INTERWELL TRACER METHOD USING PARTITIONING COMPOUNDS NATURALLY EXISTING IN CRUDE OIL FOR DETERMINATION OF RESIDUAL OIL SATURATION

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Summary

Beside the interwell tracer method in which the artificial tracers are injected into the reservoir, the method of using partitioning organic compounds in crude oil components such as alkylphenols and aliphatic acids as the Natural Partitioning Interwell Tracers (NPITs) to determine residual oil saturation (Sor) has drawn attention as a potential complementary method. Owing to the solubility into both oil and water phases, the concentration of NPITs in oil and also in produced water decreases along water injection time. Based on the similarity with chromatographic retardation principle used in the artificial interwell tracer method, residual oil saturation in the swept area between well pair can be determined by mean transit time from the concentration curve of NPITs analysed in produced water and partitioning coefficients K_d *measured in the laboratory.*

The paper presents the results of using NPITs to calculate Sor based on the data simulated by the UTCHEM simulator on the models of five-spot and direct-line. The results showed that the pairs of compound having partitioning coefficients K_d *in range up to 3.0 can be used to estimate Sor in the injection stage from 1 to 3 pore volumes (PV) with 5% deviation from the Sor value given by the model. The paper also discusses the limitations of the proposed NPIT method that need to be improved and solved in future researches.*

Key words: *Natural partitioning interwell tracer (NPIT), partitioning coefficient, residual oil saturation, numerical simulator.*

1. Introduction

Beside the conventional interwell tracer method in which the artificial tracers are injected into the reservoir, the method of using partitioning organic compounds existing in crude oil such as alkylphenols and aliphatic acids as the Natural Partitioning Interwell Tracers (NPITs) to determine residual oil saturation (Sor) has drawn attention as the potential complementary method [1, 2].

Alkylphenols and aliphatic acids, the organic compounds existing in crude oil, are soluble in both oil phase and water phase in which the distribution of its concentrations between phases is defined by its partitioning coefficient K_d [3, 4]. During water injection, those compounds gradually dissolve into water phase under concentration equilibrium condition that causes reduction of their concentration in both oil phase and water phase. Akasawa and Sinha [1, 2] have proven that the concentration curves of those partitioning compounds obtained by analysis of produced water can be converted into the similar form of injected interwell tracer curves. By applying the chromatographic retardation principle of partitioning solutes moving in mobile phase (water) in contact with immobile phase (residual oil), the residual oil saturation can be determined based on the retardation in transit time of a pair of NPITs and their partitioning coefficients K_d measured in the laboratory under reservoir condition.

This paper presents the preliminary results of using the chromatographic retardation principle to calculate Sor based on the data simulated by the UTCHEM simulator on the models of five-spot and direct-line.

2. Mathematical equations using NPITs for Sor calculation

Suppose the formation contains 2 phases, oil and water, the advection, dispersion and exchange transport of compound k between phases is given by the equation:

$$\varphi \frac{\partial C_k}{\partial t} + \nabla \vec{N}_k = 0 \qquad (1)$$

Where C_k is the concentration of compound in the phases, which is described as:

$$C_k = \sum_{p=1}^{n_p} S_p C_{kp} \qquad (2)$$

and N_k is a flux of compound k including advection and dispersion:

$$\vec{N}_k = \sum_{p=1}^{n_p} \left(C_{kp}\vec{u}_p - \varphi S_p \vec{K}_{kp}.\nabla C_{kp} \right) \qquad (3)$$

In which, $n_p = 2$: number of phases; S_p: saturation of phase p; C_{kp}: concentration of compound k in phase p; K_{kp}: dispersion tensor of compound k in phase p; u_p: velocity of phase p and t: time.

The initial and boundary conditions are as follows:

$$\begin{array}{ll} C_{kp}\big|_{injector} = 0 & t > 0 \\ \begin{cases} C_{kp} = C_{kpI} & t = 0 \\ C_{kp} = 0 & t \to \infty \end{cases} & \end{array} \qquad (4)$$

Where C_{kpI} is the initial concentration of compound k in phase p in formation.

