Monitoring Sweep Efficiency of Low Salinity Waterflooding in Sandstone Reservoir using Radioactive Tracer

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***Abstract*— Waterflooding is a common secondary recovery oil extraction method that can enhance oil recovery up to 45 percent overall recovery factor. Waterflooding is commonly used due to its availability, cost effectiveness and simplicity. Sweep efficiency is to determine the effectiveness of oil recovery. Radioactive tracer was introduced to get the optimum RTD model which indicate the mechanism of the system. Sweep efficiency was assumed to increase its value when low salinity brine is used as compared to seawater injection due to capillary pressure, interfacial tension and wettability. In this study, low salinity brine with value of 0.5 g/ L NaCl, 1.0 g/L NaCl and 1.5 g/L NaCl were injected into packed column. The sandstone sample were analysed using FESEM to analyse for chemical composition of rock. Sweep efficiency was analysed with and without the use of radioactive tracer. Technetium-99m (Tc-99m) radioisotope with half-life of 6 hours was injected into the column. Results from radioactive tracer test showed that the optimum RTD model for this system is perfect mixer in series with exchange model which indicate the mobilization of oil from attached fine particle. The percent oil recovery decreased with increasing brine salinity. Sweep efficiency monitored using radioactive tracer increase for lower salinity solution, LSW and 500 ppm, 39.49% and 41.36% respectively. Volumetric sweep efficiency decreases as salinity increase. This study can conclude that low salinity NaCl brine gives higher volumetric sweep efficiency.**

Keywords – Waterflooding, sweep efficiency, sandpack column, radioactive tracer.

I. INTRODUCTION

Oil recovery is typically accomplished via primary recovery, secondary recovery and tertiary recovery. Primary recovery uses natural mechanism which is the pressure that naturally exists in the reservoir to push the oil to surface. As the pressure depletes, secondary recovery is initiated, where water or gas will be injected from as the drive mechanism for oil to be displaced. The overall recovery factor for secondary recovery is about 35 to 45 % original oil in place [1].

The injection of water, also known as Waterflooding, within Malaysia fields such as Tapis and Guntong had been proven to increase the overall oil recovery [2]. Common accessibility of water, ease of connection with water, retention of hydraulic head in injection well, water that able to move through an oil-bearing formation, and efficiency of water in sweeping the oil can be counted as the factors of popularity for waterflooding [3].

Waterflooding is commonly used as secondary recovery compared to gas flooding since water is easier to control and is easily accessible. Properties of water injected to reservoir play an important role to ensure the oil can be transported to the production well. Water injection properties need to be modified depending on condition of reservoir and the type of hydrocarbon in the reservoir.

The efficiency of waterflood recovery can be evaluated from few factors including efficiency of primary recovery, connate water saturation, sweep efficiency, saturation of residual oil and crude shrinkage [4]. The efficiency may differ between sandstone and carbonate reservoir. Carbonate reservoir seems to have more complicated structure compared to sandstone reservoir [3]. Hence, by studying the effect of those factors, efficiency of waterflooding for both reservoirs can be improved from time to time depending on reservoir conditions.

To evaluate the effectiveness of the waterflooding, sweep efficiency evaluation need to be done. Sweep efficiency experiment has been conducted all around the oil and gas industry. Studies have been done using core flooding, simulation, analytical model or evaluation using substitution index [5]. There are studies on sweep efficiency waterflooding for carbonate reservoir. But the evaluation of waterflooding using radiotracer for sandstone reservoir is very limited.

Several factors will be discussed to investigate the sweep efficiency of waterflooding. Sweep efficiency is important to indicate whether trapped oil from primary recovery is displaced by the injected water or not. If the sweep efficiency for waterflooding is low, it means that the water injected to reservoir is insufficient to drive the oil towards production well.

The knowledge of the total/swept efficiency is not a simple task because the reservoirs are underground formations and therefore remote to man and conventional tools. Tracers is a tool that accesses and runs across the reservoir, contacting portions of interest and giving information about the total/swept efficiency [6].

