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Experimental study on the variation of relative permeability due to clay minerals in low salinity water-flooding

Changkyun Kim, Jeonghwan Lee*

Department of Energy and Resources Engineering, College of Engineering, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju 61186, Korea

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ABSTRACT

This study presents experimental results on the variation of relative permeability due to clay types and contents in low salinity water-flooding. To analyze the effect of clay types and contents on relative permeability, core-flooding using unconsolidated sand core samples was conducted. Relative permeability curves were measured from the experiments using the Johnson, Bossler, and Naumann (JBN) method. From the results, the moving range (S_{or}-S_{wi}) of the relative permeability curve was proportional to the clay contents of kaolinite. The moving range for illite also showed a relative permeability curve proportional to the clay contents, but it was less than that for kaolinite. To extend the equation of the Honarpour end-point relative permeability curves in low salinity water-flooding, end-point relative permeability curves were matched with the experimental relative permeability curves by changing the Honarpour index N_o and N_w. Then, the difference of N_o and N_w between the conventional water-flooding and the low salinity water-flooding was correlated with the clay contents. Based on the results, extended functions of index N_o and N_w were proposed to describe the relative permeability curves applied to low salinity water-flooding. It is believed that end-point relative permeability curves can be determined by the proposed N_o and N_w instead of the conventional exponent index in low salinity water-flooding with reservoirs containing kaolinite.

1. Introduction

Due to the continuous decrease in the global oil price, a number of alternatives are needed to produce oil commercially. Therefore, Improved Oil Recovery/ Enhanced Oil Recovery (IOR/EOR) techniques, as shown in the Fig. 1, have been studied to improve oil recovery. As one of the oil recovery techniques, water-flooding has generally been conducted as a secondary recovery to maintain the reservoir pressure by injecting the water recovered at primary recovery. For an alternative to secondary recovery, low salinity water-flooding, which can be operated commercially compared to other EOR methods, has been conducted and studied continuously. Jadhunandan (1990) and Jadhunandan and Morrow (1995) reported oil recovery improvement by low salinity water, when a reservoir contains high salinity formation water and clay minerals. Yildiz and Morrow (1996) introduced the improvement of recovery due to chemical influences through low salinity water-flooding experiments on high salinity sandstone cores. Most experimental studies of wettability alteration were conducted with bead packs or other models, although some more recent studies have used reservoir rock such as epoxy or Wood's metal which can be solidified in situ (Anderson, 1984). Yang et al. (2015) reported the impact of brine composition and salinity on the wettability of sandstone, whereby the wettability can be changed by changing the brine composition and salinity. It is believed that presence of clays is important in the low salinity effect. It may be necessary to have kaolinite. Kaolinite and illite are non-swelling clays that tend to detach from the rock surface and migrate when the colloidal conditions are conducive for release (Mohan et al., 1993). Different authors reported the importance of different types of clays. Larger et al. (2006) suggested that kaolinite played the most important role and proposed a correlation between kaolinite content and additional oil recovered by low salinity water-flooding. Austad et al. (2010) identified the effect of clay types using adsorption tests. They proposed a chemical mechanism for wettability alteration during low salinity water-flooding. Skrettingland et al. (2011) reported incremental oil recovery of 2% of OOIP by injection of diluted seawater using clayey cores from Snorre field. Wang and Alvarado (2011) used bottle test and optical microscopy and found that kaolinite and silica dispersion in low salinity environment made the water-oil emulsion more stable. They concluded that more stable emulsion could act as mobility control agents and hence contribute to enhanced oil recovery. Barnaji et al. (2016) conducted visual investigation to analyze the effects of clay minerals using micromodel. In the

* Corresponding author.
E-mail address: jhwan@jnu.ac.kr (J. Lee).

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Nomenclature

k_{rnw}	non-wetting phase relative permeability
k_{rw}	wetting phase relative permeability
k_{rnw}^{o}	end-point non-wetting phase relative permeability
k_{rw}^{w}	end-point wetting phase relative permeability
S_w	water saturation
S_{nwr}	residual non-wetting phase saturation
S_{wr}	residual wetting phase saturation
N_o	non-wetting phase Honarpour exponent
N_w	wetting phase Honarpour exponent
C_k	Kaolinite contents (fraction)
ΔN_o	difference of N_o in LSI to HSI
ΔN_w	difference of N_w in LSI to HSI
N_{wl}	exponent N_w in low salinity water-flooding
N_{wh}	exponent N_w in honarpour index
N_{ol}	exponent N_o in low salinity water-flooding
N_{oh}	exponent N_o in honarpour index