Equation (1) can be solved with the following assumptions: the phasic concentration equilibrium of compound k is instantaneously achieved while oil/water contacting; the partitioning coefficient is constant; no mass transfer of compounds on the boundary of studied zone except boundaries of injection well and production well; at the boundaries of injection well and production well, the diffusion effect is ignored due to the high velocity of water; the degradation, absorption and interaction of compounds are not considered. Equation (1) is then re-written as below:

$$\begin{aligned} &\sum_{p=1}^{n_p} K_{dkp} \iiint \left(\varphi S_p \left(C_{kw} - C_{kwI} \right) \right) dV_R \\ &+ \sum_{wells} \left(q \sum_{p=1}^{n_p} K_{dkp} \int_0^t f_p \left(C_{kw} - C_{kwI} \right) d\tau \right) = 0 \end{aligned} \qquad (5)$$

Where, $K_{dkp} = C_{kp}/C_{kw}$ is the partitioning coefficient of compound k, equal to the ratio of compound concentration in phase p to that in water; C_{kwI} is the initial concentration of compound k in formation water; f_p is fraction of phase p in fluids at production well and q is total production flow.

Equation (5) shows that, if partitioning coefficient K_{dkp} of compound k is measured in laboratory, the saturation of phase p (S_p) in the swept area by water can be calculated by analysis of concentration C_{kw} of the compound in produced water collected at the production well.

Due to $K_{dkw} = C_{kw}/C_{kw} = 1$; f_p at injector =1; $q_{inj} = -q_{prod}$, equation (5) is converted to:

$$\sum_{p=1}^{n_p} K_{dkp} \iiint \left(\varphi S_p \left(\frac{C_{kw} - C_{kwI}}{C_{kwI}} \right) \right) dV_R + q_{prd} m_{0Ck} = 0 \qquad (6)$$

Where, m_{0Ck} is zero-moment of concentration of compound k given by:

$$m_{0Ck} = \int_0^t \left(1 + \left(f_w + K_{dkp} f_o \right) \left(\frac{C_{kw} - C_{kwI}}{C_{kwI}} \right) \right) d\tau \Big|_{producer} \qquad (7)$$

The average transit time of the compound k is defined as:

$$\bar{t}_k = \lim_{t \to \infty} m_{0Ck} = \int_0^\infty \left(1 + \left(f_w + K_{dkp} f_o \right) \left(\frac{C_{kw} - C_{kwI}}{C_{kwI}} \right) \right) d\tau \Big|_{producer} \qquad (8)$$

When t → ∞, the combination of equation (6) with equation (8) gives:

$$V_w + K_{dkp} V_o = q_{pro} \bar{t}_k \qquad (9)$$

Equation (9) contains two unknowns, water volume V_w and oil volume V_o, therefore it needs at least 2 compounds with different K_d to calculate oil saturation S_o as shown in equation (10) below.

$$S_o = \frac{V_o}{V_p} = \frac{\bar{t}_2 - \bar{t}_1}{\left(K_{d2} - 1 \right)\bar{t}_1 - \left(K_{d1} - 1 \right)\bar{t}_2} \qquad (10)$$

Equation (10) was derived by Sinha và Asakawa [1], which is similar to the equation used for artificial partitioning interwell tracer [2]. The NPIT method is of interest to researchers working in the field of environmental study to assess the residues of organic compound contamination in soil.

In this research work, the injection models in five-spot and direct-line forms were created and the transport of naturally partitioning organic compounds was simulated by using UTCHEM simulator to give the concentration of the compounds at the production well. The obtained concentration curves were then exploited to estimate oil saturation by applying equation (10) to assess the feasibility of NPIT method in the practical application.

3. Simulation results

UTCHEM (The University of Texas's Chemical Simulator) is the software for simulating reservoir model with multiphase, multicomponent developed by Texas University. UTCHEM allows simulation of advection, dispersion and exchange of solutes between phases in reservoir media, including the leaching process of oil

***Table 1.** The partitioning organic compounds used in the models*

Partitioning organic compounds	Partitioning coefficient $K_d = \frac{C_o}{C_w}$	Initial concentration in oil (mg/L)	Initial concentration in formation water (mg/L)
Phenol	0.16	1.6	10
4-Methyl Phenol (4MP)	0.58	5.8	10
2-Methyl Phenol (2MP)	0.75	7.5	10
4-Propyl Phenol (4PP)	1.34	13.4	10
3,4-Dimethyl Phenol (34DMP)	1.61	16.1	10
2,4-Dimethyl Phenol (24DMP)	3.09	30.9	10
4-Ethyl Phenol (4EP)	7.37	73.7	10

organic components from oil phase to water phase during oil production [6].