Tracers can be divided into three types which are water based, gas based and steam based. It can be differentiate based on the function and solubility of tracers. Water based tracers can be used in waterflood, as well as enhanced oil recovery (EOR) processes such as polymer flood, ASP flood, and microbial flooding. The tracers is soluble in water and do not degrade over time [7]. Tracer is good for detecting the polymer concentration in EOR [8]. In this study, Technetium-99m (TC-99m) radioisotope was used due to its properties as a good superconductor at very low temperatures and have anti corrosive properties [9].

Low salinity water flooding (LSWF) has the advantage to improve oil recovery compared to conventional seawater injection in carbonate reservoir [5]. The chemical mechanism on low salinity water injection is affected by pH, clay minerals, wettability and polar components [10]. However, test on sandstone reservoir is still limited. Due to this, this study focuses on the use of LSWF in sandstone reservoir. By conducting this experiment, sweep efficiency can be analysed to improve the recovery of oil.

II. METHODOLOGY

A. Brine Solution

Table 1 Composition of brine

Chemical	Formation Water (FW)[11]	Sea Water (SW) [11]	Low Salinity Water (LSW)[11]	Brine in this study (NaCl)
NaCl (g/L)	28.295	11.354	1.135	0.5, 1.0, 1.5
CaCl (g/L)	0.887	0.471	0.047	-
$MgSO_4$ (g/L)	0.079	1.440	0.144	-
pH	8.62	8.35	7.03	6.10,6.39, 6.81
TDS (ppm)	29260	13265	1326.5	500, 1000, 1500

The brine solution was prepared using NaCl and reverse osmosis (RO) water based on the concentration shown in Table 1. The solutions were stirred at 350 rpm for 10 minutes at room temperature.

B. Packing of column

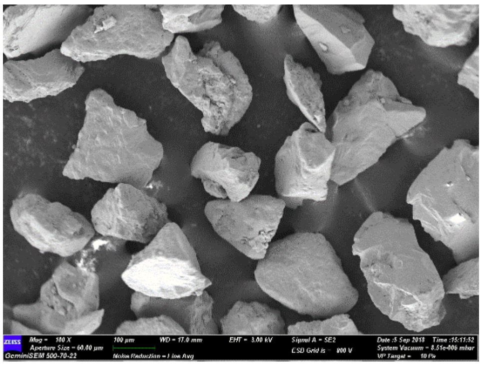

Fig. 1 FESEM result from sand samples

Sand samples collected from Pantai Bagan Lalang, Sepang, Selangor, Malaysia (2.595983,101.693319) were dried in the oven at 100^{o}C for 2.5 hours to ensure no moisture content. The sand was then sieved for size of 150 µm. Fig. 1 shows sand sample that were analyzed using FESEM to verify the composition. It consists of elements such as O, Na, Mg, Al, Si, Cl, and Fe with weight percent of 56.65, 1.74, 0.64, 1.87, 36.11, 2.34, and 0.64, respectively. The sand collected at 150 µm tray were packed into a PVC column (length = 32 cm, inner diameter = 5 cm). The sand was compacted at each interval of 10 cm using a wooden stick to ensure proper packing was achieved. The column was vacuumed for 30 minutes using a vacuum pump to ensure no air was trapped in the column. The average porosity and permeability were measured which is 41.49 cm^3/g and 3.56 mD.

C. Injection of formation water

The experimental setup is shown in Fig. 2. After the column was packed with sand with no gas left in the column, injection of formation water was done until saturation. The valve at the outlet end of the column was left open to allow any residual air to escape to the atmosphere. This is done to make sure that there was no air left in the column and the column is fully saturated with formation water.

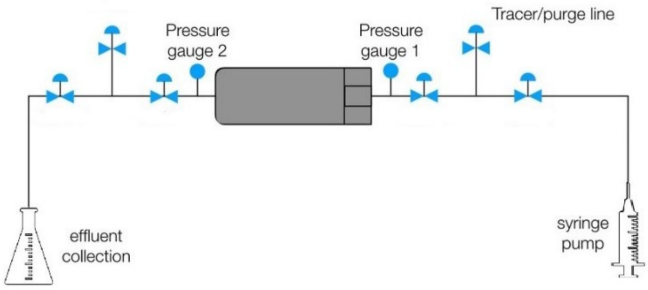

Fig. 2 Schematic diagram of sandpack column setup with radioactive tracer

D. Injection of oil

Kerosene (viscosity = 1.64 cP) was injected using a syringe pump at rate of 2 ml/min to minimize any channeling or bypass. The pumping was continued until no water (only oil) was produced at the effluent. Formation water that drained out from column was collected and measured at every interval of 20 ml to calculate the oil saturation.

