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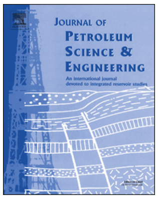

Monitoring the influence of dispersed nano-particles on oil–water relative permeability hysteresis

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ABSTRACT

In recent years, polysilicon nanoparticles are used to enhance the oil recovery through the water injection process in oilfields. The contributing mechanisms are the reduction of interfacial tension and wettability alteration which lead to improving or decreasing the oil phase relative permeability and can be traced by change of relative permeability curves. However, profound understanding of the effect of dispersed nano-silica particles on the hysteretic behavior of relative permeability curves remains a controversy topic in the literature.

The current study illustrates the influence of dispersed silica particles on hysteretic trend of two-phase curves of oil–water relative permeability. Displacement tests of light crude oil by water as well as water dispersed Nano-silica particles were performed on a sandstone rock sample, and the relative permeability curves of oil and water phases were considered for two successive cycles of imbibition and drainage processes. Primarily, the results revealed that the degree of hysteresis in two phase relative permeability decreased as the dispersed nano-silica particles were used in the tests; besides the hysteretic behavior of relative permeability curves decreased as the injection proceeded into its second cycle. Moreover, the relative permeability of non-wetting phase changed significantly while the changes for wetting phase did not appear quite considerable. The results of this work can help with finding an appropriate relative permeability curves during EOR processes in case of changing the direction of displacement.

1. Introduction

Nowadays, nanoscience and technology has been used in oil and gas industry for improving oil and gas recovery. There are many areas in which nanotechnology can contribute to raise the efficiency of production, by making it less expensive and more environmentally attractive than those that are readily available (Sunjay, 2011). The nano-fluids are made by addition of nano-particles to fluids with the purpose of intensification and improvement of some features at low concentrations of the dispersing medium which leads to the following advantages: increase in sedimentation stability and creation of thermal, optical, stress–strain, electrical, rheological and magnetic properties that strongly depend on the size and shape of the nano-particles (Romanovsky and Makshina, 2004). SiO_2 nano-powder is a new type of augmented injection agent that has the ability of stronger hydrophobicity and lipophilicity, and can be absorbed on the rock surface leading to changes in the rock wettability level. It can be classified into two types: lipophobic and hydrophilic polysilicon nanoparticle (LHPN) and hydrophobic and lipophilic polysilicon nanoparticle (HLPN) (Ju et al., 2002; Ju and Fan, 2009; Suleimanov et al., 2011). On the other hand, it can reduce the Inter Facial Tension (IFT) between two phases, enhance oil effective permeability and reduce injection pressure and augment injection rate (Wang et al., 2010). One of the effective methods applied to trace the dominant mechanism during displacement of such fluids is to extract the relative permeability curves.

There are two basic approaches for extracting relative permeability curves from laboratory core flood tests. In the steady-state method, the fluids are injected simultaneously into core plug samples. In the unsteady-state method, a fluid is injected to displace another fluid already available in the core. Processing the data of steady-state test is relatively simple, but its experiments are time consuming. On the contrary, unsteady-state laboratory tests can be performed rapidly, but data processing is a much more difficult task. Moreover, the steady state methods have been occasionally used in determination of three-phase relative permeability curves (Masihi et al., 2011); while, it is more common to use unsteady state displacement experiments in two

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Nomenclature

S_{w_c}	connate water saturation, percent
σ	surface tension, N/m^2
d_e	deduction of droplet shape, m
ρ^{Brine}	density of brine, kg/m^3
$\rho^{CrudeOil}$	density of crude oil, kg/m^3
S_2	Saturation in the core outlet, percent
f_o	fractional flow of oil, fraction
W_i	cumulative invading-phase injection volume, m^3
I_r	injectivity capacity, fraction
u	flowing velocity, m/s
ΔP	pressure drop, kPa
μ_w	viscosity of water, cP
μ_o	viscosity of oil, cP
PV	volume of injection based on pore volume of core sample
$S_{o,w}$	saturation of oil/(nanofluid or water) phase
$S_{o,w(min)}$	minimum saturation of oil/(nanofluid or water) phase
$S_{o,w(max)}$	maximum saturation of oil/(nanofluid or water) phase
$K_{r_{o,w}}$	relative permeability of oil/(nanofluid or water) phase
$K_{r_{o,w\ (min)}}$	minimum relative permeability of oil/(nanofluid or water) phase
$K_{r_{o,w\ (max)}}$	maximum relative permeability of oil/(nanofluid or water) phase
$K_{r_{o,w\ (norm)}}$	normalized relative permeability of oil/(nanofluid or water) phase
λ	exponent of capillary pressure curve
P_d	displacement threshold pressure defined from capillary pressure curve