UTCHEM was used to run with two water injection models: the quarter five-spot pattern, which is a common model in stratified sediment reservoir; and the direct-line pattern, which is typical model in edge water injection or gravity injection. The models describe 3-D reservoir having initial oil saturation (Soi) of 0.65 and residual oil saturation (Sor) of 0.35. The quarter five-spot model has the size of 165 x 165 x 12m divided into 55 x 55 x 4 grid cells and the direct-line model has the size of 200 x 100 x 8m divided into 25 x 50 x 4 cells in corresponding ratio of length to width d/a = 2.

The general parameters of the models are:

- Porosity $\varphi = 0.2$; water viscosity $\mu_w = 0.7$cp; oil viscosity $\mu_o = 4$cp;

- Longitudinal and transversal dispersion coefficients are $\alpha_{DL} = 0.03$m and $\alpha_{DT} = 0.003$m, respectively.

- Phasic permeability curve is described in accordance with Corey, with critical water saturation $S_{cwr} = 0.3$; Sor = 0.35; water endpoint: 0.15; oil endpoint: 0.85; water exponent: 1.5; oil exponent: 2; end point mobility ratio = 1.

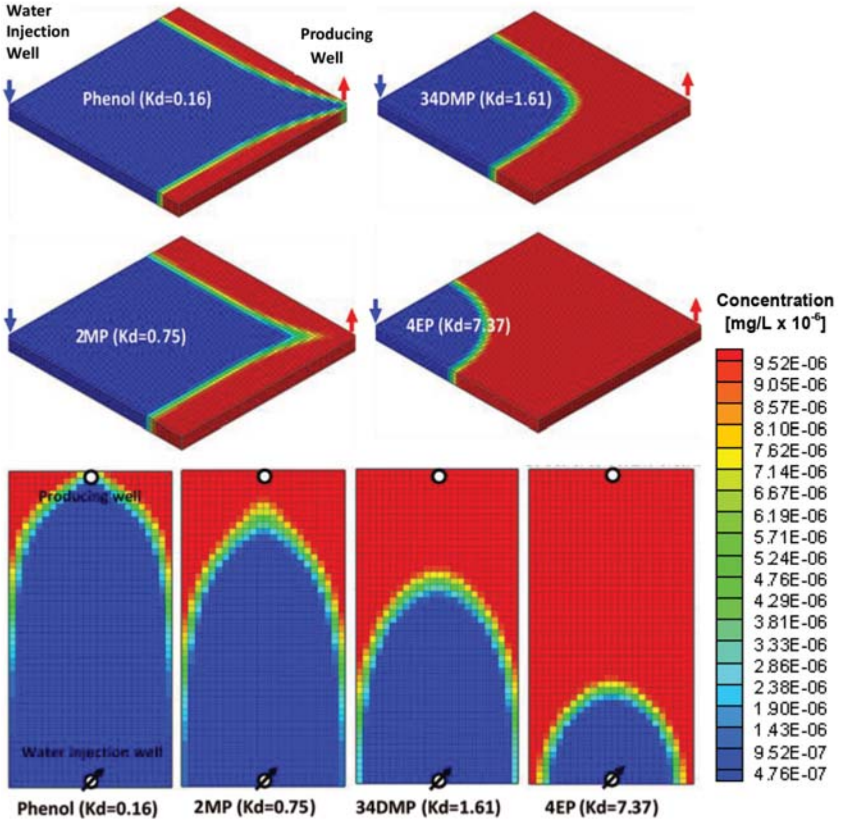
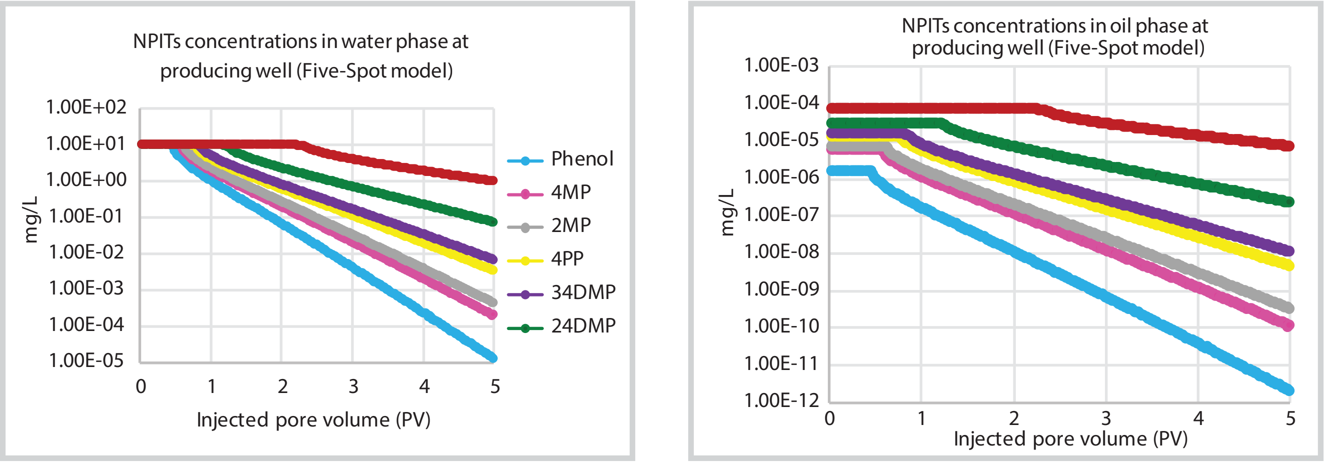


