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A comprehensive framework for the theoretical assessment of the single-well-chemical-tracer tests

Rasoul Khaledialidusti *, Jon Kleppe

Norwegian University of Science and Technology, Norway

A B S T R A C T

Single-well-chemical-tracer (SWCT) is the most commonly used field method to determine oil or water saturation in one-spot pilot. This method is a complex process due to many effective parameters and non-ideality factors involved. Understanding the extent to which theses parameters might affect the SWCT test profiles could help us to manage and design the SWCT test more efficient at different reservoir conditions. This paper proposes a comprehensive framework of a new approach to highlight different aspects of the SWCT tests theoretically before implementing the field test. In order to accomplish the task, combining of numerical and analytical solutions have been used.

The devised algorithm has been programmed in six different stages. In the first four stages, all test design parameters in different investigation regions and retardation factors are calculated. The test design parameters are sizing the test volume, test timing (i.e., injection, shut-in, and production), tracer concentration during the test, and the mean residence volume. In the fifth stage, all criteria are taken into consideration to find the most efficient test designs. Then, the achieved parameters are applied in the simulation stage (sixth stage) to investigate the effect of the ester bank and concentration, ester properties, shut-in time. The geochemical speciation code PHREEQC is also used to study the level of pH-variation during shut-in time. The effects of the calcite dissolution, temperature, and initial buffer capacity have been evaluated on the probability of pH-variation. The results show that the probability of pH-variation increases with temperature and lower amount of calcite concentration.

To evaluate the workflow methodology, two different field test cases with different reservoir conditions are employed in order to reflect the influence of different stages of the algorithm. We hope that the workflow developed can be used to minimize the uncertainties and improve the quality of the SWCT tests.

1. Introduction

Determination of remaining oil saturation (S_o) is vital in managing and selecting the EOR methods for economic exploitation of a reservoir. There are many methods to determine S_o including laboratory and field methods (Kidwell and Guillory, 1980; Donaldson and Staub, 1981; Blackwell, 1985; Chang et al., 1988; Teklu et al., 2013; Khaledialidusti et al., 2014). The laboratory methods are not representative for the large scale of a reservoir and may not precisely predict S_o at reservoir scale even when performed with extreme accuracy. Therefore, field methods to determine S_o at reservoir scale are more reliable. Recently, a combination of the field methods is also proposed in order to determine a more accurate S_o (Khaledialidusti et al., 2015b). Tracer methods were introduced as the most efficient field methods largely due to (1) the measurement over large reservoir volume beyond damaged and desaturated regions and (2) non-dependency on porosity (Khaledialidusti et al., 2015b).

The earliest tracer technique is the well-to-well method (Cooke, 1971). This method employs two or more non-reactive tracers with different partitioning coefficient $\left(K = \frac{C_o}{C_w}\right)$, where C_o and C_w are the tracer concentrations in oil and water phases at equilibrium. Cooke's method includes the injection of a solution of the non-reactive tracers (e.g., 1% for each tracer) with different K-values into the reservoir (i.e., "tracer bank"). Then, this slug pushes through the formation by the volume of water (i.e., "push bank"). Different K-values lead to traveling speeds of the tracers at different velocities and thus different arriving times to the production well. The separation between tracer profiles at the production well may be employed to determine S_o. The main limitations of this method are: (a) long measuring time because of large measured volume between two wells and (b) extreme tracer dispersion especially in layered formations.

An SWCT method, which is implemented only in a one-spot pilot, was developed by Deans (1971) to resolve the barriers of the well-to-well method. The SWCT method includes the injection of the chemical reactive tracer (ester) bank into the target well. Then, the ester bank displaces away from the wellbore to a radial depth of investigation by the push bank. After the injection step, the well is shut-in for a period of 1–10 days,

* Corresponding author.
E-mail address: rasoul.khaledialidusti@ntnu.no (R. Khaledialidusti).

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Nomenclature

S_o	Remaining oil saturation
B	Retardation factor
K_{eq}	Equilibrium reaction constant
K	Ester partitioning coefficient
K_H	Hydrolysis reaction rate
X_h	Fraction of hydrolyzed ester
ρ_A	Ester density
δ	Ratio of ester solution to ester bank
C_o	Tracer concentration in oil phase
C_w	Tracer concentration in water phase
C_A	Ester concentration
C_B	Product alcohol concentration
R	Investigation region
r_w	Wellbore radius
q_{inj}	Injection rate
q_{prod}	Production rate
t_{inj}	Injection time
t_{prod}	Production time
t_{soak}	Shut-in time
t_e	Ester traveling time
t_w	Water traveling time
u_e	Ester velocity
u_w	Water velocity
C	Ratio of shut-in time to transient time
M	Ratio of injection rate to production rate
M	Ratio of injection time to shut-in time
N	Number of gridblocks
∅	Porosity
H	Interval size of the target well
V_{slug}	Ester bank volume
V_{Total}	Total injected volume
U_D	Interstitial linear "drift" velocity
D	Square of the ratio of the total "drift" to R-value
CDC	Capillary Desaturation Curve
N_c	Capillary number
N_{cc}	Critical capillary number
N_{Pe}	Peclet number
B	Grain size
u_N^*	Interstitial velocity
D_m	Molecular diffusion coefficient
D_{II}^*	Physical dispersion