case that the micromodel had no clay, low salinity water-flooding did not have any effect on oil recovery. In clayey sandstone, carboxylic acid contained in the oil binds to the Ca^{2+} that is attached on clay surface. This makes wettability change to oil-wet condition. When performing the low salinity water-flooding, the chemical reaction causes the change from the oil-wet to the water-wet. As wettability altered into water-wet, it affects the change of contact angle, capillary pressure, relative permeability, and residual saturation. Due to this reaction, water relative permeability is lower and oil relative permeability is higher in comparison to oil wet reservoir at a given water saturation (Lashgari et al., 2016). Thus, degree of the wettability alteration depends on the type and content of clay which has different capacity to adsorb carboxylate in low salinity water-flooding. However, few studies have been carried out on the variation of the relative permeability influenced by the wettability alteration due to clay types and contents in low salinity water-flooding. In reservoir simulation, the relative permeability used as input data during low salinity water-flooding can be inappropriate, if the calculation of relative permeability does not reflect the clay types and contents. This inappropriate relative permeability results in reserve estimation and production prediction with an error. End point equations proposed by Honarpour et al. (1982) are the most commonly used method for predicting relative permeability curves. In end point relative permeability, the values of relative permeability are changed by exponents (N). When N_o and N_w decrease, value of k_{ro} tends to decrease and value of k_{rw} tends to increase at a given water saturation. It means that exponents are most important parameters to describe the change of relative permeability due to wettability alteration. However, exponents used in conventional endpoint relative permeability considered only index classified as the lithology of reservoir rock such as carbonate or sandstone. So, it is essential to modify N_w and N_o to reflect the changes of relative permeability due to clay type and contents. The aims of this study are to present the effect on the variation of relative permeability due to the differences between clay types and contents in low salinity water-flooding and to extend the equation of Honarpour end-point relative permeability curves for application to low salinity water-flooding. To measure the relative permeability curves, core-flooding is conducted with low salinity water when the core contains high salinity water and clay minerals. The relative permeability curves from the experiments are measured using the Johnson, Bossler, and Naumann (JBN) method.

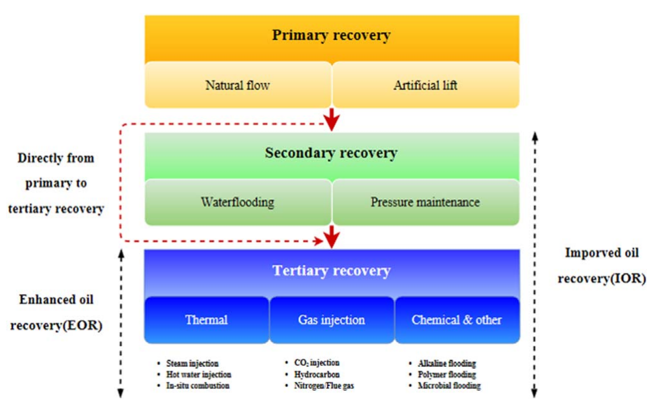

Fig. 1. Enhanced oil recovery chart.

2. Theoretical background

Oil attaches to cations because the carboxylate component which forms an ionic bridge with the cation, such as Ca^{2+} and Mg^{2+}, is adsorbed on the clay surface. Due to this chemical bonding, the initial rock wettability inside the reservoir is changed to an oil-wet condition (Austad et al., 2010). Carboxylate polar compounds push the most unstable cations on the clay surface, forming a reservoir of oil-wet condition when the reservoir contains high salinity formation water. In this condition, multicomponent ion exchange (MIE) occurs when low salinity water is injected into the reservoir as an EOR method. Because of MIE, wettability changes into a water-wet condition and the residual oil saturation is reduced. As a consequence, oil recovery is improved (Morrow et al., 1998; Boussour et al., 2009). Changes of wettability also affect the relative permeability curves that represent the flow of fluids. The relative permeability curves in low salinity water-flooding shift to the right side of the X-axis compared to those in conventional water-flooding, as shown in Fig. 2.

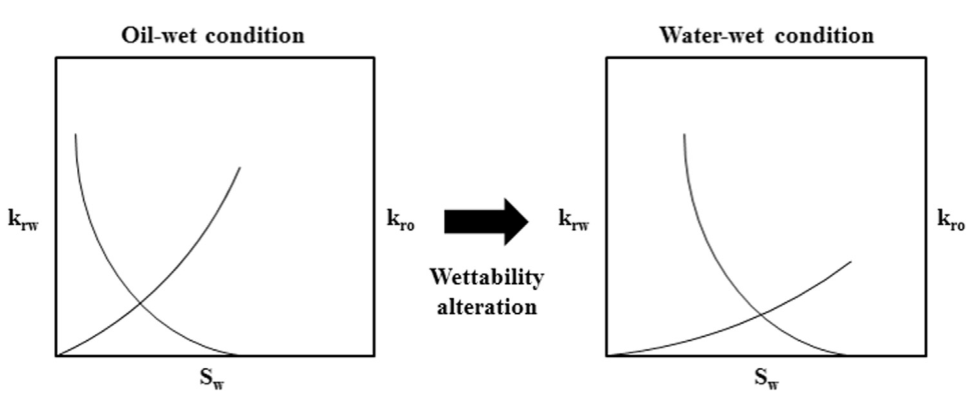

Fig. 2. Movement of relative permeability curve due to wettability alteration.