***Figure 1.** Concentration distribution of phenol, 2MP, 34DMP and 4EP in five-spot (top) and direct-line (bottom) at 0.6PV*

The initial concentration and partitioning coefficient of the partitioning organic compounds in crude oil referred to in the experimental data of Tracer Lab of CANTI are listed in Table 1. All compounds are supposed to have the same density, ankane number and chemical properties but different partitioning coefficients.

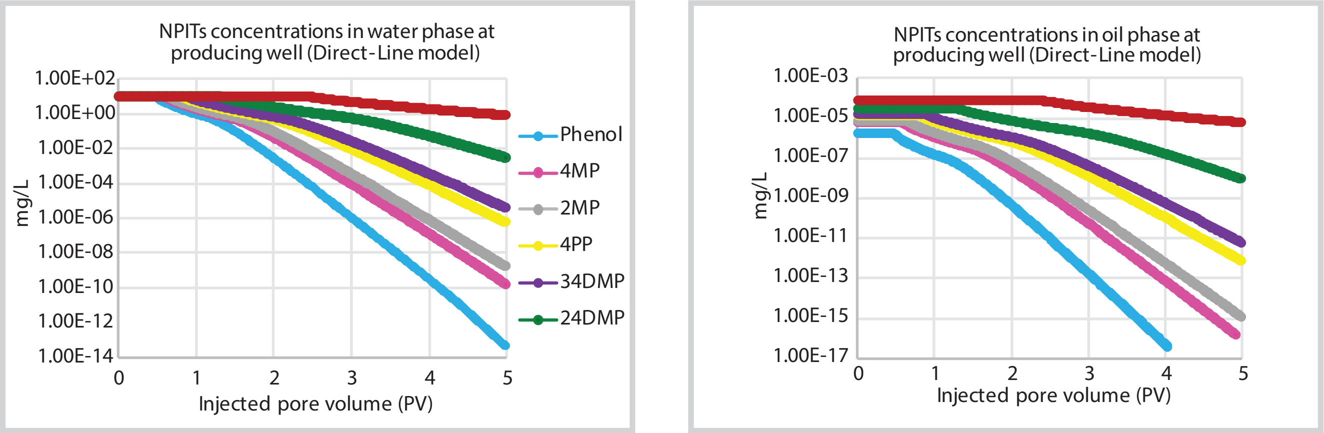
Water injection last till 5 pore volumes (PV) of model in order to recover most of the compounds in producer. Concentration of the compounds was supposed to instantaneously achieve equilibrium between oil and water during water injection. Figure 1 illustrates concentration distribution in the model at 0.6PV stage of water injection. Figures 2 and 3 show the concentration curves of the compounds in water and oil obtained at the producer. Figure 4 and 5 introduces the calculated results of oil saturation S_o in accordance with equation (10), whereas average transit time is calculated from equation (8).