E. Waterflooding

SW/LSW/NaCl brine was injected using a syringe pump at a rate of 2 ml/min to let the solution displace the oil. Injection of brine was continued until no more oil was produced at the effluent. Oil produced at effluent was collected and recorded at every interval of 20 ml to calculate the oil recovery.

F. Tracer injection

The main inlet valve was checked to ensure its closure. Radioactive isotope was injected at the tracer inlet and valve was then closed. Valve at tracer inlet was opened to flush the tracer using LSW/NaCl brine. Injection of LSW/NaCl brine began and count was started. Oil at effluent was collected and recorded for oil recovery calculation.

Result from tracer's detector was introduced in retention time distribution that can be divided into few types of model such as axial dispersed plug flow, axial dispersed plug flow with exchange, perfect mixers in series, perfect mixers in series with exchange, perfect mixers in parallel and perfect mixers with recycle [12].

Each of the model represent the system when run in RTD software and few parameters need to be considered in order to get the suitable model. Results from RTD software was compared with experimented result to get the best fit line from each different model.

G. Volumetric sweep efficiency

Volumetric sweep efficiency was used to investigate the pore volume contacted by injected fluid divided by total pore volume of a portion of reservoir interest. Volumetric sweep efficiency is affected by few aspects such as mobility ratio, gravity forces and capillary forces [3].

III. RESULTS AND DISCUSSION

A. Waterflood test

The trends of oil recovery for four different brines are shown in Fig. 3. The percent of oil recovery initially increases linearly from beginning of NaCl injected until the amount of 150 ml because NaCl injected swept the oil that previously in the column easily. Then, the oil recovery start to increase slowly and maintain the recovery since column was saturated with NaCl. Low salinity brine expands the double layer between divalent ions and oil. This allows for easier desorption of oil bearing the divalent ions to occur. The experiment done for LSW and 500 ppm were conducted with radioactive tracer until the tracer were all flushed from the column hence limit the observation of effluent, as can be seen in Fig. 3 where only the end results were obtained.

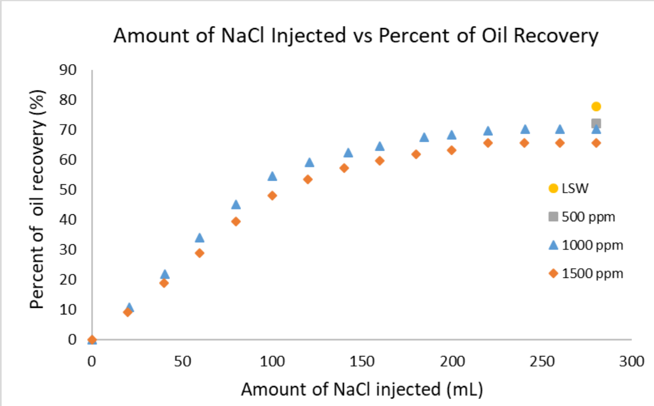

Fig. 3 Amount of NaCl injected for interval of 20 ml

The overall final oil recovery for the different brines is plotted as shown in Fig.4. The oil recovery decreases as the NaCl brine salinity increases from 500 ppm to 1500 ppm based from the effect of ion exchange [13]. However, LSW with concentration of 1326.5 ppm showed a different pattern of oil recovery from NaCl brine. This could be due to the chemical and ionic composition in the solution that lead to lesser desorption of oil from rock surface. pH of NaCl brine increases by salinity, when pH increased to more than 4, the negative charges on rock surface and brine interface increases makes the hydrophilicity of rock increases.

