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Low salinity waterflooding investigation using radioactive tracer in different sand pack configurations

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ABSTRACT

Waterflooding is a simple secondary oil retrieval method practiced worldwide to assist and improve oil recovery. Consequently, understanding the flow behavior of the injected water is essential to ensure an efficient waterflooding process. Nevertheless, literature on utilizing radiotracers to investigate fluid flow behavior in oil reservoirs is limited. The current study observed and compared horizontal and vertical fluid flows in simulated sandstone reservoirs. Low salinity water of 500 ppm sodium chloride solution was injected into vertically and horizontally sand-packed columns at a flow rate of 3.5 mL/min. Subsequently, technetium-99m radioisotopes with a half-life of six hours were injected into the columns as tracers. The residence time distribution for both setups fitted the perfect mixer in the series model. Nonetheless, the calculated sweep efficiency and overall oil recovery percentage were higher for the horizontal than the vertical configuration, demonstrating that gravitational forces affect the flow behavior of fluids in oil reservoirs.

Keywords: enhanced oil recovery; waterflooding; low salinity water; sweep efficiency; tracer

1. INTRODUCTION

The global requirement for energy increases daily and petroleum is the primary fuel that contributes to meeting the demand. Numerous oil fields are becoming mature as oil production rises, hence the requirement for enhanced oil recovery methods (Attar, 2017). Improved oil retrieval techniques target the hydrocarbons that remain untapped in formations that are either trapped in swept zones or have a low sweep efficiency. Primary oil recovery methods only recover 12 to 15% of the original oil contents (Sun et al., 2018), but secondary retrieval processes have been demonstrated to increase oil production.

Waterflooding is a secondary recovery method most commonly practiced in the petroleum industry to prolong reservoir pressure, thus stemming production decline. During the process, the properties of the injected water play an important role in producing or transporting the oil to the production wells. Injecting low salinity water (LSW) into petroleum reservoirs has been performed since the 1960s (Shalabi et al., 2014). Studies have claimed LSW injections in secondary and tertiary modes could improve oil retrieval, compared to injections with high salinity water (Aziz et al., 2020; Webb et al., 2003).

Investigations on the sweep efficiency of waterflooding have been conducted through core flooding, simulation, analytical model, and evaluation via substitution, while research on waterflooding with radiotracers for sandstone reservoirs has rarely been performed. Tracers demonstrated the overall water-oil injection pattern from a developed RTD model (Othman et al., 2020). Moreover, utilizing tracers in petroleum reservoirs is thought to aid in characterizing inaccessible rock formations (Melo and Almeida 2017). Nevertheless, employing radiotracers in the Malaysian oil and gas industry is still in its preliminary research and development phase.

The tracers utilized in previous research have mostly been water-, gas-, and steam-based. Water-based tracers, such as technetium-99m (Tc-99m) and gallium-68 (Ga-68-DOTA), were employable in waterflood and enhanced oil recovery (EOR) processes (Othman et al., 2021). The initial experience of using Ga-68 was eluting it with 0.05 M HCl for activity of 90 μCi/3 mL (0.0033GBq) and directly injecting it using pulse injection upstream of the column. Nonetheless, there was no indication of tracer arrival at the output after several hours, indicating that the sole Ga-68 behaved as a sand tracer; thus, a modification was made to the respective Ga-68 solution. Chelating it with DOTA-NHS solution transformed Ga-68 into a liquid tracer and produced satisfactory results. The activity of chelated DOTA with Ga-68 was 1.142 mCi (0.042 GBq) for 600 μL. The purity of the solution was checked using a thin layer chromatography scanner which produced 99.24% radiochemical purity, indicating a homogenous solution was produced. In this study, the radioactive solution was diluted and 766 μCi/3 mL (0.028 GBq) was injected inside the sand-packed column for the water flooding activity. A very vivid signal was retrieved at the output and RTD model analysis was carried out. The results indicated that the vertical sand-packed column behaved as a perfect mixer in the parallel model. The results described that there were two series of perfect mixers, which were arranged in parallel, whereby the primary series consisted of 17 mixers and the secondary series comprised 3 mixers. No short-circuiting or channelling was found in the model, indicating that the sand was well packed inside the column. A long tail was also not observed in the RTD curve, which indicated the absence of dead zones inside the column. Moreover, the RTD model was symmetrical which signifies that a perfect mix was achieved and the radiotracer was mixed homogeneously inside the column (Othman et al., 2021).