phase systems. There are three approaches in two phase relative permeability calculations from unsteady state displacement experiments (Hussain et al., 2010; Parvazdavani et al., 2013):

(a) Analytical methods (Johnson et al., 1959; Toth and Civan, 2002); (b) Semi-analytical methods (Civan and Donaldson, 1989; Udegbunam, 1991); (c) History matching method (Archer and Wong, 1973).

However, at the absence of gravity effects and lack of capillary dominancy, the Johnson, Bossler, Naumann (JBN) method can be selected due to its simple and quick calculating procedure.

Since the mechanisms activated by the use of nanoparticles have their dominant effects whenever injected via carrying fluids such as water in successive and continuous cycles of injections, the study of the hysteretic behavior of relative permeability curves are vital for clarifying two phase transport phenomenon. Curves related to hysteretic behavior of relative permeability and non-monotonic change of phase saturations have long been recognized in almost every process of oil recovery (including water flood in heterogeneous reservoirs, WAG injection, water coning, gravitational separation, steam and polymer huff-and-puff stimulations). Numerous experimental and mathematical modeling studies have focused on the examination of the two-phase history dependent flow (Braun and Holland, 1995). The hysteresis for the wetting phase is believed to be very slight and the relative permeability curve for the wetting phase is approximately similar for both drainage and imbibition processes (Aziz and Settari, 1979). Nevertheless, Jones and Roszelle (1987) presented the case of more significant difference between imbibition and drainage relative permeability for water rather than for the oil phase (Jones and Roszelle, 1987). None of the previous studies have addressed the effects of nanopowders on hysteretic behavior of two phase flow in oilfields by virtue of changing the wettability of reservoir rock through their adsorption on porous walls of sandstone samples or the change of IFT between flowing phases.

In the present study, the dominant mechanisms in nano-fluid injection in the case of EOR processes was examined. By analyzing the relative permeability curves in both cases of water and nano-fluid injection, the effect of nano-fluid flooding's on the hysteretic behavior of relative permeability curves were investigated.

2. Experimental setup and procedure

In this study, a light oil sample from one of the oil reservoir from the west Iran was used. Fluid properties are illustrated in Table 1.

Firstly, nano-particles were dispersed in the saline water phase using ultrasonic radiation with 400 W of power for 15 min. The concentration of the nano-particles was selected 0.1% (i.e. 1000 ppm) which was reported as the optimum concentration (Safari and Jamialahmadi, 2013). This content of nano-particles was solved in brine with 1% concentration (i.e. 10,000 ppm). Properties of nano-silica particles are given in Table 2.

2.1. Core sample properties

During the experiment, non-fractured (i.e. sand stone) core sample was used. The properties of the core sample with absolute permeability of 10.59 mD are given in Table 3.

2.2. Apparatus

In this experimental work, due to fast implementation, the unsteady state displacement approach was used. A schematic diagram for the connections in the displacement apparatus is illustrated in Fig. 1.

Table 1
Working fluids information at standard conditions.

Parameter		**Value at standard condition (101 kPa & 16 °C)**
API	dimensionless	41
Viscosity, μ_o	Pa s	3.25E−3
Molecular weight,	kg/mol	0.093
Density, ρ_l	kg/m^3	820
C12+ molecular weight,	kg/mole	0.250
C12+ density	kg/m^3	860
CO_2 viscosity, μ_g	Pa s	0.014E−3
CO_2 density, ρ_v	kg/m^3	1.869

Table 2
Nanosilica properties.

Parameter		**Value**
Particle	dimensionless	SiO_2
Average particle size	(m)	14E−9
Specific surface area (BET)	(m^2/kg)	200 ± 25E+3
Tamped density	(kg/m^3)	~50