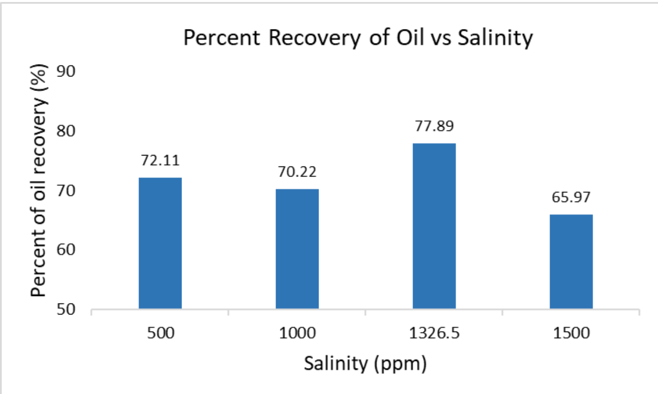

Fig. 4 Overall recovery of oil at different salinity

Sweep efficiency was calculated from the results of the experiment using radioactive tracer and is shown in Table 2. The calculation was done using the following equation:

$$\text{Drainage porous volume} = \text{Drainage area x Thickness x Porosity} \quad (1)$$

$$\text{Swept volume} = \text{Volume of peak} / 0.75 \quad (2)$$

$$\text{Swept efficiency} = \text{Swept volume} / \text{Drainage porous volume} \quad (3)$$

The sweep efficiency for 500 ppm NaCl brine is higher than LSW because present of cation type in LSW disturb the double layer expansion that changed the charge from positive to negative and the particle surfaces became strongly negative [14].

Table 2 Result of swept efficiency based on RTD results

	LSW	0.5 g/L NaCl
Salinity (ppm)	1326.5	500
Drainage area (cm^2)	19.63	19.63
Thickness (cm)	30.80	30.80
Porosity (cm^3/g)	40.04	39.99
Drainage porous volume (cm^3)	242.00	241.78
Cumulative production at peak (cm^3)	71.67	75.00
Swept volume (cm^3)	95.56	100.00
Sweep efficiency (% PV of drainage)	39.49	41.36

As shown in Fig. 5 , volumetric sweep efficiency was calculated using equation below:

$$E_V = \frac{S_W - S_{WC}}{1 - S_{WC} - S_O} \quad (4)$$

Where S_w is the average water saturation in column, S_{wc} is the irreducible water saturation and S_o is the average oil saturation in swept zone [15].

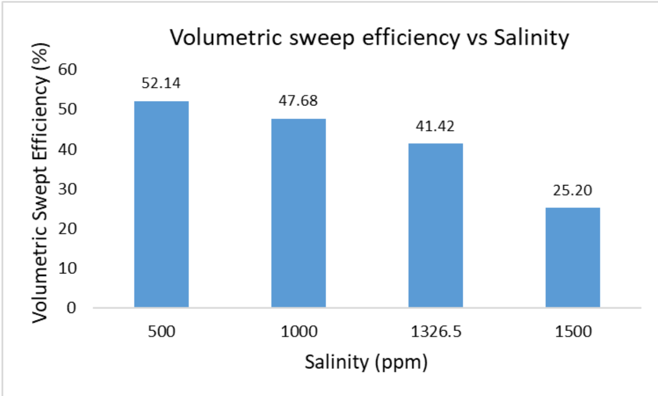

Fig. 5 Volumetric sweep efficiency of various salinity waterflooding

Fig. 5 shows volumetric sweep efficiency decreases with higher brine salinity. The sweep efficiency decreases with effect of double layer expansion. This can be proved from double layer expansion mechanism where surface charges change with decreasing brine salinity. Low brine salinity increases the detachment pressure of the oil from rock hence double layer at rock surface expand.