Tc-99m is primarily employed in nuclear medicine and proves suitable for liquid flow. The isomer, also known as nuclei, can survive for an extended period in its excited state and emits 140 keV gamma rays without beta rays before returning to its normal state (van der Velden et al., 2019). The present study focused on the injection of LSW in horizontally and vertically configured sand-packed columns to differentiate the oil recovery horizontally and vertically.

2. MATERIALS AND METHODS

2.1 Materials

The sand samples employed in the current study were acquired from Pantai Bagan Lalang, Sepang, Selangor, Malaysia. First, the samples were sieved to obtain a uniform sand particle grain size of 150 μm. Subsequently, the sand was oven-dried at 100 °C for three days to remove excess water. The sand had to be dry to ease the packing process later as well as to not interfere with the injected formation water and brine composition.

The NaCl brine (LSW) and formation water (FW) solutions in the current study were prepared at room temperature, which was the commonly employed method in previous investigation (Zhang et al., 2007). Table 1 lists the composition of the solutions.

Table 1. Composition of brine solutions

Type of solution	NaCl (g/L)	$CaCl_2$ (g/L)	$MgSO_4$ (g/L)	TDS (PPM)
Formation water (FW)	28.295	0.887	0.079	29260
Brine NaCl (LSW)	0.5	-	-	500

Note: TDS in total dissolved solids.

2.2 Sand-packed column preparation

The sand-packed columns employed in the present study were constructed from transparent polyvinyl chloride (PVC) tubes at 32-cm long and with a 5-cm interior diameter, as shown in Figure 1. The dry sand samples were then packed and compacted into the column and vigorously shaken to ensure proper packing.

2.3 Sand-packed column saturation with the formation water

The sand-compacted columns were filled with formation water until the sand was saturated and the amount of formation water injected was recorded. The columns were deemed saturated when only a few drops of formation water could be collected at the effluent end.

2.4 Sand-packed column saturation with the model oil

In the current study, the sand-packed columns were injected with kerosene (1.64 cP viscosity) as the model oil using a syringe pump at a rate of 3.5 mL/min until saturation. The oil was continuously pumped until the collected effluent contained only kerosene and the amount of oil injected was recorded. The columns were left to age overnight. The formation water was retrieved during the kerosene injection for oil saturation assessment.

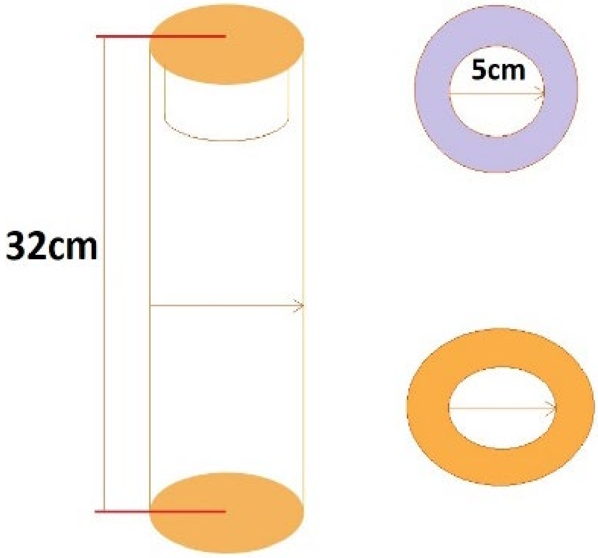

Figure 1. Sand-pack measurements

2.5 Sand-packed column waterflooding with LSW

Waterflooding evaluations were conducted to extract the oil from the sand-packed columns by injecting 500 ppm LSW with a syringe pump at a rate of 3.5 mL/min. During the assessments, the columns were set in horizontal and vertical configurations. The effluent was collected at 20 mL intervals to measure the oil recovery. The LSW was injected into the columns until the effluent procured was kerosene-free. The entire procedure was done in triplicate and the average value was taken as the response variable.

2.6 Technetium radiotracer injection

Approximately 5 mL of Tc-99m was eluded from a Mo-Tc generator. The radiotracer of activity 0.37 GBq/5 mL (10 mCi/5 mL) was injected into the columns for experimental utilizations. Subsequently, the radiotracer was injected with the brine solution at the inlet of the sand-packed column during the waterflooding assessments. Sodium iodide (NaI) scintillation detectors were placed at multiple locations around the sand-packed columns as shown in Figure 2. The parameters involved in the tests are shown in Table 2.