Figures 2 and 3 show the concentrations of NPITs in oil phase and water phase are reduced with time, in which the greater K_d the slower reduction



(a) *(b)*

Figure 2. *Concentration curves of NPITs in water phase (a) and oil phase (b) at the production well in Five-spot model*



(a) *(b)*

Figure 3. *Concentration curves of NPITs in water phase (a) and oil phase (b) at the production well in direct-line model*

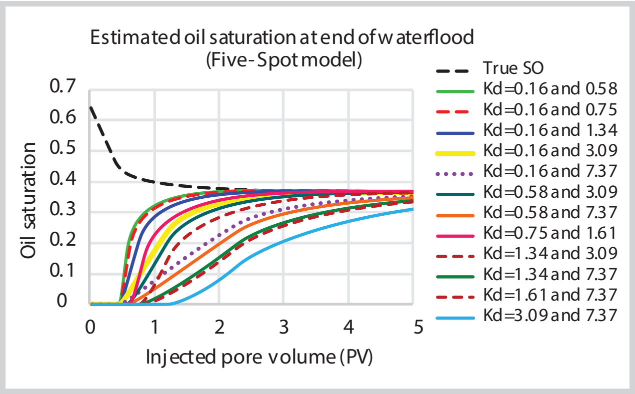


Figure 4. *Values of Sor calculated from equation (10) by using the pairs of NPITs at different accumulated injection volume in five-spot model*

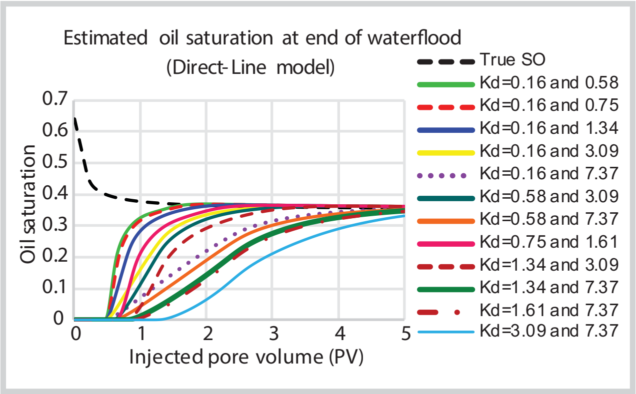


Figure 5. *Values of Sor calculated from equation (10) by using the pairs of NPITs at different accumulated injection volume in direct-line model*

rate. In Figures 4 and 5, the values of Sor calculated from equation (10) using the different pairs of compounds are being asymptotic to the value of model. The different pairs give different asymptotic time. The smaller K_d pair gives the quicker asymptotic time that is helpful to estimate Sor at early stage of water injection, while the greater K_d gets later asymptotic time that is suitable to estimate Sor at the later stage of injection. It is possibly recognised from Table 2 that, the pair of compounds NPITs having K_d smaller than 3.0 can be used to calculate Sor at deviation to that of model in the range of 5%, when applying at the stage from 1 to 3PV which is common in the practice of water injection.