B. RTD Result

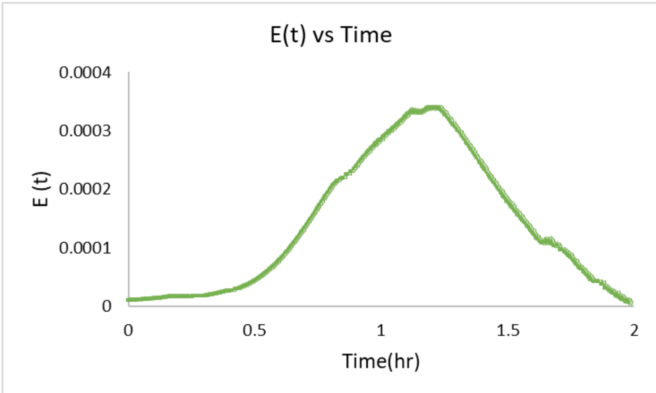

Fig. 6 E(t) vs time for LSW injection test

Data shown in Fig. 6 was gathered from detector at effluent of the column for LSW injection. Data was run in an in-house RTD software version 1 developed by International Atomic Energy Agency (IAEA) to test for suitable model that shows the reaction in the system as shown on Fig. 6 (a), Fig. 6 (b) and Fig. 6 (c). As shown below, Fig.6 (a) is result of RTD for perfect mixer in series model, Fig. 6 (b) for perfect mixer in parallel and Fig. 6 (c) for perfect mixer in series with exchange. The model with smaller number of root mean square (RMS) were chosen as the optimum model. As for LSW injection, the optimum model is perfect mixer in series with exchange with RMS of 1.5×10^{-10} as shown in Figure 6 (c).

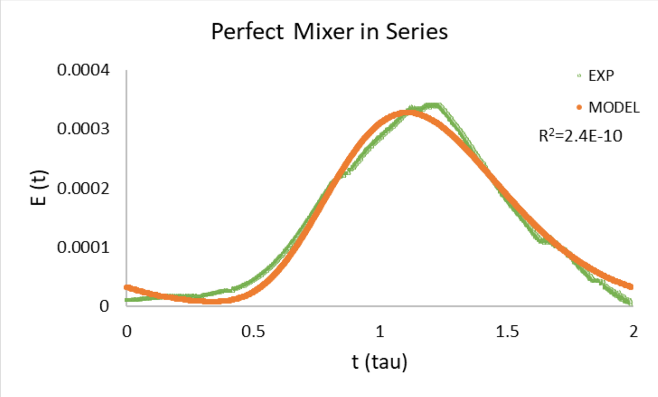

Fig. 6 (a) RTD for perfect mixer in series model

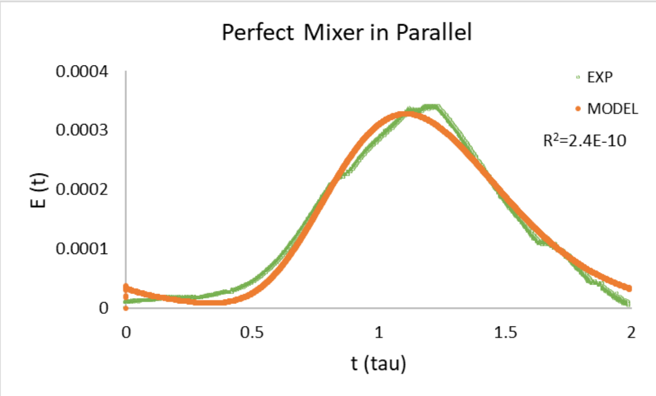

Fig. 6 (b) RTD for perfect mixer in parallel model

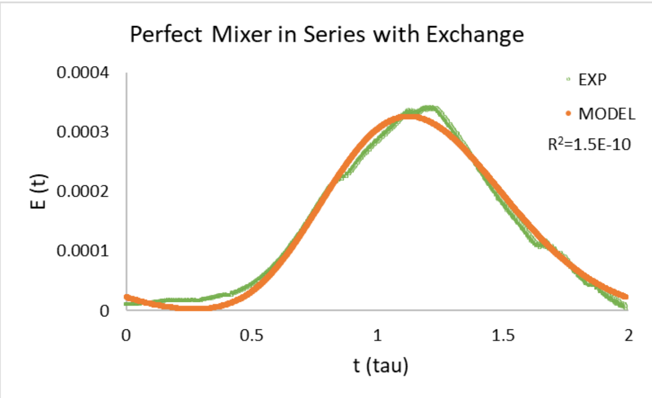

Fig. 6 (c) RTD for perfect mixer in series with exchange model

For 500 ppm brine injection, data gather as in Fig. 7. Data was extrapolated as in Fig. 8 since it has not reached its background number when the data was collected hence data should be treated. Extrapolation is required to make the tracer concentration rates go back to zero after the end of the data acquisition. This step was performed by the multiplication of the obtained data by a decaying exponential function [12]. The graph was extrapolated using $C(t)$=1547.4$e(-0.00003t)$.