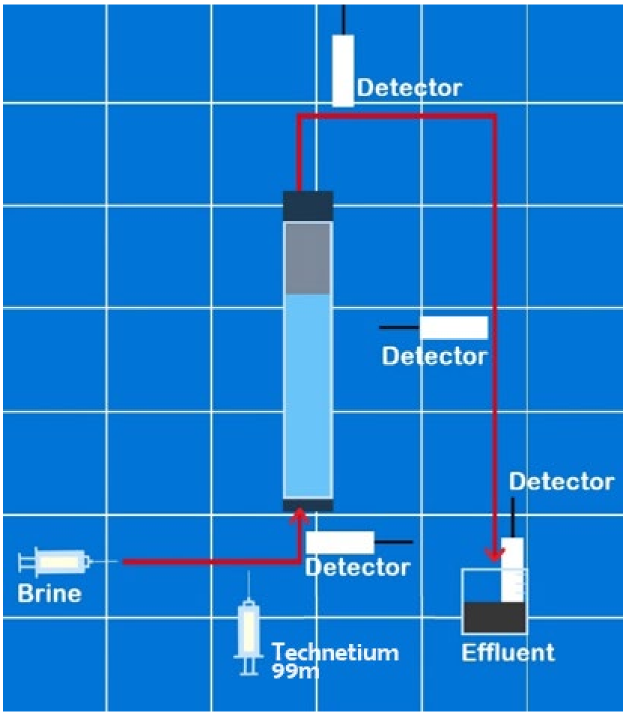

Figure 2. Radioactive setup of the sand-packed column

Table 2. The parameters with horizontally and vertically configured sand-packed columns

Parameters	Horizontal	Vertical
Flow rate, Q (mL/min)	3.5	3.5
The volume of formation water (mL)	275.5	307.9
The volume of waterflooding (mL)	515.5	635
Dose rate of Technetium tracer (μSv/h) per 1 mL	1300	120
Saturated kerosene (mL)	178.9	198

The inlet valve was shut closed when the sand column was saturated with the injected formation water. Subsequently, the brine was continuously supplied into the columns while injecting the tracer into the columns. The effluent was collected and recorded for oil recovery during the brine-tagged tracer operations. The data collected were then analyzed for retention time distribution (RTD) measurements and the construction of an RTD model. The model was analyzed with RTD software developed by the International Atomic Energy Agency (IAEA) to optimize the experimental curve. Based on the process behavior, the RTD model could provide insights into the parameters of the columns, allowing improvements in oil recovery techniques (IAEA, 2008).

2.7 Oil recovery, sweep efficiency, and volumetric sweep efficiency calculations

The oil recovery in the current study was calculated as the ratio between the extracted oil and the original amount of oil in place in the column (Equation 1).

$$Oil\ recovery = \left(\frac{extracted_{oil}}{original_{oil}}\right) \quad (1)$$

Drainage porous volume, V_{dp}

The drainage porous volume corresponded to the ratio of water drained from the column with a saturated sample to the total volume of the sample, which was determined according to Equation 2.

$$V_{dp} = D_A \times h \times \varphi \quad (2)$$

where D_A is the drainage area, h is the thickness and φ is the porosity.

Sweep volume, V_s

The sweep volume, V_S, is the volume a syringe transfers as it shifts up and down at peak volume, V_p (Equation 3).

$$\frac{V_p}{0.75} \quad (3)$$

Sweep efficiency, S_E

Equation 4 was employed to calculate the sweep efficiency in this study, which measured the effectiveness of EOR process that depended on the volume of the column.

$$Sweep\ efficiency = \frac{V_s}{V_{dp}} \quad (4)$$

where V_S and V_{dp} are the sweep volume and the drainage porous volume, respectively.

Volumetric sweep efficiency, E_v

Volumetric sweep efficiency, E_v is the volume of floodable pore volume, where the fraction of the total volume is contacted by the injected water. This is calculated using Equation 5.

$$E_v = \frac{S_w - S_{wi}}{1 - S_{wi} - S_o} \quad (5)$$

where S_w is the water saturation, S_{wi} is the irreducible water saturation, and S_o is the average oil saturation in the swept zone (Yuan and Li 2013). In petroleum engineering, S_{wi} is the ratio of the immobile water volume in the rock pore space to the pore volume of the reservoir rocks, while S_w is the ratio of the pore volume occupied by water to the pore volume of the rock (Cheng et al., 2017). The volumetric sweep efficiency is used to evaluate the estimated effect of the reservoir, which is the part of the reservoir that is not swept by the injected water (Cobb and Marek, 2003). Several factors, including mobility ratio, gravity forces, and capillary forces, have an impact on volumetric sweep efficiency (Groenenboom et al., 2003).