depending mainly on the reservoir temperature. During this period, the ester hydrolyses via reaction with the formation water to produce a kind of product alcohol (second tracer) and a small amount of acid (Ester + H_2O ↔ Alcohol + Acid). At the end of this period, the unreacted (remaining) ester and the product alcohol are located together away from the wellbore before the production step. During the production step, samples of the produced water are collected at the wellhead and analyzed for the tracer concentrations. The effect of different K-values leads to an observable separation between the product alcohol and unreacted ester profiles.

Although the SWCT method overcomes the limitations of the well-to-well method, other limitations are encountered. These are: (a) a shorter depth of the investigation region (R-value) that is typically in the range of 10–50 (ft) (Deans and Carlisle, 2007), and (b) the effect of the product acid on the pH of the environment that is evaluated in this paper.

Larger R-values are more promising for the determination of S_o because of the larger measured volume and being further away from the wellbore damage and capillary desaturated zone. In practice, however, reaching the larger R-value is limited by some restrictions such as hydrolysis reaction during injection and production times and detection limit of tracers.

The other difficulty of the SWCT method is the effect of the product acid on the reliability of the S_o measurement. Wellington and Richardson (1994) believed that the product acid affects the S_o measurement. However, Deans and Ghosh (1994) and Ghosh (1994) contradicted that belief. We believe that the effect of the product acid on the reliability of the test results depends on many parameters such as reservoir temperature and pH, formation brine, rock compositions, ester bank and concentration, and shut-in time. In this paper, all of these effective parameters and all geochemical reactions that could affect the pH of the reservoir during the SWCT test have been taken into account using PHREEQC (Parkhurst and Appelo, 1999), which is a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. The main objective of this research is to highlight different aspects of the SWCT tests and the extent to which theses aspects affect the SWCT test profiles.

A comprehensive framework has been devised by the use of numerical and analytical analysis to take into consideration all parameters that affect the SWCT test profiles. The analytical solution is based on the assumptions of the ideal SWCT test and the effects of the non-idealities on the deviation from the ideal test have been considered. These assumptions are: (1) water soluble product alcohol, (2) impulse ester injection, (3) no dispersion and mixing effects, (4) no reaction during transient (injection and production) time, (5) no fluid drift (i.e., ester is stationary during shut-in time), and (6) flow reversibility.

2. SWCT test design

All of the effective parameters on the SWCT test are linked together as a chain and they also influence each other considerably, as shown in Fig. 1.

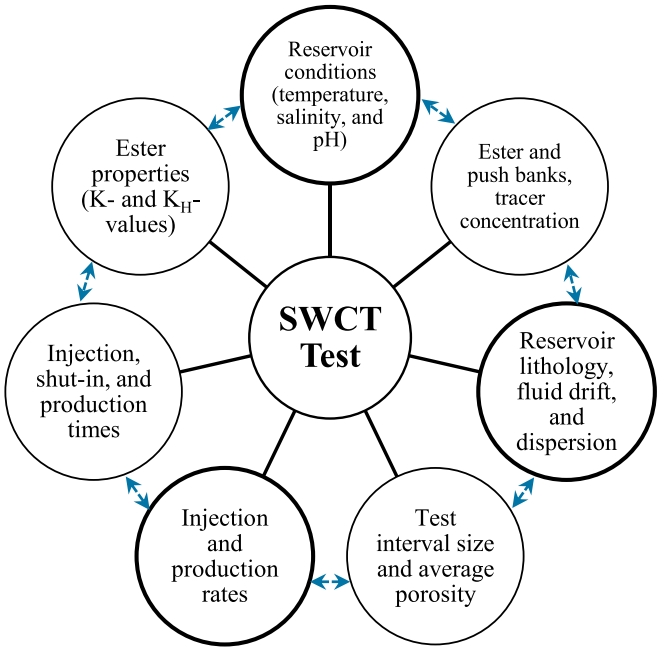

Fig. 1. Effective parameters on the SWCT test design.