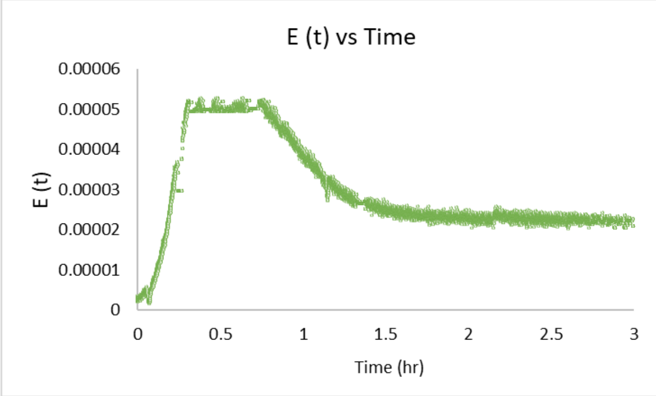

Fig. 7 Original E(t) vs time for 500 ppm

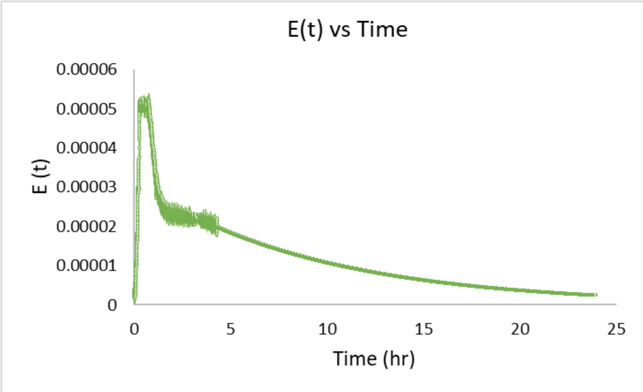

Fig. 8 Extrapolated data for 500 ppm

As shown below, Fig. 8 (a) is result of RTD modelling for perfect mixer in series and Fig. 8 (b) is for perfect mixer in series with exchange. Based on Fig. 8 (a) and Fig. 8 (b), the optimum model is perfect mixer in series with exchange with RMS of 1.87×10^{-10}. This model can be described as dispersed plug flow with exchange where the volume of oil initially in column and volume of brine injected was considered. There is exchange of liquid where oil was detached from rock surface and transport by brine injected.