2.8 RTD model analysis

RTD models can describe the hydrodynamic behavior processing reactors (IAEA, 2008). The RTD is a fundamental parameter in designing reactors as it provides the period the particles reside in a particular vessel. Moreover, it provides information that enables characterizing the extent of the deviation of the particles from their ideal behavior. The RTD in the current study was calculated according to Equation 6.

$$E(T) = \frac{C(t)}{\int_0^\infty C(t)dt} \quad (6)$$

where *C(t)* represents the radiotracer concentration monitored with a scintillation detector in counts per second (cps). The detected signal was normalized by dividing it by the area under the curve.

3. RESULTS AND DISCUSSION

3.1 Oil recovery efficiency

The average percentages of oil recovered from the horizontal and vertically configured sand-packed columns are illustrated in Figure 3. The horizontal setup yielded a higher percentage of total oil recovery compared to the vertical arrangement. This might be due to gravitational forces exerting more pressure on the vertical column, hence reducing oil production. The error bars display the deviation from the maximum and minimum values that were recorded for the three replicate experiments.

The calculated parameters, leading up to the sweep efficiencies for both column configurations are summarized in Table 3. The horizontal arrangement recorded a higher sweep efficiency than the vertical configuration. The difference in values might be due to the downward gravitational force that resulted in additional resistance for the injected water to flow upwards to the trapped oil location.

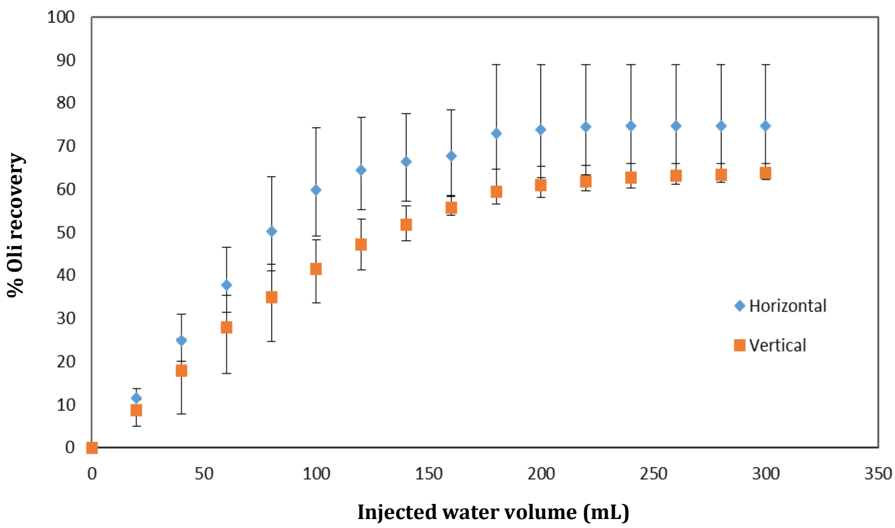

Figure 3. Percent oil recovery of horizontal and vertical configurations

Table 3. Calculated sweep efficiency for the horizontally and vertically configured sand-packed columns

Parameter	Horizontal	Vertical
Porosity (cm^3/g)	39.99	48.62
Drainage porous volume (cm^3)	242.00	293.95
Cumulative production at peak (cm^3)	75.00	62.00
Swept volume (cm^3)	100.00	82.67
Sweep efficiency (% PV drainage)	41.36	28.12

The results in Table 4 are vice versa to sweep efficiency. This is due to the downward gravitational force from the irreducible saturated water, which is displaced by oil that is higher than the horizontal setup. The volumetric sweep efficiencies are compared in Figure 4.