***Table 2.** Results of Sor calculation in comparison with Sor from model using NPITs of different K_d*

	Five-Spot Model			**Direct-Line Model**		
Accumulated injection volume	1PV	3PV	5PV	1PV	3PV	5PV
Sor from model	0.38	0.36	0.36	0.37	0.36	0.35
Values of Sor calculated from equation (10) by using the pairs of NPITs at different accumulated injection volume. The relative deviation of calculated Sor to modelled Sor is given in parentheses						
Phenol & 4MP **(K_d = 0.16 & K_d = 0.58)**	**0.32** (14.1%)	**0.37** (1.5%)	**0.36** (1.5%)	**0.31** (15.1%)	**0.37** (2.8%)	**0.36** (3.1%)
Phenol & 2MP **(K_d = 0.16 & K_d = 0.75)**	**0.32** (16.3%)	**0.37** (1.5%)	**0.36** (1.5%)	**0.30** (17.1%)	**0.37** (2.8%)	**0.36** (3.1%)
Phenol & 4PP **(K_d = 0.16 & K_d = 1.34)**	**0.28** (25.3%)	**0.37** (1.5%)	**0.36** (1.5%)	**0.28** (24.8%)	**0.36** (2.3%)	**0.36** (3.1%)
Phenol & 24DMP **(K_d = 0.16 & K_d = 3.09)**	**0.16** (58.1%)	**0.36** (0.1%)	**0.36** (1.5%)	**0.17** (54.8%)	**0.35** (0.6%)	**0.36** (2.8%)
Phenol & 4EP **(K_d = 0.16 & K_d = 7.37)**	**0.07** (81.5%)	**0.31** (12.8%)	**0.35** (0.6%)	**0.07** (80.0%)	**0.31** (13.3%)	**0.35** (1.0%)
4MP & 24DMP **(K_d = 0.58 & K_d = 3.09)**	**0.11** (70.6%)	**0.36** (0.8%)	**0.36** (1.5%)	**0.12** (66.2%)	**0.35** (2.1%)	**0.36** (2.6%)
4MP & 4EP **(K_d = 0.58 & K_d = 7.37)**	**0.04** (88.8%)	**0.30** (16.5%)	**0.35** (1.2%)	**0.05** (87.1%)	**0.29** (17.5%)	**0.35** (2.1%)
2MP & 34DMP **(K_d = 0.75 & K_d = 1.61)**	**0.21** (44.5%)	**0.37** (1.3%)	**0.36** (1.5%)	**0.22** (40.7%)	**0.36** (1.0%)	**0.36** (3.0%)
4PP & 24DMP **(K_d = 1.34 & K_d = 3.09)**	**0.04** (89.5%)	**0.35** (2.9%)	**0.36** (1.5%)	**0.06** (84.3%)	**0.34** (5.4%)	**0.36** (2.2%)
4PP & 4EP **(K_d = 1.34 & K_d = 7.37)**	**0.01** (97.0%)	**0.27** (23.9%)	**0.35** (2.5%)	**0.02** (95.5%)	**0.27** (25.2%)	**0.34** (4.5%)
34DMP & 4EP **(K_d = 1.61 & K_d = 7.37)**	**0.005** (98.7%)	**0.26** (26.7%)	**0.35** (3.0%)	**0.01** (97.5%)	**0.26** (27.9%)	**0.33** (5.5%)
24DMP & 4EP **(K_d = 3.09 & K_d = 7.37)**	**0.00** (100.0%)	**0.21** (41.8%)	**0.33** (7.0%)	**0.00** (100%)	**0.21** (42.0%)	**0.31** (11.9%)

The results also showed that the NPIT method can be applied for thedetermination of Sor for both five-spot and direct-line modes. However, the error of calculation is a little larger in the direct-line model.

4. Conclusions

The injection models in five-spot and direct-line forms were created and the transport of natural partitioning organic compounds was simulated by using UTCHEM simulator to give the concentration values of the compounds at the production well. From the obtained concentration curves, the NPIT method was then applied to calculate the residual oil saturation based on the principle of chromatographic retardation of the pair of partitioning compounds having different partitioning coefficients. The calculated values of Sor were compared with the values given by the models to assess the feasibility of the NPIT method.

The results showed that the pairs of compounds NPITs having K_d smaller than 3.0 can be used to calculate Sor at deviation to that of model in the range of 5%, when applying at the stage from 1 to 3PV which is common in the practice of water injection.

However, the simulation has not taken into account the effect on the concentration curves from water injection adjustment, reservoir heterogeneity, temperature change and the contribution of water injection from different sources, etc. In addition, the application of the principle of chromatographic retardation was based on the conditions that the concentration curves of NPITs have to be obtained from the beginning time of water breakthough with the availability of initial concentration from formation water. In fact, this condition is only applicable when the sampling survey commences along with water injection and lasts till water injection accumulation over 1PV.

Anyhow, determination of Sor value in the water-out reservoir is a manifest demand before proceeding to enhanced oil recovery. Low costs and the possibility to deploy the method on a series of production wells are great advantages ands further researches should be conducted to improve the method for practical application.

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