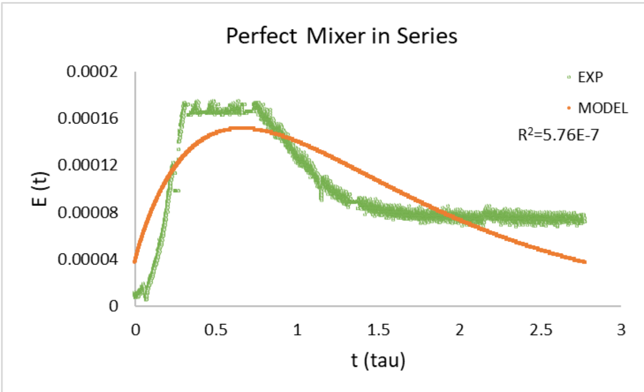

Fig. 8 (a) RTD for perfect mixer in series model

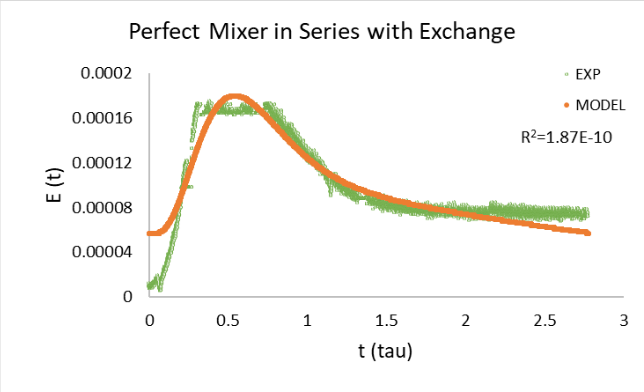

Fig. 8 (b) RTD for perfect mixer in series with exchange model

IV. Conclusion

As for conclusion, the higher the salinity of brine, the lower the oil recovery. NaCl salinity of 500 ppm showed the highest recovery as compared to 1000 and 1500 ppm. With decrease of salinity, double expansion layer is thicker hence oil was easily detached from rock surface. Therefore, the sweep efficiency decreases respectively with the increase in the brine salinities. Even though sweep efficiency monitoring is limited due to usage limitation of radioactive, result from RTD simulation can be discussed. For RTD model, this study can conclude that the system fit the perfect mixer in series with exchange model indicating the detachment of oil from rock. It is suggested future research to use gamma camera in radioactive tracer to give a clear view on how the brine is being swept, other properties such as permeability can also be determined from radioactive tracer and RTD results as compared to conventional method, arrangement of column could be changed to vertical direction for full recovery of oil, and position of pressure gauge should meet the rock surface.

ACKNOWLEDGMENT

Thank you to my supervisors, Dr. Nor Roslina Rosli and Dr. Erfan Mohammadian, for guiding me along the project. Not to forget, supervisor, Dr. Noraishah Othman, and staffs at Nuclear Agency Malaysia. Last but not least, Faculty of Chemical Engineering and Universiti Teknologi MARA for giving me this opportunity to run this project.

References

[1] P. Zitha, R. Felder, D. Zornes, K. Brown, and K. Mohanty, “Increasing Hydrocarbon Recovery Factors,” *Soc. Pet. Eng.*, pp. 1–9, 2011.
[2] S. Selamat, S. A. Samsuddin, and N. A. Halim, “SPE 145123 Evaluation and Optimization of Enhanced Oil Recovery by WAG Injection at Tapis and Guntong Fields , Malaysia,” 2011.
[3] J. Forrest F. Craig, *The Reservoir Engineering Aspects of Waterflooding*. 1971.
[4] Callaway F.H., “Evaluation of Waterflood Prospects,” 1959.
[5] E. W. Al-Shalabi and K. Sepehrnoori, “A comprehensive review of low salinity/engineered water injections and their applications in sandstone and carbonate rocks,” *J. Pet. Sci. Eng.*, 2016.
[6] M. A. Melo and A. R. Almeida, “Determining the Swept Efficiency of Waterflooding Using Tracers,” no. March, pp. 15–16, 2017.
[7] C. Laboratories, “ProTechnics,” *Protechnics*, 2015.
[8] L. Yan, T. Yin, W. Yu, L. Shen, M. Lv, and Z. Ye, “A water-soluble oil-displacing agent with tracer properties for enhancing oil recovery,” *RSC Adv.*, vol. 5, no. 53, pp. 42843–42847, 2015.
[9] E. S. Radiation, “EPA Facts About Technetium-99.” 2002.
[10] J. Da and C. Ferreira, “Master in Petroleum Technology Skule Strand Low Salinity Effect After Sea Water Flooding In Sandstone Reservoirs,” 2012.
[11] Y. Zhang, X. Xie, and N. R. Morrow, “SPE 109849 Waterflood Performance by Injection of Brine With Different Salinity f or Reservoir Cores,” 2007.
[12] H. Kasban, O. Zahran, H. Arafa, M. El-kordy, S. M. S. Elaraby, and F. E. A. El-samie, “Laboratory experiments and modeling for industrial radiotracer applications,” *Appl. Radiat. Isot.*, vol. 68, no. 6, pp. 1049–1056, 2010.
[13] H. N. Al, S. Ali, K. A. Ralph, and F. Patrick, “Sequential injection mode of high - salinity / low - salinity water in sandstone reservoirs : oil recovery and surface reactivity tests,” *J. Pet. Explor. Prod. Technol.*, no. 1, 2018.
[14] R. A. Nasralla, H. A. Nasr-el-din, and A. Texas, “Double-Layer Expansion : Is It a Primary Mechanism of Improved Oil Recovery by Low-Salinity Waterflooding ?,” no. February, pp. 49–59, 2014.
[15] Y. Fu-qing and L. Zhen-quan, “An Easy Calculation Method on Sweep efficiency of Chemical Flooding,” pp. 496–501, 2013.