Table 4. Calculated volumetric sweep efficiency for both horizontally and vertically configured sand-packed columns

Parameters	Horizontal	Vertical
Average water saturation, S_w	0.351	0.409
Oil saturation, S_o	0.649	0.591
Irreducible water saturation, S_{wc}	0.11	0.173
Volumetric sweep efficiency (%)	53.2	57.00

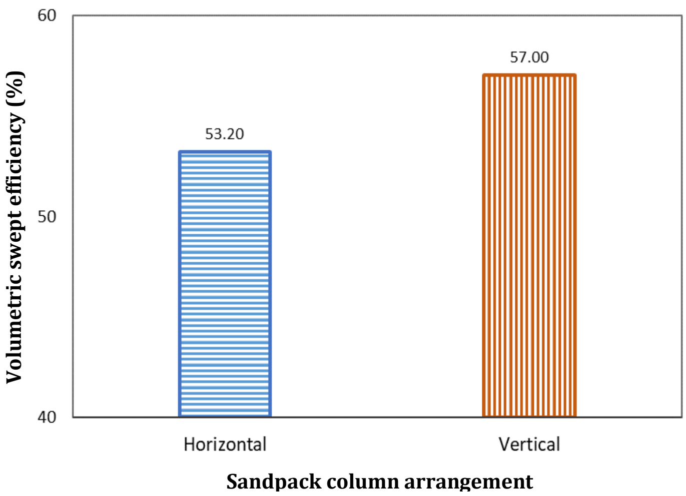

Figure 4. Volumetric sweep efficiency comparison

3.2 RTD Model

The data obtained were analyzed with the RTD software to acquire suitable models describing the radiotracer experiments. The perfect mixer with the exchange model gave the ideal RTD representation for the horizontal arrangement, as shown in Figure 5, while the perfect mixer in parallel model best fit the vertical configuration (see Figure 6). The residual error value was minimum in the model representing the horizontal setup. Based on the model, two zones were present in the horizontal sand-packed column, namely the primary and dead zones (IAEA, 2008). The dead zone locked the residual oil, trapping it, thus resulting in it not participating (exchanging) actively during the waterflooding operation, reducing the oil yield (IAEA, 2008).

