. 2). Water is pumped at first. Since, the pumping will starts at t = 350, the pressure difference increases and stabilize at t = 800. The voltages also changes, stabilizing at the same as the pressure. Duration time from 350-800 days depends on desired of slug size. CO_2 is pumped to the model after the desired slug of water obtained. The voltage reading changes close to the initial value because gas acts as a non-polar hydrocarbon. The pressure difference remains constant since the gas was pumped. Coupling coefficient can be calculated based on the value of voltage and pressure difference. The presence of water and gas maintain the reservoir pressure. Coupling coefficient is always negative, implying that the zeta potential is negative. According to the formula given, streaming potential signal will be known. Streaming potential signals will increase in the present of water and lower in the present of gas. Figure 4 show the illustration for experimental results.

The value of streaming potential can be used to predict the ratio of water and gas that would be injected

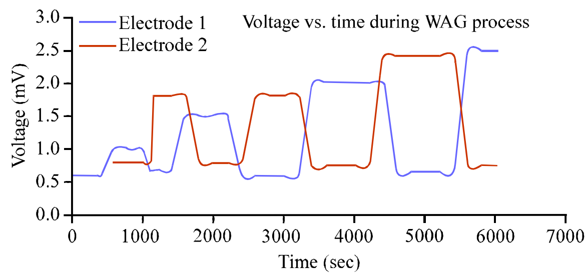

Fig. 5: Relationship between streaming potential with time

to model. So, the waterfront can be controlled and prevent early water breakthrough. Figure 5 shows the relationship between streaming potential with time. The value of voltage would be up and down when the time was increased.

FUTURE WORK

For the future work, the numerical simulation will be conducted. This study will be run by using ECLIPSE software. This simulator can be used in multiphase and EOR process, simulator will be modified in application of WAG process.

The 3D reservoir model will be based on the model used by Saunders *et al*. (2006, 2008) as a base case. The horizontal sandstone reservoir layer contains a single vertical production. This is completed over the central 80 m of the 100 m thick layer, which lies between 600 and 700 m in depth. The shales are water saturated and thus electrically conductive, but the water is immobile. The refinement of the grid around the well allows a high degree of resolution in calculating fluid flow while reducing the computational burden of modeling in a large domain.

Production from the model will be creating a shock-front-dominated displacement of oil by water and gas, reflecting the rock and fluid properties. Ahead of the shock front, oil is flowing in the presence of connate water; water at the middle shock and behind the shock front, gas is flowing in the presence of residual oil.

A waterfront approaching a production well can be detected and monitored before it arrives because the electrical potential decays slowly with distance away from the front. The potential measured at the well will increase as the distance to the water front decreases. It is because the peak of the electrical signal associated with the front moves closer. The peak signal arrives at the well at water breakthrough.

The maximum potential measured at the well will changes sharply while the water front is approximately 100 m away from the well. Water front could be detected at a significant distance from the well. The streaming potentials value will be waving since the presence of multiphase flow. The voltage decrease with the present of the gas because gas is non-polar hydrocarbon.The streaming potential value will be high when it near to the well. The peak of the potential curve will be located at the position of the advancing waterfront. The curve will be encompasses the production well when the front closer is several tons to hundreds of meters away as shown in Fig. 6.

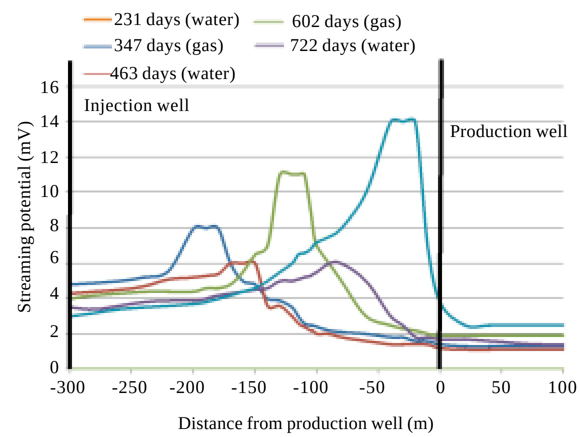

Fig. 6: Streaming potential value during WAG process

CONCLUSION

This project could present new findings in the correlation study between streaming potential signal and waterfront progression during Water Alternate Gas (WAG) process. This fundamental knowledge could lead to monitoring the progress of water and gas in a WAG process is key in the effectiveness of this enhanced oil recovery method. Measurement of the streaming potential provides another method besides using tracers to monitor the WAG profile. Better monitoring will lead to more efficient displacement and great benefits in term of economy and environment.

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