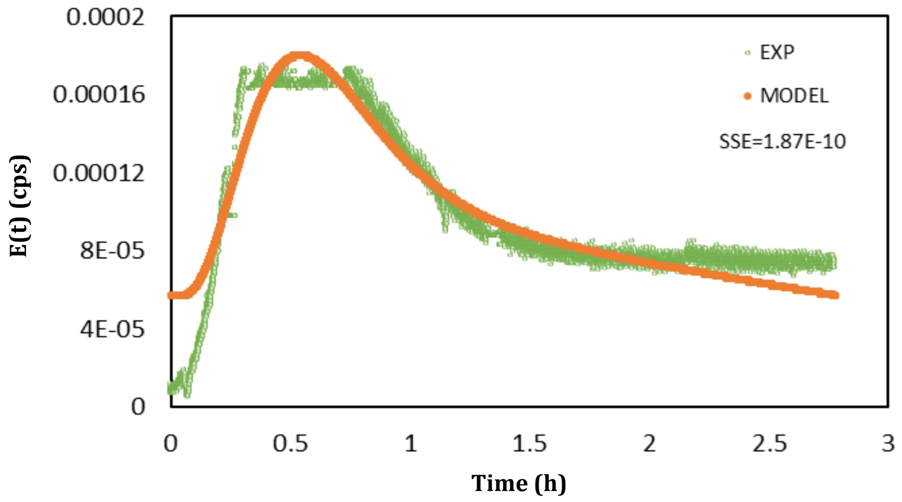

Figure 5. Perfect mixer in series with exchange model for the horizontal column

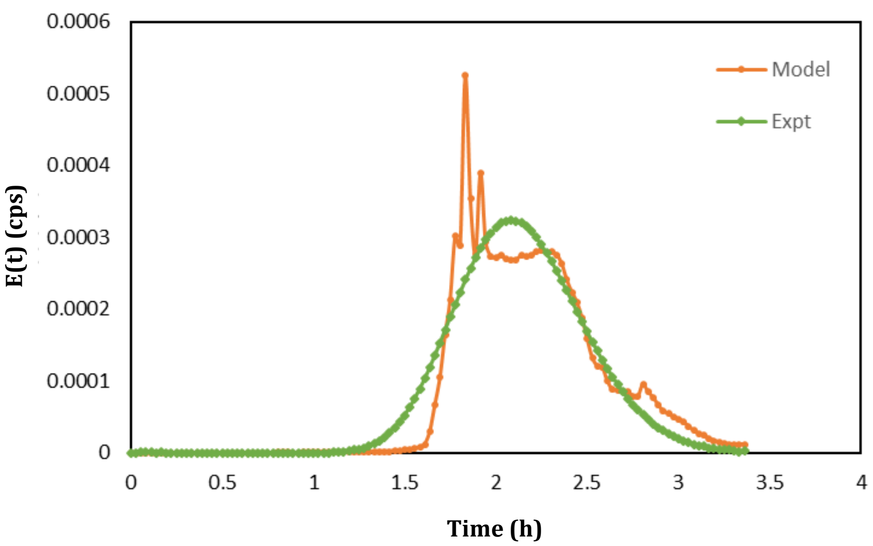

Figure 6. Perfect mixer in parallel model for the vertical column

The two distinctive peaks observed denoted that the sand-packed columns possessed parallel path lines or channels. Channeling, also known as fingering, is a common anomaly detected during chemical processes. The configuration of the compacted sand in the column was random, hence the introduction of several channels that dispersed the brine-tagged tracers during waterflooding. The dispersion probably resulted in the brine possessing less energy to displace the oil, thus leading to diminished oil recovery. This is a natural phenomenon that is being studied by many other researchers to tackle the issues of low oil recovery caused by fingering (Luo et al., 2017; Tang et al., 2020).

3.3 Summary of the horizontally and vertically configured columns

The study demonstrated that the position of the sand columns significantly influenced the overall oil recovery. The comparison can be observed in Table 6 that summarizes the overall observations from this study.

Table 6. Data summary of the sand-packed columns

	Horizontal	Vertical
Average percent recovery	74.73%	63.75%
Sweep efficiency (PV drainage)	41.36%	28.12%
Volumetric sweep efficiency	53.0%	57%
RTD model	Perfect mixer in series with exchange model	Perfect mixers in parallel model
Sums of error	1.87×10^{-10}	1.39×10^{-9}

The amount of oil recovered from the horizontal position was higher than the vertical arrangement. The liquid in the vertical sand column possessed a slower flow rate from opposing gravitational forces, while the fluid in the horizontally configured column encountered minor gravitational force.

The sweep efficiency in the drainage pore volume of the horizontal configuration was superior to the vertical arrangement, at 41.36% and 28.12%, respectively. Salinity also contributed to the oil recovery percentage as lower salinity brine resulted in the oil rapidly separating from the rock surface due to the thicker double expansion layer. Nevertheless, as the brine salinity increased, the sweep efficiency decreased. The sweep efficiency is affected by double-layer expansion where the charges become more negated to oil-brine and sandstone-brine interfaces, where there is a repulsing force between the sandstone and oil (Anjirwala, 2017). As a result, the expansion of the double layer stabilizes the water film surrounding the sandstone, hence, brine injected can sweep the oil that is attached to the sandstone. Nevertheless, as the brine salinity increased, the sweep efficiency decreased.

The calculated values of the horizontal and vertical volumetric sweep efficiency were 53% and 57% respectively. This was due to gravitational force being higher in vertical arrangement. The irreducible saturated water displaced by oil was also higher in the vertical arrangement.

The calculation for pore volume drainage sweep efficiency took into account the size of the sand-pack pore volume drainage efficiency. However, the volumetric sweep efficiency took into account the water saturation, oil saturation, and irreducible water saturation. The calculation of volumetric sweep efficiency only provided a basis calculation using only oil production data. On the other hand, the calculation required reliable estimates of floodable pore volume in the water-sweep zone. Thus, from the data obtained, the horizontal setup was much better than the vertical setup since it produced a better oil yield, the sweep efficiency was higher than in the vertical configuration due to less gravitational force, and the volumetric sweep efficiency was also less than in the vertical. However, the irreducible saturated water displaced by oil was greater in the vertical arrangement. Consequently, the horizontal position was better than the vertical arrangement for oil recovery via waterflooding.

4. CONCLUSION

The investigation on the different types of flow in packed columns in different configurations was successfully executed. Two main conclusions were derived: the arrangement of the sand pack provided different total oil yields and the RTD models provided excellent explanations of why the oil recovery was not optimized during the waterflooding experiments. The RTD models could provide insights to reservoir engineers on the similarity of the fluid flow behavior in reservoir rocks to the fluid flow in other manmade structures such as tanks and pipes. The current study also observed that the horizontal arrangement of the sand-packed column produced a better oil yield, and the utilization of LSW increased the swept efficiency.

Many other factors may be studied in the future to fully understand the rock and fluid flow behavior in oil reservoirs. A field emission scanning electron microscope could be employed for the sand sample to establish its properties such as composition, pH and, surface charges. Variations in these parameters and their interactions between oil-water-rock could affect the performance of EOR processes. Porous micro models could also be utilized to visualize the fluid flow behavior in porous media and consequently increase or extend the life of mature oilfields.

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